Decentralised location proof system

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Chapter 1

Introduction

1.1 Project and Motivation

Location verification is the process of verifying whether a *node* (computer) is physically present at a location it claims to be. Existing location proof systems attept to use centralised, trusted "authoritive" nodes to provide proof of another node's location. These approaches require investment in infrastructure, and are subject to privacy violation and denial of service attacks. This project aims to present a *decentralised* solution to this problem. A decentralised location proof system is a system in which there is no "authoritive source" trusted and relied upon to provide and store sensitive location information.

This project describes a decentralised location proof system that is capable of operating on *mobile nodes* (mobile devices). I propose a design in which location proofs are obtained using other untrusted mobile nodes as *alibi's*. Proofs will be created as two mobile nodes communicate over an ad-hoc bluetooth network, transfer encrypted location information, and publish it on a public append-only bulletin board, known as a *blockchain*. The decentralised nature of the system means that there is no single point of failure, no entity controlling the security of every node's location proofs, and no entity capable of violating another node's privacy. This is because in a decentralised system, no node is "in charge", and no node has more authority in the system than any other node.

1.2 Report outline

This report consists of four additional chapters, listed biefly below.

1.2.1 Background

Chapter 2 begins with a brief introduction to the problem space. A brief explanation of decentralised and distributed networks, as well as the blockchain is then presented, in the context of location proof systems. The chapter closes with an explanation of the design goals defined for this project.

1.2.2 Design

Chapter 3 explains the design of the decentralised location proof system in detail. It begins with an overview of the entire system, and then details the design of each specific part.

1.2.3 Evaluation

Chapter 4 presents an evaluation of the system described in the design, with respect to the goals laid out in Chapter 3.

1.2.4 Future work

Chapter 5 presents the conclusions of the project, and details interesting areas for possible future work relating to the project.

Chapter 2

Background

2.1 Proving your location

As an increasing amount of personal information is accessible on the internet and therefore on mobile devices, we are losing the security that previously existed by requiring physical interaction between humans to transfer sensitive data.

Location proof is a large part of that security. There is currently no ubiquitous method of *proving* your location at a given time digitally. Many companies, such as Netflix, use GeoIP databases such as MaxMind [6] to estimate a users location based on his IP address. This technique is inaccurate and easily bypassable using proxy servers or VPNs.

One newer, more advanced tecnique of location observation is Constraint-Based Geolocation [7]. This is an active geolocation technique, compared with GeoIP verification which is static. It estimates the location of a users IP address by calculating the latencies between the user's machine and multiple surrounding machines with fixed, known locations. However, even advanced systems like these can easily be bypassed, using IP spoofing techniques, proxy servers, VPNs, or by using anonymising networks such as TOR [9].

Better solutions to this problem exist. *Location proof systems* allow users of the system to *prove* their location to another user, by creating *location proofs*. Location proofs vary from system to system. In essence, a location proof is a piece of data, potentially signed or encrypted by another party, which attests the location of a user at a specific time. Examples of location proof systems are discussed in detail in section 2.3.

2.2 Distributed and decentralised systems

A *distributed* system is a system which distributes the computation of a task across multiple nodes (computers) connected over a network. These nodes then work together and communicate to complete the task by passing messages over the network [10].

For example, Google search indexes are not computed on just one node, rather on a network of nodes that communicate by sending messages to each other. Google therefore *distributes* the task of calculating search indexes across multiple nodes. This two main advantages; It is less time consuming, because different index calculations can be computed on different nodes at the same time, and it's scalable, because nodes can be added or removed from the network dynamically, to meet demand.

A *decentralised* system is similar to a distributed system, except no node is in charge. Nodes in a decentralised network still communicate by passing messages to each other over the network, but unlike a distributed system, they arent assigned tasks by a central or master node. Bitcoin [12] is a good example of a large-scale decentralised system. Two nodes in the Bitcoin network can choose to send money between themselves, creating a transaction. They make the details of that transaction public. The two nodes therefore create and publish the transaction iwithout coordination from a central node.

In the context of a location proof system, I consider a distributed location proof system to be one where the task of facilitating user proof request and creation is distributed across multiple *worker nodes*, which are controlled and coordinated by a central node. This allows a higher volume of proofs to be created concurrently compared with using a single node, while maintaining centralised and simple control over the system. This is shown in figure 2.1.

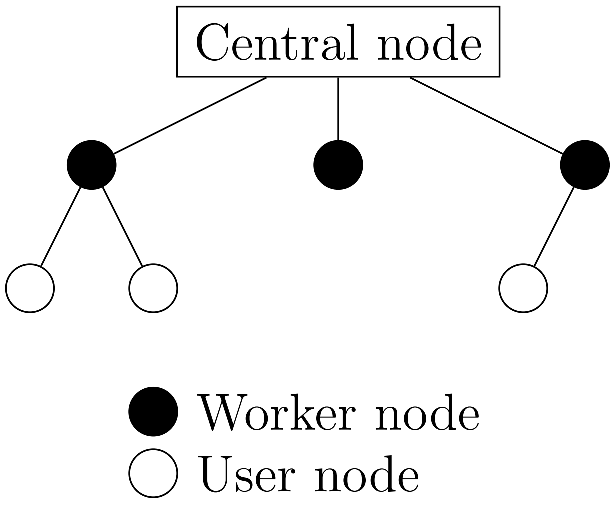


Figure 2.1: Distributed location proof system

I consider a decentralised location proof system to be one where no node is in charge of controlling or coordinating the system. Nodes can create and publish location proofs between themselves, without the need for a central third party to coordinate the interaction (figure 2.2). This makes coordination more complex, but means that no node is considered to be "in charge" of the system.

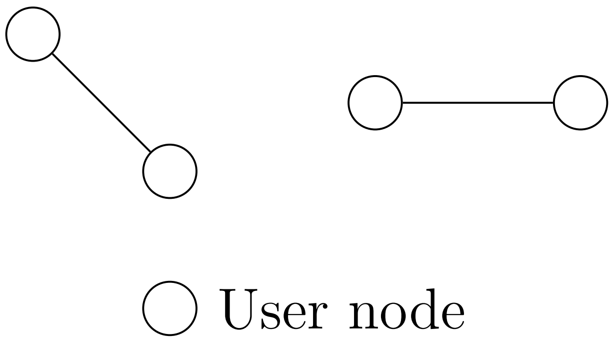


Figure 2.2: Decentralised location proof system

2.3 Existing location proof systems

Location proof systems are expected to be accurate and tamper-proof. For this reason, existing solutions [1, 2, 3] have chosen to use a central authority to issue proofs, or to regulate proof issuance.

