Blockchain and cryptocurrencies

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1 Introductory concepts

1.1 Hash functions

A hash function is a fuction that maps an arbitrary long input string to a fixed length output string. Let h refer to an hash function of length n:

$$h\colon \{0,1\}^* \to \{0,1\}^n$$

m is usually called "the message", while d is usually called "the digest" and it can be seen as a compact representation of m. The length of d is the

Hash functions are usually used to provide data integrity and they're also used to length of the hash. construct other cryptographic primitives such as MACs and digital signatures.

1.1.1 Desired properties

An hash function should ideally meet these properties:

- **Computational efficiency**: given m, it must be easy to compute $d = h(m)$
- **Preimage resistance** (also called **one-way property**): given $d = h(m)$, it must be computationally infeasible computing m (m is the preimage)
- **Weak collision resistance** (also called **2nd preimage resistance**): given m_1 and $d_1 = h(m_1)$, it must be computationally infeasible finding a $m_2 \neq m_1$ so that $h(m_2) = d_1$
- **Strong collision resistance**: it must be computationally infeasible finding paris of distinct and colliding messages. Two messages $m_1 \neq m_2$ collide when $h(m_1) = h(m_2)$.
- **Avalanche effect**: changing a single bit of m should cause every bit of $d = h(m)$ to change with probability $P = 0.5$

1.1.2 Examples of hash functions

- **MD5**: published in 1991, it's a 128-bit hash function that was used for file integrity checks. Today it's considered unsecure and it shouldn't be used anymore.

- **Secure Hash algorithm 1 (SHA-1)**: 160-bit hash function that was used in SSL and TLS implementations. Today is considered unsecure and it's deprecated.
- **SHA-2**: family of SHA functions which includes SHA-256, SHA-384 and SHA-512. SHA-256 is currently used in several parts of the Bitcoin network.
- **SHA-3**: latest family of SHA functions, it is a NIST-standardized version of Keccak, which uses a new approach called "sponge construction" instead of the Merkle-Damgard transformation previously used. This family includes SHA3-256, SHA3-384 and SHA3-512.

1.1.3 Design of SHA-256

1.1.4 Message Authentication Codes (MACs)

A MAC is an hash function which uses a key and which can therefore be used to provide both integrity and authentication (proof of origin). Authentication is based on a key pre-shared between the sender and the receiver. The receiver can verify both integrity and authentication of a message by computing the MAC function of the message and comparing it with the one received from the sender: if they are the same then integrity and authentication are confirmed (note that it is assumed that only the sender and the receiver know the key).

MAC functions can be constructed using block ciphers or hash functions:

- in the first approach, block ciphers are used in the Cipher block chaining mode (CBC mode): the MAC of a message will be the output of the last round of the CBC operation. The length of MAC in this case is the same as the block length of the block cipher used to generate it.
- In the second approach they key is hashed with the message using a certain construction scheme. The most simple ones are *suffix-only* and *prefix-only*, which however are weak and vulnerable:
  - suffix-only: $d = MAC_k(m) = h(m|k)$, where h is an hash function
  - prefix-only: $d = MAC_k(m) = h(k|m)$, where h is an hash function

1.2 Digital signature

Digital signatures are used to associate a message with the entity from which the message has been originated. They provide the same service as MACs (authentication and non-repudiation) plus the non-repudiation.

Digital signature is based on public key cryptography: Alice can sign a message by encrypting it using its private key. Usually however, for efficiency and security reasons, Alice doesn't encrypt the message but its digest (hash of the message). Figure 1 shows how a generical digital signature function works.

An example of digital signature algorithms are RSA and ECDSA.

