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Distributed Computing

Towards Datamarkets with Bitcoin

Master Thesis

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Abstract

In recent years, there has been a widespread expansion of data collection and complex methods to analyze such collected data. Everyone is constantly generating data by using a large range of computers, smartphones, and gadgets. In addition, there is an emerging trend towards the Internet of Things technologies that consist of billions of sensor nodes bridging the gap between the physical and the digital world, and creating massive amounts of data, but with no incentive to share.

In order to provide an incentive for the sensor node owners to share the generated data, these sensor networks have to initiate data markets that interested customers can subscribe to and pay for the acquired data. Bitcoin provides an Internet-native payment mechanism and protocols on top of Bitcoin are able to support small payments and avoid high cumulated transaction processing costs.

This thesis proposes a centralized secure scheme that allows data purchasing from any Internet-connected sensor node using the Bitcoin payments. Based on micropayment channels to aggregate payments and minimize transaction fees, and on contracts between the protocol participants to minimize trust, the scheme allows human judgements to be taken out of the loop and supports complete automation.

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Chapter 1

Introduction

The Internet of Things (IoT) is a novel concept that has rapidly expanded in the latest years, refering to the network formed by any physical object, embedded with sensors and connectivity - such as Radio-Frequency Identification (RFID) tags, sensors, smartphones, etc. - that enables such nodes to exchange data. This technology allows these objects to be sensed and controlled remotely (IoT Survey), having a great impact on the every-day life of users, and resulting in efficiency and financial benefits.

Sensor nodes with Internet connectivity enable attractive sensing applications in various domains, ranging from health-care, security and surveillance, environmental monitoring, agriculture automation, energy consumption, transportation, etc. (Sensing as a Service paper) introduces the concept of Sensing as a Service, in which a number of sensors offer their generated data as a service to interested entities through a central operator in exchange for a pre-established price quote.

Most existing payment protocols for the Sensing as a Service model involve a third-party, which results in higher costs and reduced efficiency. Another approach is to rely on Bitcoin, a decentralized electronic payment system. Bitcoin has at its root the blockchain, a transaction database that is shared by all network nodes. However, these solutions fail to address the scalability problem of Bitcoin: they rely on atomic operations that are completed directly on the blockchain, thus increasing its size and moving Bitcoin towards centralization, since only a few nodes will be able to process a block.

IoT has a huge economic potential and areas of application include: road surveillance - interested in road condition data generated by cars (Nericell, VTrack), weather forecast - in data sensed by private weather stations, transportation - paying per distance or number of bus stops, paying for Internet by used traffic, etc. In this manner, IoT entities can act as active participants in a self-created data market. However, it is still lacking an efficient payment method and is limited by high transaction costs.

In this context, the project proposes a centralized, low-trust and secure scheme that allows and incentivizes sensor nodes to share sensed data and get paid in exchange in bitcoins. The presented solution utilizes micropayment channels to solve Bitcoin's scalability problem by bundling several small payments for each set of acquired data and only publishing the final, aggregated transaction to the network. In order to confer a low-trust relation between the system entities, the protocol relies on contracts that pass the payment obligation down from the buyer to the central coordinator, and then to the sensor node. In addition to the theoretical model, a proof-of-concept is built based on the Android built-in sensors.

1.1 Background

In the following sub-sections, the background on the used concepts and sub-protocols is presented.

1.1.1 Bitcoin

Since its invention in 2008 [Satoshi paper], Bitcoin has grown into a global electronic payment system. It uses peer-to-peer technology to transfer funds, with no need for a central authority such as a financial institution and low transaction fees, making it an attractive alternative to traditional payment methods. A proof-of-work system and cryptographic protocols are the building blocks of the protocol, with peers participating in the network being responsible for processing transactions and issuing of bitcoins.