A hardware technique [1], developed by Brassil et al. of HP Laboratories, operates by supplementing existing WiFi access points (*AP's*) with *femtocells.* A femtocell [13] is a small cellular antenna that connects to a mobile carrier via the Internet, which allows mobile networks (e.g. networks used for calls and texts) to be extended on demand. Location verification over the internet is made possible by determining which femtocell a mobile node is connected to as it transfers data via Wi-Fi. This is possible because the central server in the location verification system has access to the mobile operator's user data.

This solution requires investment in additional hardware to supplement existing WiFi access points, and requires access to mobile providers' user database to identify users locations (see figure 2.3).

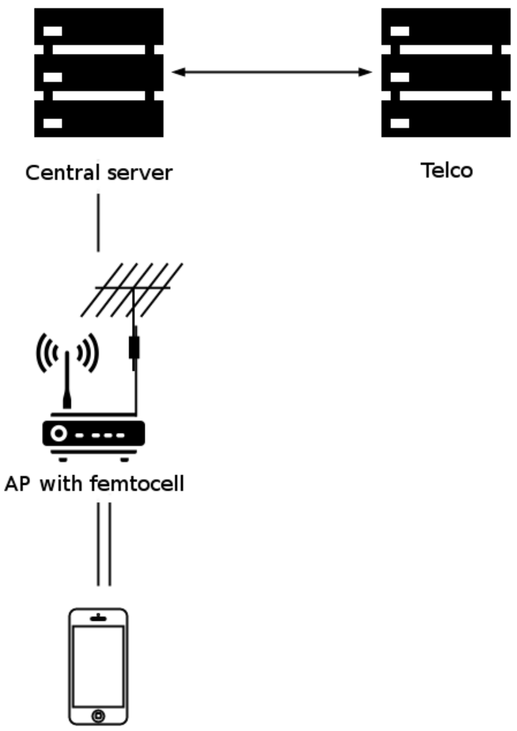


Figure 2.3: Hardware-based proof system (Adapted from Brassil et al. [1])

The use of a centralised system, as described above, creates security, privacy and vulnerability issues. An attacker who succeeds in compromising the security of the central server can violate the privacy of the users of the system, and potentially track their location. This is because in this system, location proof data resides with the central server. This means that the user has no control over the security of their proofs, and an attacker could sieze them. The central system architecture is also vulnerable, in the sense that a resource availability attack such as a DDoS attack [14] could render the central architecture unavailable, making location verification unavailable.

Luo et al. propose a system that uses software installed on Wi-Fi access points to allow users to create location proofs [2]. In their system, each access point is given a *group signature* by a central server, and can sign location proofs for users (figure 2.4).

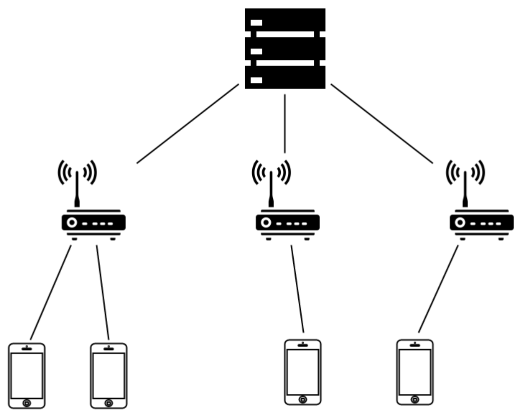


Figure 2.4: Access point proof system (Adapted from Luo et al. [2])

Users can request a location proof from any access point, and receive a proof encrypted by the AP with the group signature, as shown in figure 2.5. This can then be submitted to a Verifier.

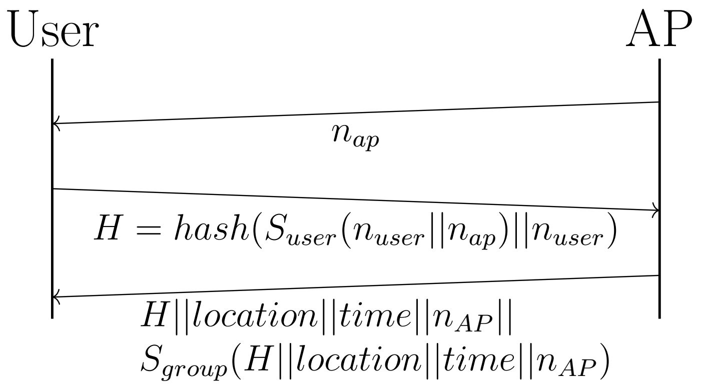

User
AP
n_{ap}
$H = hash(S_{user}(n_{user}||n_{ap})||n_{user})$
$H||location||time||n_{AP}||$
$S_{group}(H||location||time||n_{AP})$

Figure 2.5: Proof request with group signature (Adapted from Luo et al. [2])

This system creates *proactive* location proofs. A proactive location proof is one which is created before it is needed. The user creates application-independent location proofs, and can use them at a later time with any application(s) he chooses.

A system proposed by Khan et al. takes a different approach, by using other users as witnesses to a location claim [3]. In this system, a *witness* physically located near the user is used by the central server to verify the user's location claim (figure 2.6). Like the model proposed by Luo et al., this system allows the user to have control over their own privacy, as the user owns the location proof.