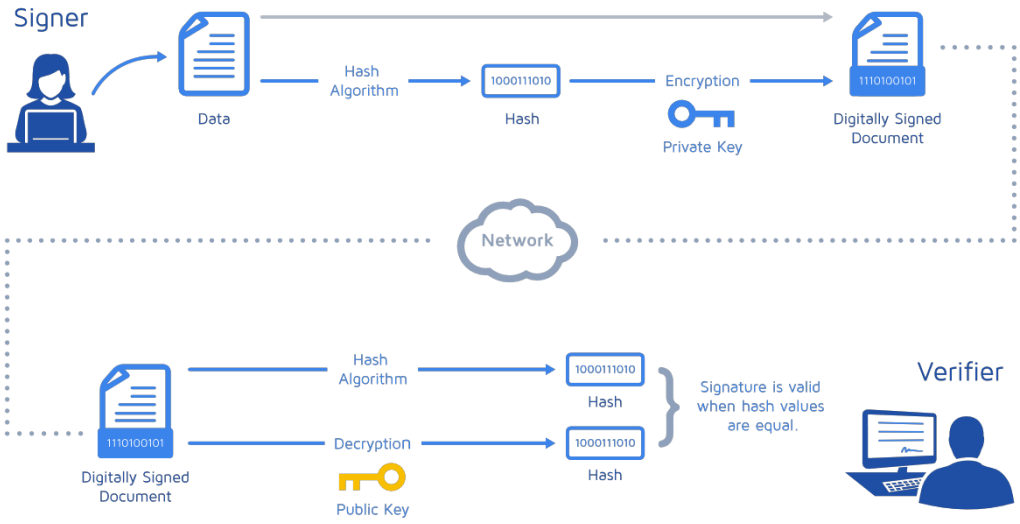

Figure 1: digital signature signing and verification scheme

1.3 Elliptic Curve Digital Signature Algorithm (ECDSA)

ECDSA is a variant of the Digital Signature Algorithm (DSA) which uses elliptic curve cryptography.

1.3.1 Key pair generation

1. Define an elliptic curve E with modulus P, coefficients a and b and a generator point A that forms a cyclic group of order p, with p prime
2. Choose a random integer d so that $0 < d < q$

3. Compute the public key B so that $B = dA$

The public key is the sextuple $K_{pb} = (p, a, b, q, A, B)$, while the private key is the value of d randomly chosen in Step 2: $K_{pr} = d$

1.3.2 Signing a message

1. Choose an ephemeral key K_e, where $0 < K_e < q$. It should be ensured that K_e is truly random and no two signatures have the same key because otherwise the private key can be calculated
2. Compute $R = K_e A$
3. Initialize a variable r with the x coordinate value of the point R
4. The signature on the message m can be calculated as follow:

$$S = (h(m) + dr)K_e^{-1} \bmod q$$

where $h(m)$ is the hash of the message m. The signature is the pair (S, r).

1.3.3 Signature verification

A signature can be verified as follow:

1. Compute $w = S^{-1} \bmod q$
2. Compute $u_1 = wh(m) \bmod q$
3. Compute $u_2 = wr \bmod q$
4. Calculate the point $P = u_1 A + u_2 B$
5. The signature (S, r) is accepted as a valid signature only if:

$$X_P = r \bmod q$$

where X_P is the x-coordinate of the point P calculated in Step 4

1.4 Distributed systems

1.4.1 What is a distributed system

Blockchain at its core is basically a distributed system, therefore it is essential to understand distributed systems before understanding Blockchain.

A distributed system is a network that consists of autonomous nodes, connected using a distribution middleware, which act in a coordinated way (passing message to each other) in order to achieve a common outcome and that can be seen by the user as a single logical platform.

A node is basically a computer that can be seen as an individual player inside the distributed system and it can be honest, faulty or malicious. Nodes that have an arbitrary behavior (which can be malicious) are called *Byzantine nodes*.