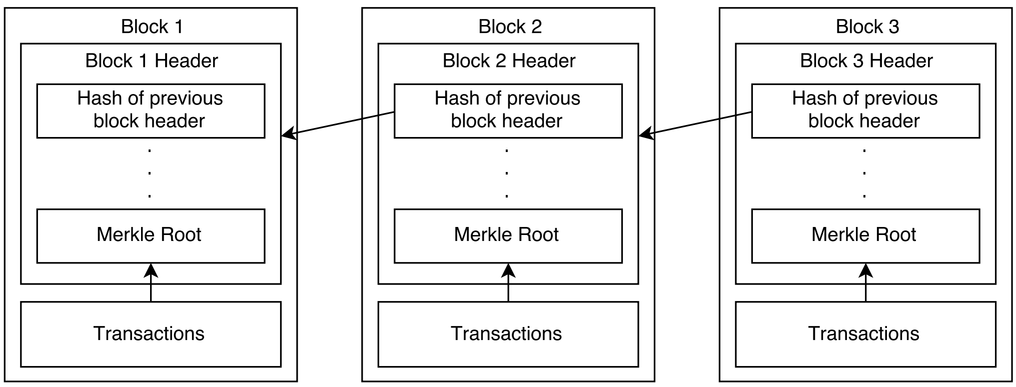


Figure 1.1: A simplified representation of the Bitcoin blockchain.

Bitcoin relies on public key cryptography to authenticate transactions. Each peer in the network has one or more public and private key pairs that are stored in a file called a wallet. In order to support and authenticate transactions, an address is derived from the public key and is disclosed together with it to the participants. In this cash system, transactions consist of one or more inputs (references to previous transaction outputs) assigning the value of all inputs to one or more outputs. An output consists of a tuple of a specified bitcoin amount, and an output script, called pubscript. This special script describes conditions that need to be satisfied in order for the amount to be claimed by an entity. In most cases, the script only requires a signature matching the address, which proves the possession of the corresponding private key. The difference between the total input amount and the total output amount in a transaction represents the transaction fee. A peer holding a private key can sign a transaction spending some of its wallet's amount to some other address, and any other peer that sees this transaction can verify the signature using the peer's public key. In order to claim an output, the payee must prove that it possesses the private key corresponding to the public key included as the destination of the transaction. Thus, the available funds are represented by the amount of all unspent transaction outputs the peer possesses a private key for.

In order to be validated and accepted by the peers, a transaction needs to be broadcast to the network. Special network nodes, called miners, will then timestamp it by applying a hash function into a continuously growing chain of hash-based proof-of-work. This forms a record, called the blockchain, containing all transactions in Bitcoin ever made, that cannot be changed without redoing the entire proof-of-work. The public ledger is distributed to all network peers and is crucial for protection against double spending and modification of older transactions. The proof-of-work performed in Bitcoin is based on HashCash POW [cite], which means new blocks (containing one or more transactions) are only accepted into the ledger if the hash of the block header contains a specified number of zeros as a prefix (adapted dynamically to produce bitcoins at a constant rate). The header of each block contains, among other data, a 4-byte nonce, that miners permute until the hash fulfills the criteria. Once it does, the new block is broadcast to the network and verified by the other peers before being added to the blockchain. This PoW takes advantage of the random nature of cryptographic hashes, making it impossible to modify the data to obtain predictable hashes. The computation, called mining, is incentivized through fees that are earned by the nodes performing it.

1.1.2 Micropayment channels

Unlike traditional payment methods, Bitcoin transactions are very cheap in terms of fees, but still have a considerable cost given the mining and storing they require. The context of Internet of Things requires a high volume of small-value payments, thus the overall fees might reach and surpass the value of the actual transactions. In addition to this, broadcasting several transactions to the Bitcoin network in a very short time window will trigger network anti-flooding algorithms, which will result in either the transactions being delayed or, even worse, not relayed. Last, the payee of such small transactions will end up with a wallet full of "dust", and spending such money is expensive fee-wise.

To address these issues, the construct of payment channels was introduced in Bitcoin. After an initial setup process between the two participants, the payer can start sending tiny payments to the other party off the blockchain at high speed, without paying high transaction fees, in a trust-free manner.

Consider a buyer that is interested in data generated by sensor nodes in a IoT network. In exchange for the obtained data, it will pay the data provider in bitcoins. Since none of the participants know each other, a zero-trust solution is necessary to reassure both the buyer that it will not lose its bitcoins in case the sensor node does not provide the data, and that the sensor node will not provide the promised service without getting remunerated. The construct works in two stages. First, the buyer creates a multi-signature transaction, a shared account requiring signatures of both participants to spend from it, that pre-allocates a certain amount of bitcoins for use in the channel. If the buyer signs and sends this bond transaction to the sensor node, the node could simply broadcast it and keep the money hostage, thus the buyer keeps the transaction private for now and creates another one, called a refund transaction, and sends it to the other peer to sign it. This transaction refunds the entire value to the buyer, but it time locked using the nLockTime feature of Bitcoin, ensuring it will not become valid until some time in the future (channel lifetime). If the sensor node vanishes at any point, the buyer can then use the refund transaction to get all the money back at channel expiration time.