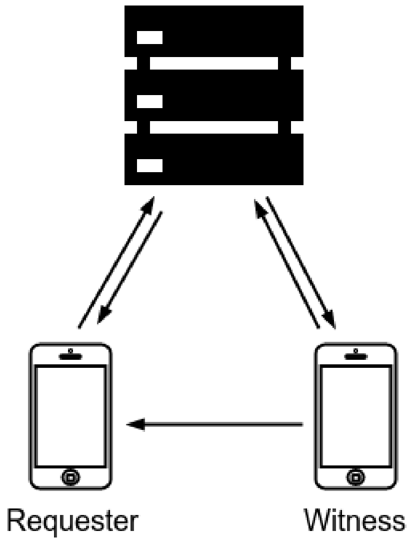


Figure 2.6: Proof system using witnesses (Adapted from Khan et al. [3])

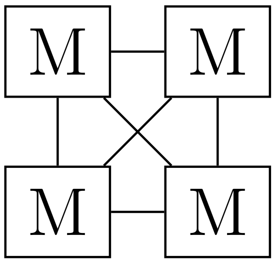
2.4 Blockchain

In Bitcoin [12], the entire transaction history is stored in the *blockchain*. This is a decentralised, append-only ledger (database) [11]. The blockchain is maintained by a network of *miner* nodes competing to collect transactions into a new block, sign that block by solving a difficult puzzle known as a *proof-of-work*, and append it to the ledger. It is used in Bitcoin to enforce consensus; every miner in the network agrees that all blocks in the blockchain are valid, due to the presence of their associated proof-of-work.

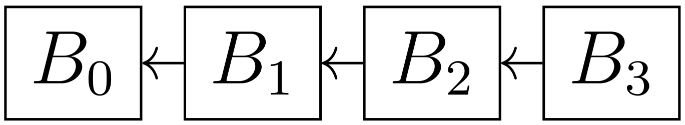
A proof-of-work is a solution (a numerical value) to a problem which is computationally expensive to solve, but computationally cheap to verify that the solution is correct. As blocks are added to the blockchain, the amount of work required to generate the proofs-of-work for the entire chain increases. Because proof-of-work solutions also incorporate some information about the previous block in the chain, changing data inside a block in the blockchain would not just require regeneration of the proof-of-work for that block, but for all successive blocks as well. Therefore the blockchain is tamper-proof, assuming that the majority of the CPU power in the miner network is controlled by honest nodes [12].

To add a transaction to the blockchain, a user will send the transaction to a miner node. That miner node propagates the transaction to other miner nodes in the network, and they each try to include it in the next block by solving the proof-of-work. A simple overview of the system is shown in figure 2.7.

Once a proof-of-work has been solved, the solution is distributed to all other miners in the network to prove that the solver expended significant computational effort to solve it. This is a proof of resource ownership, meaning that by solving the proof-of-work, the miner has shown that it has significant computational resources and is therefore considered a valid miner. Once other miners in the network verify that the proof-of-work is correct, the block (and therefore all transactions contained in it) is considered the newest block in the tamper-proof chain, and miners begin working on the next block.



(a) Miner node network



(b) Blockchain

Figure 2.7: Blockchain overview

2.5 Design goals

Before designing the system, a number of goals must be defined and an attempt made to satisfy them in the design. My design goals are listed below.

- The system must be *privacy preserving*. It must not be possible for a malicious user to obtain any additional information from an honest user than the information the honest user intended to release.
- False location proofs must be detectable. It must be possible to detect any location proofs attempting to prove false information.
- The system must be decentralised, and cannot rely on any central nodes. This is discussed in section 2.5.1.
- The design must conform to the desirable properties defined in OTIT (discussed in section 2.5.2).
- The system must not be vulnerable to any known threats (section 2.5.3).

2.5.1 Central services

Location proof systems which rely on central noes, such as those discussed in section 2.3, have a fundamental weakness. These systems assume that the central node is honest, always available, and cannot be compromised by an attacker. Since the central node is in charge of coordinating the system, compromising it allows an attacker potentially unlimited control over the system. This completely violates a users privacy in a location verification system, as the central node may contain sensitive information about users and their location, or a means of retrieving sensitive information, such as decryption keys. Users of the system also have to assume that the central node is available at all times, otherwise the system is considered unavailable, or “down”.

These problems do not occur in a decentralised location proof system, because no node is considered to be “in charge”. This lack of authority prevents privacy breaches, but presents other issues. System coordination, which is easily maintained by the central node in a centralised system, is now maintained by each participant in the decentralised system.

2.5.2 OTIT

Khan et al. present the *OTIT* model, a “model for designing secure location provenance” [4]. It defines the following 8 desirable properties of a location proof system:

Chronological: Location proofs should be ordered according to the sequence of their creation.

Order preserving: The order in which the proofs were entered into the proof chain should always be maintained.

Verifiable: A Verifier should be able to verify or reject the claim by the user that he has visited the given location(s).

Tamper evident: A Verifier should be able to detect if the proof chain has been tampered with or modified by an unauthorised party.

Privacy preserved: When the proof chain is verified for specific location proofs, privacy is preserved for the other location proofs within the chain.

Selective In-sequence privacy: The user should be able to choose not to reveal some location proofs within the proof chain when seeking verification.

Privacy protected chronology: The system should ensure that the user does not hide important information from the items within the subset of the proof chain.

Convenience and derivability: The system shold ensure that the user does not burden the Verifier with a large amount of data to analyse in order to verify his location.

2.5.3 Threats

A number of related publications [2, 3] have identified various potential threats (or attacks) on location verification systems. These are outlined below.

False presence: A dishonest user tries to obtain a location proof for a false location.

Malicious intruders: A malicious intruder offers to help another user prove a false location, but doesn't prove a false location for himself.

Curious users: A curious user learns another user's identity by monitoring its location proofs.

Malicious applications: The application that the user is proving his location to takes advantage of the user's information.

Eavesdroppers: An eavesdropper intercepts or modifies communication between two honest users.

Wormhole attacks: An attacker records network traffic in one location and replays it in another location (at another time).

Weak identities: A user gives his public key or identity to another colluding user in order to create a location proof.

False timestamping (backdating, future dating): In a backdating attack, the attacker creates a location proof with a past timestamp. In future dating, the attacker creates a location proof with a future timestamp

Implication: A malicious user, or group of colluding malicious users, create a false location proof for an honest user.

False assertion: Two malicious users collude to create a false location proof for themselves.

Proof switching: A malicious user modifies one of its existing honest proofs to spoof a false location.

Relay attack: A malicious user creates a location proof with an honest user by relaying his requests through a colluding *proxy user*, who is physically present at a location that the malicious user wishes to create false proofs at.