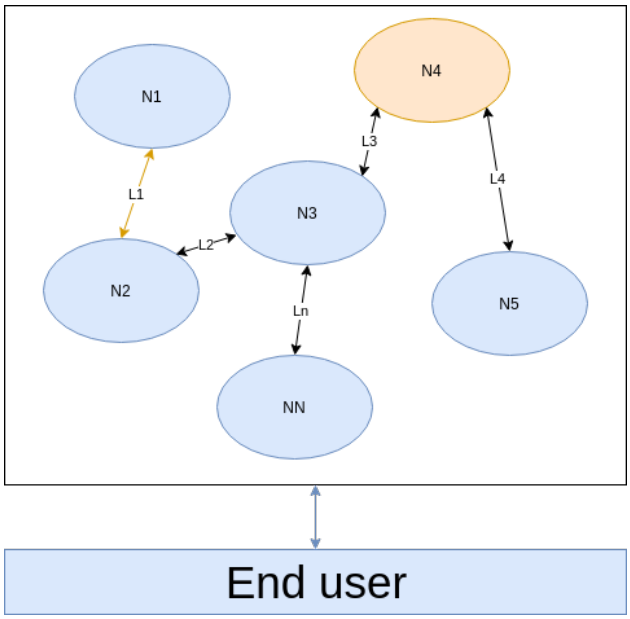

Figure 2: design of a distributed system. N4 is a Byzantine node while L1 is a broken/slow network link

The main challenge in a distributed system is the fault tollerance: even if some of the nodes fault or links break, the system should tollerate this and should continue to work correctly. There are essentially two types of fault: a simple node crash or the exhibition of malicious or inconsistent behavior arbitrarily. The second case is the most difficult to deal with and it's called

Byzantine fault. In order to achieve fault tolerance, replication is usually used.

Desired properties of a distributed system are the following:

- **Consistency**: all the nodes have the same lates available copy of the data. It is usually achieved through consensus algorithms which ensure that all nodes have the same copy of the data
- **Availability**: the system is always working and responding to the input requests without any failures
- **Partition tolerance**: if a group of nodes fails the distributed system still continues to operate correctly

There is however a theorem, the *CAP theorem*, which states (and proves) that a distributed system cannot have all these three properties at the same time. In particular, the theorem states that in the presence of a network partition (due for example to a link failure) one has to choose between consistency and availability.

1.4.2 The Byzantine Generals Problem (BGP)

The Byzantine Generals Problem (BGP) is a problem described by Leslie Lamport [9] in which a group of generals, each one leading a portion on the Byzantine army, are surrounding a city and they have to formulate a plan for attacking it (simplifying, they have to decide wheter to attack or retreat from the city). Their only communication way is the messenger and they have to agree on a common decision. The issue is that some of the generals may be traitors trying to prevent the loyal generals from reaching an agreement by communicating a misleading message. The generals need an algorithm to guarantee that all the generals agree on the same plan (attack or retreat) regardless of what traitors generals do. Loyal generals will always do what the algorithm says they should, while the traitors may do anything they wish.

As an analogy with distributed systems:

- generals can be considered as nodes
- traitors can be considered Byzantine nodes
- the messenger can be seen as the channels of communication between the generals.

1.4.3 Consensus

Consensus is the process of agreement between untrusted nodes on a data value. When the involved nodes are only two it's really easy to achieve consensus, while in a distributed system with more than two nodes it is really hard (in this case the process of achieving consensus is called *distributed consensus*). The data valued agreed is the majority value, therefore the value proposed by 51% of the nodes.

A consensus mechanism must meet these requirements:

- **Agreement**: all the correct (non faulty/malicious) nodes must agree on the same value
- **Termination**: the execution of the consensus process must come to an end and the nodes have to reach a decision
- **Validity**: the agreed value must have been proposed by at least one honest node
- **Fault tolerance**: the consensus algorithm must be able to run even in the presence of one or more Byzantine (faulty or malicious) nodes
- **Integrity**: the nodes make decisions only once in a single consensus cycle (in a single cycle a node cannot make the decision more than once).

1.4.4 Byzantine Fault Tolerance (BFT)

A distributed system is said to be Byzantine Fault Tolerant when it tolerates a the class of failures that belong to the Byzantine Generals' Problem [8]. In other words, a Byzantine Failure is a fault that presents different symptoms to different observers and for this reason BFT is really difficult to achieve.