Once the refund has been signed by the sensor node, the buyer can safely send the signed bond transaction. After verifying the signature, the server signs it as well and broadcasts it to the network, locking in the money and opening the channel between the two parties.

At this point, the work-and-pay cycles can begin. Initially, the buyer creates a new transaction spending from the shared account and adds two outputs: one to its own address with the full amount, and one to the address of the payee. After signing it, the buyer sends it to the peer. When new data is requested from the data provider, the transaction is updated by the buyer, with increasing value to the sensor node and decreasing value allocated to its own address. In each update cycle, the transaction is signed and handed over to the other party. When the time comes and the buyer wishes to close the channel, it notifies the sensor node, which in turn signs the transaction with the highest value alloted to it and broadcasts it to the network. This step closes the channel, unlocking the buyer's remaining money and making the sensor's money available for spending. The buyer could be tempted to broadcast an older transaction that gives less money to the sensor node than it deserved for the provided data, but it is missing the sensor's signature. Thus, the construct of micropayment channels prevents misbehavior from both parties.

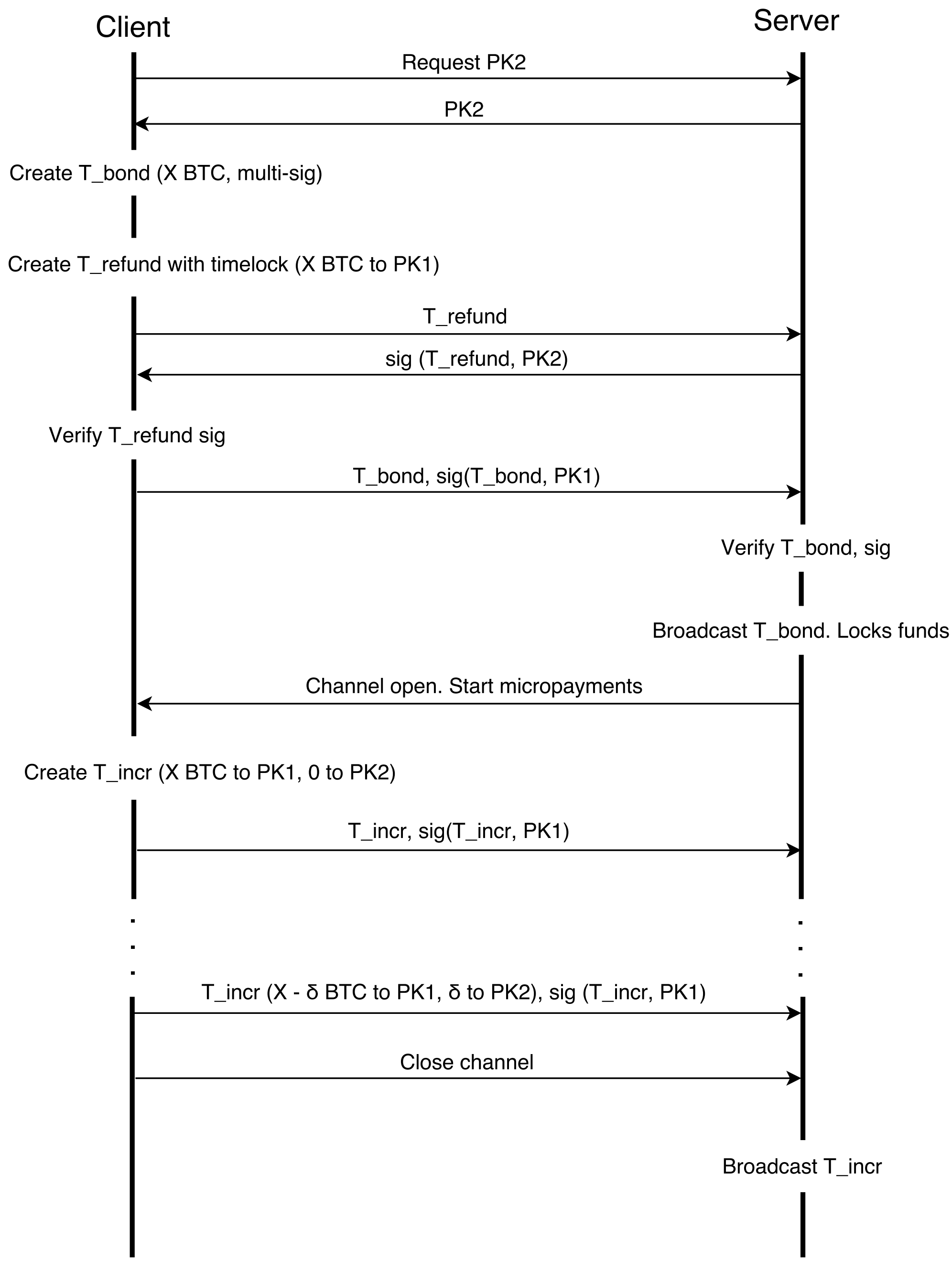
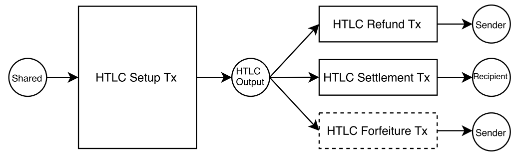