Sybil attack: A Sybil attack occurs when a single malicious user of the system generates multiple *pseudoidentities* and masquerades as multiple users [5].

Chapter 3

Design

The location proof system I propose allows *mobile nodes* to create location proofs by initiating an *exchange* with another anonymous mobile node. When two mobile nodes are in close physical proximity, they initiate an exchange in the background over a short range, ad-hoc network such as Bluetooth. On completion of the exchange, both nodes can generate their own *transaction*, a cryptographically secure proof of location, attested by the other mobile node.

To create a transaction, two mobile nodes anonymously exchange their GPS coordinates and current time over the ad-hoc network. Both nodes then check that these parameters don't differ from their own observed parameters by more than some value ϵ. Once satisfied, they each create an encrypted, privacy-protecting transaction logging their location and the identity of the other mobile node (the *alibi*) used to create the transaction. This transaction is published onto a public, append-only bulletin board known as a *blockchain* [11]. Once given permission from a mobile node, a *Verifier node* can consult the data in blockchain and determine whether or not the mobile node is present at its claimed location.

Any mobile node acting as an alibi in a transaction will share details of its most recent transactions with the other mobile node in the exchange. This means that when the mobile node seeks verification from a Verifier node, the Verifier can examine the mobile node's alibi's, and each of the alibi's recent alibi's, forming a large tree of connections which can be used to verify or reject the mobile nodes claimed location. Only the owner of the transaction can give permission to a Verifier to check its location history, by providing the Verifier with the keys needed to decrypt the transactions.

Figure 3.1 provides an overview of the operation of the proposed system.

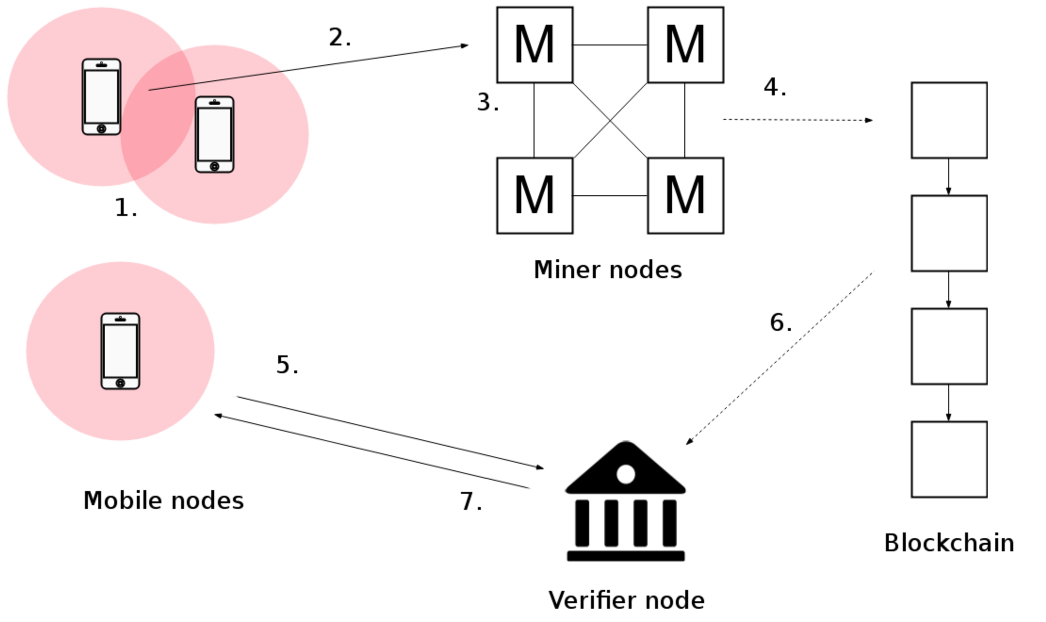


Figure 3.1: Design and operation overview

1. Two mobile nodes come in close physical proximity and create an ad-hoc network, over which they initiate an exchange and each create a transaction.

2. Both mobile nodes publish their own transaction to a Miner node.

3. The Miner node who received the transaction distributes it across the Miner network.

4. One Miner node solves the proof-of-work for a block of transactions, and the new block is appended to the blockchain.

5. A mobile node requests verification from a Verifier node (request structure is explained in section 3.3).

6. The Verifier node uses the public blockchain to examine the requesting node's transactions and determine their validity.

7. The Verifier accepts or rejects the mobile node's claimed location based on its analysis of the transactions in the blockchain.

3.1 Identities

In order to preserve user's privacy, a user will only ever use an identity for one transaction, before generating a new one. This prevents curious users from watching the public blockchain for a known identity and tracking it. However, to prevent identity theft, it is important for the Verifier to be able to prove that a mobile node is the owner of each identity. This is achieved using a public/private key pair for each mobile node.

When a mobile node is first joins the network, it generates a public/private key pair. To maintain anonymity, the mobile node will use the public key to encrypt *nonces* to create *identities*, and use these to identify itself in a transaction. A different identity will be created for each transaction. During the verification stage, the node will provide the Verifier with its public key, along with the list of the nonces used to generate its n most recent transactions (see figure 3.5). This allows the Verifier to calculate all of the node's identities, and prove that they were all created by the same node. The Verifier can then retrieve the transactions associated with those identities from the blockchain. The Verifier will also ensure that the node owns the private key associated with the provided public key, to prevent a weak identity attack.

3.1.1 Nonce list

A *Nonce List* is simply a list of all of the nonces a mobile node has used so far to generate identities. When a mobile node wishes to generate a new identity, it must first generate a new nonce which is then encrypted to create the identity. The nonce is appended to the mobile node's nonce list, so it can be used later during verification (see section 3.3).

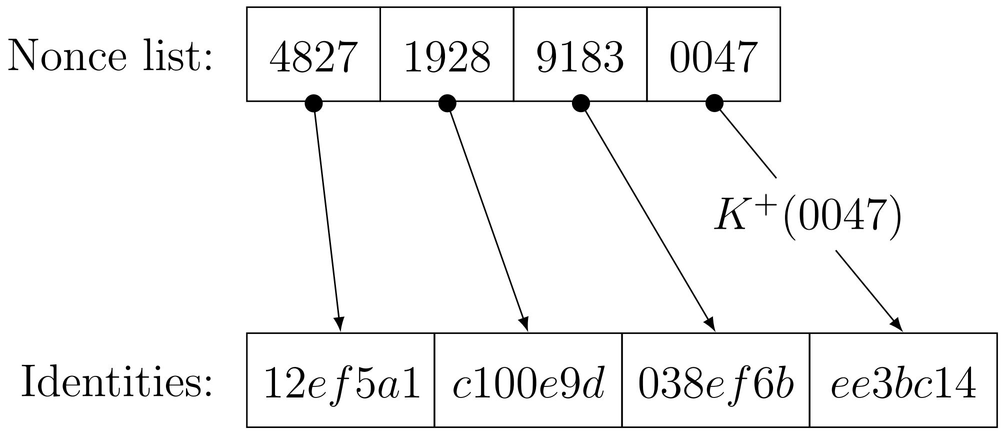


Figure 3.2: Identity generation from Nonce List

In figure 3.2 above, nonce 0047 is encrypted with K^+ to create identity $ee3bc14$. By providing the nonce list and K^+, a node can prove that it created all of the identities in the identities list. It must also verify that it owns K^-, its private key.

3.1.2 Identity duplication

Since all identities are generated from random nonces, there is nothing to prevent two nodes from generating the same identity and using it in different transactions. It is therefore possible that during verification, a Verifier node may find multiple transactions with the same ID while searching the blockchain. The Verifier will have a decryption key for the transaction it is searching for, which will only successfully decrypt one of the transactions with the duplicate ID. The Verifier will try to decrypt each one until it finds one that can be decrypted successfully.

3.2 Transactions

During an exchange between two nodes, a number of different items must be shared and calculated. Figure 3.3 describes and explains an honest, successful exchange, assuming an ad-hoc Bluetooth network has already been set up between nodes A and B.

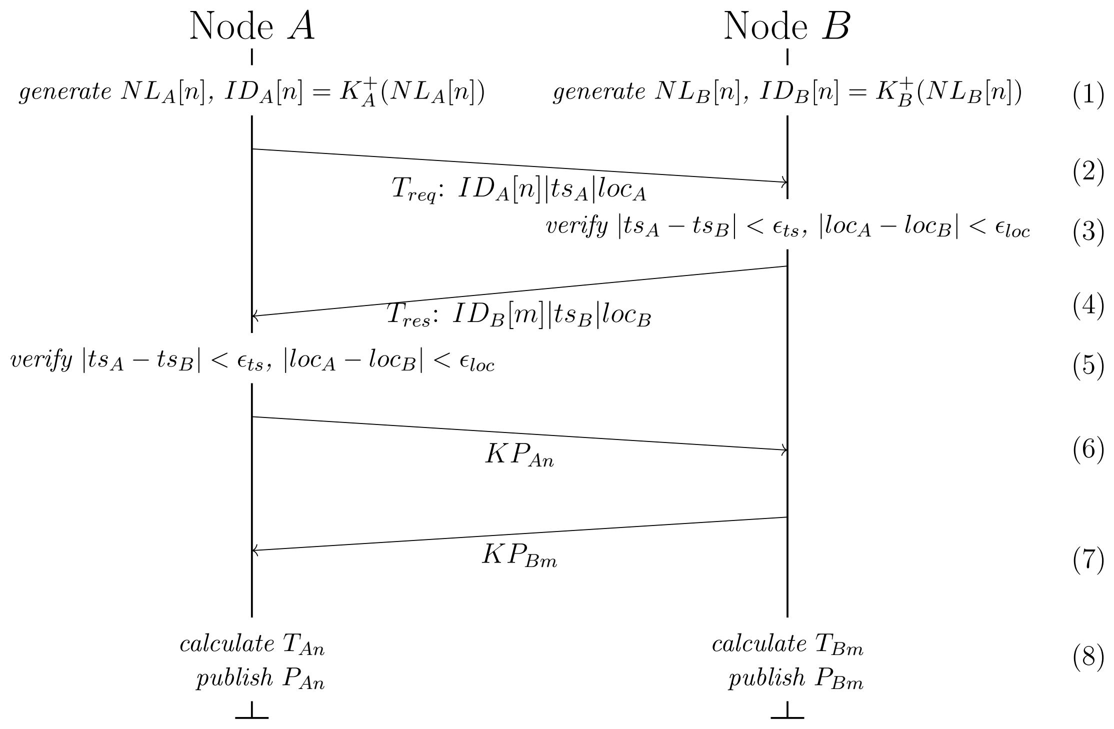

Node A
Node B
generate $NL_A[n]$, $ID_A[n] = K_A^+(NL_A[n])$
generate $NL_B[n]$, $ID_B[n] = K_B^+(NL_B[n])$
(1)
T_{req}: $ID_A[n] | ts_A | loc_A$
(2)
verify $|ts_A - ts_B| < \epsilon_{ts}$, $|loc_A - loc_B| < \epsilon_{loc}$
(3)
T_{res}: $ID_B[m] | ts_B | loc_B$
(4)
verify $|ts_A - ts_B| < \epsilon_{ts}$, $|loc_A - loc_B| < \epsilon_{loc}$
(5)
KP_{An}
(6)
KP_{Bm}
(7)
calculate T_{An}
publish P_{An}
calculate T_{Bm}
publish P_{Bm}
(8)

Figure 3.3: Honest, successful exchange

(1) Before the exchange begins, both nodes generate a new entry in their nonce list (e.g. $NL_A[n]$), and generate a new identity from that nonce (e.g. $ID_A[n]$).

(2) Node A sends its identity to Node B, along with its observed current timestamp ts_A and current GPS location loc_A.

(3) Node B verifies that the observed timestamp and GPS location received from Node A are within an acceptable difference from its own observations. This difference is defined by some system constant ϵ.

(4) If Node B verifies the parameters received from Node A, it will respond with its own identity and observations for A to verify.

(5) Node A verifies that the parameters received from B differ by no more than ϵ from its own observed parameters.

(6) Node A sends KP_{An}, its *nth Key Packet.* Key Packets are used to provide alibi credibility, and are discussed in section 3.2.4.