Figure 1.2: Micropayment channel protocol: setting up the shared account (bond transaction), creating the refund transaction, and updating the incremental payment transaction.

```
OP_IF
    2 <pubKey_A> <pubKey_B> 2
    OP_CHECKMULTISIG
OP_ELSE
    OP_SHA256 <H>
    OP_EQUALVERIFY
    2 <pubKey_A'> <pubkey_B> 2
    OP_CHECKMULTISIG
OP_ENDIF
```

(a) HTLC pubScript.



(b) HTLC Transaction structure.

1.1.3 Hashed Time-Lock Contracts (HTLCs)

Since the project proposes a three-component system in which payments need to be forwarded from the buyer all the way to the data sensor nodes, a blockchain enforced contract needs to be set in place in order to prevent the intermediaries from delaying or keeping these funds for themselves.

To create an HTLC, a special HTLC setup transaction is set up that can only be claimed by the final recipient B of the payment using a previously created secret. First, the payee A has to generate a secret R and hash it to obtain H. Then H and the recipient's Bitcoin address are directly transferred to the payer. At this step, all nodes on the payment path between the sender and the recipient need to create HTLC setup transactions connected to the output of a shared account using the provided hash H. The output of the HTLC setup contains a pubScript as shown in 1.3a, which requires a signature from both participants (first branch), or the next hop provides R' such that it hashes to H. Once all setup transactions are in place, the recipient B can release R to claim the funds from the previous node. The secret is then revealed step by step by all nodes on path all the way back to A, which completes the transfer.

To prevent the intermediaries from delaying the funds, stealing or keeping them hostage, HTLC refund, settlement and sometimes forfeiture transactions are created, all three types claiming the HTLC output. The *HTLC refund* transaction is similar to the refund that is created in the micropayment channel setup protocol, but has a higher time lock to give the sender enough time to react, should the receiver not cooperate. The *HTLC settlement* transaction guarantees the receiver it can pull the funds if it is in the posession of the secret. It is important for the sender to use different signing keys A and A' for the two branches of the HTLC output. Otherwise, the receiver could simply reuse the signature of the settlement transaction in the if-branch and claim the funds without ever revealing the secret, since the signature is valid for the entire pubScript. Lastly, the *forfeiture transaction* addresses the case in which the sender and the receiver agreed to void the HTLC and remove the output. If the receiver comes in possession of the secret at a later stage, it still has the signed settlement transaction that it could simply broadcast and steal the bitcoins. Because of this, every time the receiver backs off from the HTLC, it creates and hands over a forfeiture transaction that transfers the bitcoins back to the sender. Should the receiver broadcast an older setup transaction, the sender can simply use the forfeiture to get the money back.

1.2 Related work

Following the expansion trend of the Internet of Things technologies, there has been an increasing interest in creating secure payment protocols that allow customers to acquire sensor data efficiently.