(7) B responds with its own Key Packet.

(8) Both nodes generate their own transaction T, using their alibi's Key Packets. These are then used to generate P, the data published onto the public blockchain.

3.2.1 Key Lists

When a node is initialised, it must begin to record two *Key Lists* for itself. A *Key List* is a list of encryption keys previously used for transactions. For example, $KL_{AT}[n]$ and $KL_{AL}[n]$ are the two keys used to encrypt node A's nth transaction and matching chronological link, respectively. These *Key Lists* and are assumed to have been initialised and populated before the transaction described in Figure 3.3 begins.

3.2.2 Transaction creation

Once nodes have exchanged *Key Packets*, their communication is finished and they can close their ad-hoc channel. Each node creates a new transaction, T, and generates data P to publish onto the public blockchain. The following transaction will be created by node A, after communicating with node B:

$$T_{An} = KL_{AT}[n](ts|loc|ID_A[n]|ID_B[m]|KP_{Bm})$$

Where:
n is node A's current transaction number (i.e. A has published $n-1$ transactions before now).
$\mathbf{KL_{AT}}$ is A's transaction *Key Lists*, used to encrypt transactions.
ts is the timestamp of the transaction, as recorded by node A.
loc is the GPS coordinates of the transaction, as recorded by node A.

$\mathbf{ID_A[n]}$ is A's *nth* identity, used for this transaction only.
$\mathbf{ID_B[m]}$ is B's *mth* identity.
$\mathbf{KP_{Bm}}$ is B's *Key Packet* at time m. Its exact contents are discussed in more detail in section 3.2.4

3.2.3 Publishing to the blockchain

After creating T_{An}, node A must publish it to the public blockchain. The data published must be searchable in order to provide a Verifier with some way of identifying specific transactions. Nodes use their current ID as the identifier for the transaction.

Backwards-chaining is an important part of verifiability. The Verifier must be able to prove that the proof chain provided by the mobile node has not been chronologically re-ordered. This is the "order preserving" property of OTIT [4]. The transaction must therefore be accompanied by a link to the node's chronologically previous transaction. This link is encrypted with $KL_{AL}[n]$, A's *nth link* key list, to prevent a curious user from monitoring the public blockchain to observe a user's transaction publishing activity. The timestamp ts_A is also included in the backwards-chaining data, to verify the "order preserving" property. A's transaction data P_{An} will therefore be in the form:

$$P_{An} = ID_{An}|KL_{AL}[n](ID_A[n-1]|ts_A)|T_{An}$$

To publish P_{An}, A must send P_{An} to a miner node, who will add it to its *pending transaction* queue, and send it to other miners in the network to add it to their queues as well. The transaction will signed into the next block in the blockchain, once the next proof-of-work is solved.

Node B, A's alibi for the above transaction example, will publish P_{Bm} after the exchange. If B's transaction is not available on the blockchain, A's transaction will be considered invalid and disregarded during verification. A transaction T_A in the blockchain must be accompanied by a reference to some valid alibi transaction T_B, and T_B must reference T_A, otherwise the proof is not considered credible by a verifier.

3.2.4 Key Packets

The key packet is more than simply a list of keys that a mobile node has used to encrypt its transactions; in order to preserve the “selective in-sequence privacy” property of OTIT [4], a user must be able to choose transactions that he doesn’t want others to be able to decrypt. However, in order to simultaneously preserve OTIT’s “privacy protected chronology” property, the transaction backwards-chaining must not be broken. This is why two separate *Key Lists* are maintained; KL_{AL} is used to encrypt the backwards-chaining link and transaction timestamp, while KL_{AT} encrypts the transaction data. For example, if node B doesn’t want to reveal transaction T_{Bm-1}, he would reveal the following key packet:

$$KP_{Bm} = (\{KL_{BL}[m], KL_{BT}[m]\}, KL_{BL}[m-1], \{KL_{BL}[m-2], KL_{BT}[m-2]\})$$

In this case, $KL_{BT}[m-1]$ has not been included with $KL_{BL}[m-1]$, in order to protect the privacy of this transaction. This means that a node who received this key packet will not be able to decrypt B’s transaction T_{Bm-1}, but can still prove that a transaction exists at that time and in the correct sequence, as B will still provide $KL_{BL}[m-1]$. This may be needed, for example, if node B doesn’t want to allow anyone to decrypt any transactions he has created within 5km of his home, in order to protect his privacy.

3.2.5 Aborting transactions

A node may decide to abort a transaction if it thinks it is in contact with a malicious node. In figure 3.4, node A encounters a malicious node M, who tries to spoof its identity with A. Node A will abort the transaction once it notices that $|ts_A - ts_M| \geq \epsilon_{ts}$, or $|loc_A - loc_M| \geq \epsilon_{loc}$.

To abort the transaction, A terminates the ad-hoc network with node M, and won’t publish anything onto the blockchain. This means that even if M fabricates some data from A and publishes a transaction onto the blockchain, the matching transaction from A will not be present, so the transaction will be disregarded by any verifiers.

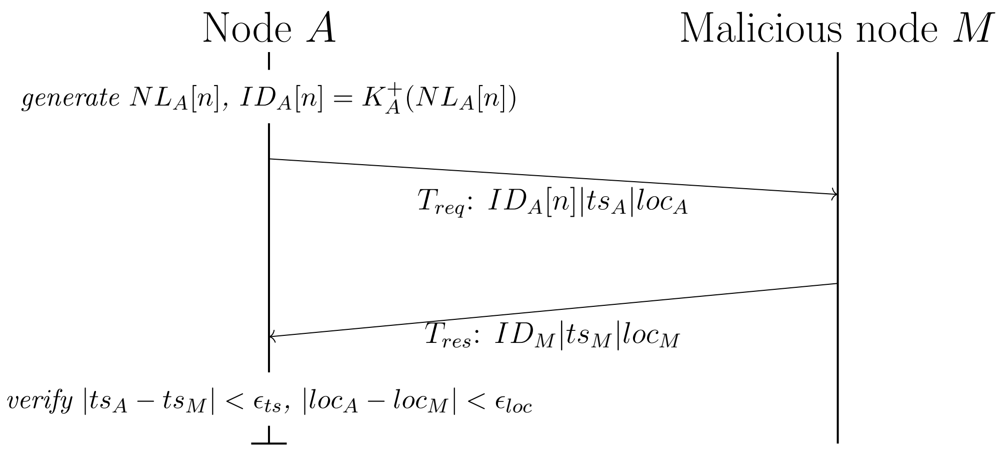

Node A
Malicious node M
generate $NL_A[n]$, $ID_A[n] = K_A^+(NL_A[n])$
T_{req}: $ID_A[n]|ts_A|loc_A$
T_{res}: $ID_M|ts_M|loc_M$
verify $|ts_A - ts_M| < \epsilon_{ts}$, $|loc_A - loc_M| < \epsilon_{loc}$

Figure 3.4: An aborted transaction due to malicious node M

3.3 Verification

In the verification stage, a mobile node tries to prove its location to a Verifier node, e.g. a bank. To do this, the mobile node sends the Verifier a number of parameters, as shown in Figure 3.5.

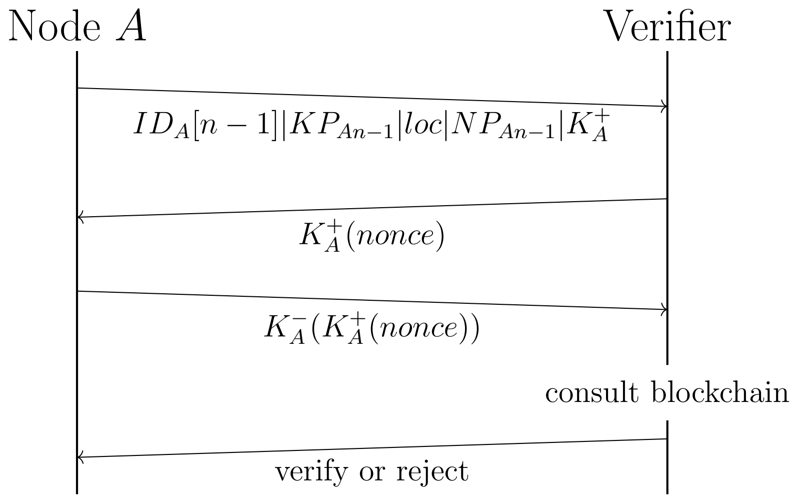


Figure 3.5: Verification request

$\mathbf{ID_A[n-1]}$ is the ID of A's most recently published transaction.
$\mathbf{KP_{An-1}}$ is A's key packet up to transaction $n-1$, and includes keys for as many transactions as A feels is appropriate in order to receive verification.
loc is A's current claimed GPS coordinates for which it is seeking verification.
$\mathbf{NP_{An-1}}$ is A's *Nonce Packet*, a subset of its *Nonce List* (section 3.1.1). A Nonce Packet is the list of the nonces used to generate A's most recent IDs, up to $n-1$, that A is willing to share with the Verifier.

The goal of the verification stage is for the Verifier to either accept or reject the location that the user is claiming. Given $ID_A[n-1]$ and KP_{An-1}, a Verifier is able to retrieve A's previous transactions, and the transactions of all of its alibi's. This will allow the Verifier to recursively inspect the transactions of all alibi's used in a nodes transactions, until it is satisfied that the location can be verified or rejected. This recursive inspection can be visualised as a tree, as shown in figure 3.6.

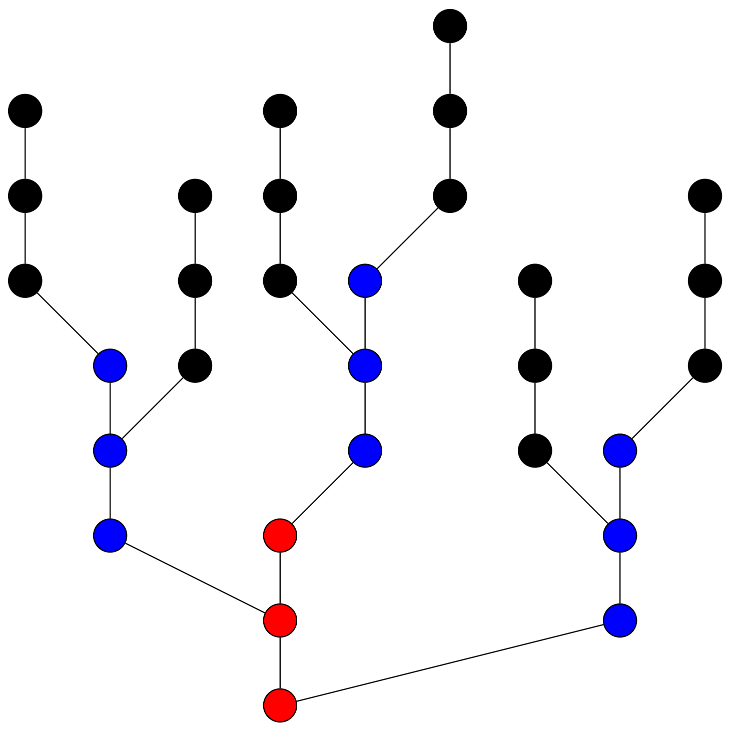


Figure 3.6: Alibi chain relationship tree

In this figure, the red chain is the requesting node's transaction chain. The blue chains are the red node's alibis' transaction chains, and the black chains are the blue node's alibis' transaction chains. If the verifier wishes to recurse more, it could inspect the black node's alibis' transaction chains. Note that this is a simple example, and $n = 3$, the length of the transaction chain subset provided for verification. In reality n should be much larger.

The Verifier uses NP_{An-1} and K_A^+ to prove that node A was the author of all of the transactions he claims to be. This prevents a collusion attack whereby nodes could share common transactions between different proof chains. When walking chronologically backwards along A's proof chain, the 3rd party will ensure that the ID used in transaction m on the proof chain matches $K_A^+(NP_{An-1}[m])$.