(IoT based on the Protocol of Bitcoin paper) introduces a new low-trust E-business architecture that is tailored for IoT. This architecture is based on Bitcoin, eliminating the need for a third-party in the process. In order to make a payment and receive the data in exchange, the buyer and the data provider make an offer-proposal exchange, then build a transaction that spends the required amount and publish it to the network. A similar approach is proposed in (When Money learns to fly), where the encrypted data is directly included in the blockchain after a payment is made, which only the buyer in possession of the corresponding private key can decrypt. In both approaches, all transactions, no matter how small, need to be published to the network, which results in high cumulated fees and time-wise inefficiency, thus being directly affected by the scalability problem of Bitcoin (cite).

Work has also been done on micropayment protocols that reduce fee costs. Amazon Flexible Payment Service uses a central provider that aggregates clients' micropayments into macropayments that are flushed to the seller at specific times. This solution does not provide anonymity, since the central provider can keep track of all payments, and moreover, was discontinued on June 1, 2015. Other protocols (Micropayments Revisited) involve a probabilistic approach. Using a selection rate s, it discards all unselected micropayments and selects one with probability s that can be deposited for an amount *1/s* times bigger than the original amount. This should ensure everyone gets, on average, the expected amount. However, this solution lacks anonymity, requires PKI certificates and comes closer to a bet than an actual transaction.

The Architecture of Coupon-Based, Semi-off-Line Anonymous Micropayment System for Internet of Things - proposes an anonymous, semi-offline micropayment system for transactions in IoT. In this approach, an electronic coin is obtained by iteratively applying a hash function to some initial seed, thus allowing the user to spend it in fractions, by presenting a set of hash chain nodes to the vendor. The protocol is designed to meet the needs of IoT transactions, however, it has limited potential to be implemented because it does not rely on an existing financial institution. Another coupon-based system has been proposed by Rivest in [PayWord and MicroMint] and was improved by Payeras-Capella (An efficient anonymous...) to integrate anonymity and prevent users from exceeding their account limit. The drawback of the latter is that the financial institution needs to be contacted directly before each payment, and any unspent value is lost in favor of the financial institution. Wilusz (Requirements and general..) solves these issues by requiring a single contact with the financial institution at coin issue time and allowing the user to use unspent fractions in future transactions. However, a clearing house is necessary to lock in the coin by the vendor, which increases transactions costs, and poses the risk of locking the coin indefinitely.

There have been some previous projects that utilize micropayment channels to pay in bitcoins in exchange for services. [Paying for Internet one byte] is a proof-of-concept allowing an access point to provide Internet access to untrusted users for bitcoins through a micropayment channel in a convenient manner. This way owners are incentivized to open up their access points and users receive Internet services in return. Though the idea of using micropayment channels for several small-valued transactions does address the scalability problem of Bitcoin, establishing micropayment channels between all pairs of buyers and service providers is rather inefficient in the context of this project.

It is worth mentioning that there have been several proposals and ideas that can be exploited to support trustless, instant, off-the-chain Bitcoin payments on bitcointalk.org by Mike Hearn, Alex Akselrod, hashcoin, Meni Rosenfeld, cjp, Tier Nolan etc.

On the Contracts page of Bitcoin, Mike Hearn (https://en.bitcoin.it/wiki/Contract#Example_2:_E describes an idea on how to trade with somebody with no trust involved, based on multi-signature transactions. The funds get locked in a shared account controlled by at least two of the three participating parties: the client, merchant and mediator. If the transaction is successful or a refund is agreed upon, the client and the merchant can move funds. If the trade fails, the client and the mediator can agree, and a charge-back occurs. Finally, if the goods are delivered but the client does not want to fulfill its part of the agreement, the mediator and the merchant agree and the merchant gets the client's money. Mike also proposed the idea of trading across multiple currencies without a third party, and Tier Nolan formalized it in a protocol that allows the exchange atomically, using time locks and hash commits.

cjp presented a draft that combines Bitcoin and Ripple to create a high-speed, scalable, anonymous, decentralized, low-trust payment network. In this Bitcoin-specialized variation of the Ripple system, neighboring pairs have a shared account that is partly allocated to one of them, and the rest to the other, as agreed between the two, which lowers the needed trust. Using sequence numbers to update this transaction as payments in the network are made and lock times to prevent blocking the money indefinitely.