There are a huge number of possible factors involved in reaching a conclusion from the data on the blockchain; some of these factors will likely be unique to certain Verifiers, and kept secret to improve reliability and avoid gaming. Some simple example factors may include:

- **Alibi credibility:** if each of the node's alibi's have little or no alibi's themselves, they won't be considered credible alibis, and the Verifier will reject his verification request.
- **Transaction relevance:** if the Verifier considers the transactions it receives to be out of date, they will be rejected on the grounds that they are no longer relevant.
- **Alibi reuse:** if the Verifier can prove that alibi's are being reused frequently, then it will reject the verification request.
  - Due to transaction anonymity, the Verifier may not always be able to tell if two alibi's are the same person or not. e.g. node A could use node B as an alibi, then wait for B to complete n more transactions, then use node B again.
  - This is not a viable attack on the verification system. Depending on the size of n, enough time may pass between both uses of node B as an alibi that the transactions are no longer relevant.

Chapter 4

Evaluation

In this paper, we have presented a model for a location proof system which aims to preserve privacy and prevent false proofs from being created.

4.1 OTIT conformance

We can compare our model to OTIT [4], a list of features and requirements necessary for designing any secure location proof scheme. OTIT presents 8 such requirements:

> **Chronological**: The chronological property of OTIT ensures that transactions are published in the order they were created. In our system we do not enforce this property at the time of transaction publication. This is to avoid revealing any transaction information to the miner nodes, therefore preserving the privacy of the transaction owner. Instead, we enforce this property at the time of verification. The chronological link created by adding $KL_{AT}(ID_{A-1}|ts_A)$ to the transaction will allow Verifier nodes to prove that the transaction is chronologically ordered, preserving OTIT's "Chronological" property.
>
> **Order preserving**: This property states that the order of transactions cannot be modified after they are created. In our system, a blockchain is used to store transactions. In a blockchain, new blocks are added in a linear, chronological order, and cannot be modified so long as the majority of miners in the network are honest [11]. Therefore the transactions stored in these blocks satisfy the "Order preserving" property

of OTIT.

Verifiable: This states that the proof, and the order or proofs, should be verifiable by a trusted auditor. In our case, a Verifier node is an auditor trusted by the mobile node seeking verification. A Verifier node may be operated by a bank, government, or any entity wishing to make use of our location proof system.

Our system inherently satisfies this property of OTIT, as Verifier nodes are required to verify or reject a mobile node's claimed location. This is done by examining the mobile node's chronological link of transactions, and recursing for each alibi used for each transaction along the chronological link until the Verifier can conclude if the transaction chain is valid or not.

Tamper evident: Our system is tamper evident. If a malicious node creates a successful transaction with an honest node, but modifies the transaction data before publishing, a Verifier node will reject the malicious transaction. This rejection will be on the grounds that the matching transaction, published by the honest node, contains contradictory data.

We assume the underlying security of the blockchain, so any malicious miner nodes will not be able to tamper with existing transaction data providing that the majority of CPU power in the mining system is owned by honest miners [12]. Therefore the tamper evident property is satisfied.

Privacy preserved: This states that the user should have control over his level of privacy exposure when using the system. In our system, this is provided using *Key Lists* 3.2. We provide two keys for each transaction; $KL_{AT}[n]$ is used to encrypt the *transaction data* for A's *nth* transaction, and $KL_{AL}[n]$ is used to encrypt the *backwards chronological link* between A's *nth* transaction and transaction $n-1$.

To control his privacy, a user can choose only to reveal $KL_{AL}[n]$ for a specific transaction n. This may be useful if a user does not wish to reveal transaction data for transactions created within a certain distance of his house, for example. Hiding $KL_{AT}[n]$ while revealing $KL_{AL}[n]$ has the advantage of preserving the user's privacy while maintaining a clear backwards chronological link of transactions for the Verifier to follow, preserving both privacy and system consistency.

Selective in-sequence privacy: This is the requirement that any proof chain must support *sub-set verification*, allowing a user to provide only a sub-set of proofs from his current proof chain for verification. Our system satisfies this property by using *Key Packets* (section 3.2.4).

In our system, a *sub-set* of A's proof chain can be defined as KP_{An}. The sub-set therefore begins with ID_{An}, and ends when there is no key $KL_{AL}[n-m]$ in KP_{An} to decrypt the link to transaction T_{An-m-1}.

Privacy protected chronology: This states that the proof system, which provides *selective in-sequence privacy*, should also ensure that the user does not "hide away" important items within the subset. This is impossible in our system due to the use of backwards chronological linking between transactions, so our model satisfies this property.

Convenience and derivability: This requirement states that the verification process should be convenient, and the user should not burden the Verifier node with a huge load of data. In our system, the data is stored in a central blockchain that the Verifier has access to, and the user provides the Verifier only with decryption keys and indexes into a sub-section of this data. Therefore the data sent to from the user to the Verifier, KP_{An}, is quite small in size.

The Verifier has the freedom to decide how comprehensively to investigate the user's data; It can bound how deeply to investigate the graph of alibi's, if at all. We therefore satisfy this requirement by allowing the Verifier to choose how complex the verification process needs to be.

4.2 Attacks on the system

4.2.1 Identity replication

By repeatedly publishing fake transactions with the same ID, a malicious user can impede the Verification of certain transactions. This is because a Verifier will have to attempt to decrypt all transactions with the same ID until it finds one that decrypts successfully. A malicious user can therefore slow down the verification stage of certain transactions by flooding the blockchain with transactions with the same ID.

This is an abuse of the system than an attack. A malicious user will not be able to target specific users' transactions, because they are privacy protected. The malicious user can therefore gain no material advantage or compromise the security of the system by using an attack like this.

To avoid this attack, Miner nodes may reject any transactions with duplicate transaction IDs. Assuming sufficiently large transaction IDs, a duplicate ID is unlikely to happen through honest operation. Miners can assume that any transactions with duplicate IDs are malicious, and reject them.

4.2.2 Sybil attack

This system is vulnerable to a Sybil attack, where a single physical node may create multiple *pseudoidentities* [5]. A suitably powerful node, or motivated attacker, could create enough pseudonyms to create a subnetwork of nodes, each creating malicious transactions with each other. This would allow an attacker to falsify a believable location proof.

It has been proven that a central certificate authority is the only method of preventing a Sybil attack [5]. Other measures, such as web of trust, increase the difficulty involved in performing an attack, but the system remains vulnerable to a motivated attacker.

Chapter 5

Future work

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