Meni Rosenfeld proposed a simple way of reusing existing micropayment channels instead of establishing new ones if a path between the payer and the payee already exists. The intermediaries would then only be trusted with the amount of a single payment from a single buyer.

Alex Akselrod - Extensible Scalable Coopetitive High Availability Trade Optimization Network - built a proof-of-concept for chained micropayment channels with two-phase commits. The original micropayment channel payment scheme is modified to allow sending funds through intermediaries. Suppose Alice, Carol, and Bob have previously set-up micropayment channels pairwise, in the given order. If Alice wants to send bitcoins to Bob through Carol, Bob first creates a random secret R, hashes it and sends the commit hash to Alice out-of-band. Then Alice can update the values on the channel with Carol using the commit hash, and Carol can do the same on the channel with Bob. In order to claim the money, Bob has to reveal the secret to Carol, and Carol can then reveal the secret to Alice up the path to receive her funds. Thus, this proposal enables friend-to-friend, instant, off-blockchain, trustless payments of arbitrary size using Bitcoin micropayment channels.

Peter Todd's proposal in Hub-and-Spoke Payments provides the an efficient way for establishing micropayment channels between peers with a central hub. This central entity plays the role of a router, basically fowarding payments from the payer to the payee. Suppose Alice and Bob have previously established micropayment channels with the hub. If Alice wishes to send bitcoins to Bob, she should normally establish a new micropayment channel with him. However, both of them have channels opened with the hub, so Alice can send the funds to the hub, and the hub can then forward the payment to Bob. Using Hub-and-Spoke payments, payments between buyers and service providers with a central coordinator can be made efficiently, saving costs in terms of fees. However, the forwarding process should be enforced and secured, part that is noted in the proposal, but without specifying an actual way to do so.

The Lightning Paper presents a promising solution to Bitcoin's scalability problem and provides a way to securely forward payments on a path of peers through blockchain enforced contracts. It solves the issue by using timelocks on a network of micropayment channels combined with Hashed Timelock Contracts (HTLC) - recipient generates random data R, hashes it to produce H and sends H to the sender of funds, together with its bitcoin address. Sender routes its payment to the receiver and when an updated transaction is received, the recipient may elect to redeem the transaction by disclosing the random data R (which pulls the funds from the sender). With the introduction of a new sighash type which solves malleability, the proposed protocol allows offchain transactions between untrusted parties with fully enforceable contracts, making Bitcoin scale to billions of users.

For the sake of completeness of this literature review, we mention the Tile-

Pay project, which promises a decentralized payment system based Bitcoin for real-time access to IoT sensors, based on micropayments. In a partnership with Cryptotronix, TilePay wants to enable cryptocurrency payments to IoT devices. However, since the announcement in December 2014, no work or detailed information on how they would achieve that has been published.

CHAPTER 2

Design

2.1 Requirements

For the presented use case, a scheme that enables sensor nodes in an Internet-of-Things network to shared sensed data and get paid in exchange must meet the following requirements:

- Provide an entity that the node can register sensor type availability to.
- Provide an entity that buyers can query for available data and that can provide sensor node contact information
- Scalability: avoid broadcasting all micro-transactions to the blockchain
- Efficiency (and speed): fast communication between components, payments and data should be confirmed and received instantly
- Secure: end-to-end security of the payments
- Anonymous: linking of buyers and sellers and identification across sessions should not be possible.

2.1.1 Achieving Scalability and Efficiency

In order to achieve scalability and efficiency, there are two important factors that need to be taken into account: the inherent scalability issue of Bitcoin and the number of peer pairs that need to interact to successfully get payments from buyers to the sensors.

Since sensor nodes are exchanging small sets of sensed data in exchange for bitcoins, individual payments made by the buyer tend to be of very small amounts. Therefore, creating new transactions for each such payment would have a very high overhead in terms of fees, which reduces the incentive for both the buyers and the sensor nodes to participate in the protocol. A high volume of transactions would also delay the transactions being confirmed on the Bitcoin network. To address these issues, the proposed system will rely on the previously introduced micropayment channels. This mechanism will allow, after a preliminary setup between the parts that wish to transact, to instantly send small amounts of bitcoins off the blockchain, bundling and publishing them to the network only at the end of a specified time window. Thus, both scalability of Bitcoin and efficiency of payments are achieved.

One issue that comes with using micropayment channels in the proposed context is that its set-up phase takes a considerable time (approximately 10 minutes, until the bond transaction is confirmed by the network). Thus, setting up a channel between all buyers and nodes becomes very inefficient time-wise and causes a lot of overhead on the network since all connections need to be maintained for the lifetime of the channel. On the other hand, if the buyers and the sensors have previously established a channel with a central entity as in the hub-and-spoke model (cite), each will have a single set-up to wait for and a single channel connection to maintain. To better illustrate the performance improvement, suppose the system runs $X = 100$ buyers and $Y = 100$ data providers. By using the initial idea, $X*Y = 10.000$ channels need to be established and maintained. With the hub-and-spoke model, however, $X + Y = 200$ channels will suffice (factor of *50*).

Last, adding a single central entity may affect the scalability of the system when the number of data providers and buyers increases, becoming a performance bottleneck. However, the concept of a central hub should be rather treated as a central cloud, which can contain several machines maintaining the connections, channels, available sensor data, and load balancers that distributed the work across the available machines.

2.1.2 Achieving Security

Talk about micropayment channels + HTLCs. Sequence diagram for full protocol.

2.1.3 Achieving Anonymity

By design, the role of the central hub is to connect data buyers and sellers, and given that the lifetime of the established micropayment channels are rather long, the hub can easily analyze the data a buyer is interested in, build a profile and ultimately, identifying it. To address the privacy issue, buyers could make use of a distributed 'onion' network, such as Tor, open several, shorter-lived sessions, over several vantage points, and spread payments and data exchanges on these session when buying different sets of data. An additional precaution is to never reuse addresses across sessions. This way, profiling becomes more difficult, and the hub can not link anymore buyers and data they have purchased through the system.

2.2 System Overview

The design of the payment system achieving the requirements above comprises three major components: one component consists of several sensor data providers (IoT sensor nodes, Android phones running specialized app, etc.), one central hub that plays an essential role in sensor node discovery and payment and data relaying, and a third component, consisting of data buyers. The communication between the buyers and the hub, and between the hub and the sensor nodes is done through TCP links.

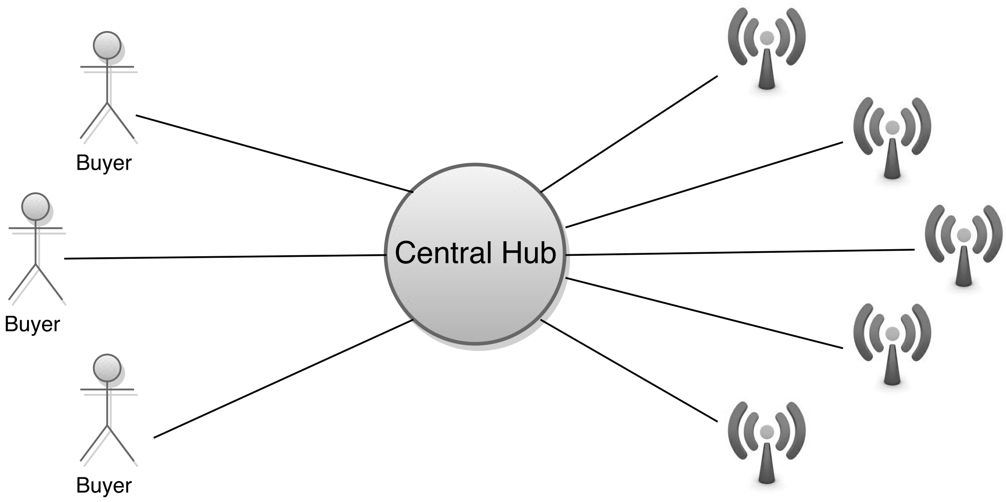


Figure 2.1: System overview: buyers, central hub, and sensor nodes.

2.3 System components

2.3.1 Buyers

2.3.2 Central Hub

2.3.3 Sensor nodes

Chapter 3

Implementation

Chapter 4

Evaluation

Chapter 5

Conclusion

Chapter 6

References

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Appendix A

Appendix Chapter