For example, a Byzantine Fault could be a node acting as a "traitors" and generating arbitrary data during the process of reaching consensus.

2 Introduction to Blockchain

2.1 What is Blockchain

From a technical point of view, Blockchain is a distributed ledger that is cryptographically secure, append-only, immutable (extremely hard to change), and updateable only via consensus among nodes.

From a business point of view, a blockchain can be defined as a platform whereby peers can exchange values without the need for a central trusted party by using transactions which are stored inside the blockchain in a verifiable and permanent way.

2.2 Blockchain features

Decentralization

This is the core feature of Blockchain. Thanks to decentralization there's no need of a central trusted entity which stores the data and validates the transaction, since the same copy of the Blockchain is stored by every node and the validation of transaction is achieved through consensus.

Distributed consensus

Blockchain have a high Byzantine Fault Tolerance[1] and allows to achieve distributed consensus, therefore allows to have a single version of a data value agreed by all parties without requiring a central authority.

High availability

Blockchain is based on a peer-to-peer network of thousands of nodes and data is replicated on each node, therefore the whole system is highly available since even if one or more nodes fail the whole network can continue to work correctly.

[1] without BFT, a peer would able to transmit and post false transactions

Immutability

All the data stored in a blockchain is immutable: once a block has been added to the blockchain, it is considered pratically impossible to change it (changing it is computationally infeasible since it would require an unaffordable amount of computing resources).

Transparency

Blockchain is shared between the nodes and everyone can see what is in the blockchain, thus allowing the system to be transparent and trusted.

Security

Blockchain ensures the integrity and the availability of the data. Since private keys and digital signatures are used, it also provide authentication and non-repudiation. It doesn't provide confidentiality, due to it's transparency feature (privacy is however required in certain scenarios, thus research in this area is being carried out).

Blockchain security is due especially to its distributed nature, since for an attacker would be a lot easier to tamper with data if it was stored on a single central entity.

Uniqueness

In Blockchain every transaction is unique and has not been spent already. This is especially usefull in cryptocurrencies applications of Blockchain, where avoidance of double spending is a key requirement.

2.3 Blockchain structure

As shown in figure 3, a blockchain consists of linked list of ordered fixed-length blocks, each of which includes a set of transactions. In this section, the generic elements of a blockchain will be presented.

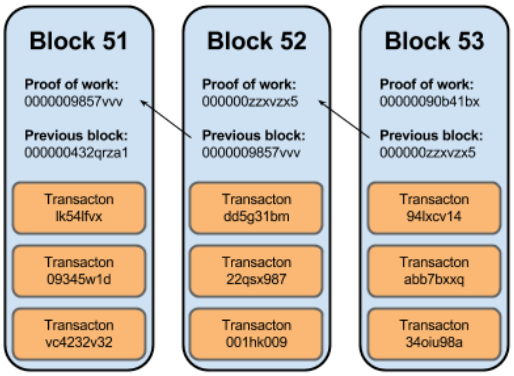

Figure 3: basic blockchain schema

Blocks

A block groups transactions in order to organize them logically and its size depends on the blockchain implementation. Generally, a block is composed of:

- a set of transactions
- a hash which identifies the block
- a pointer to the previous block hash (unless it's the genesis block)
- a nonce
- a timestamp

The *genesis block* it's simply the first block in the blockchain and therefore it can't contain any reference to the previous block.

Addresses

Addresses are unique identifiers which identify the parties involved in a transaction. An address is usually a public key or it's derived from a public key.

Transactions

A transaction is a tranfer of value from an address to another.

Peer-to-peer network

Transaction scripts

Transaction scripts are predefined sets of commands for nodes to transfer values from one address to another and perform various other functions.

Programming language and Virtual machine

A Turing-complete programming language is an extension of transaction scripts and it allows the peers to define the operations that has to be performed on a transaction, without the limitations of a non-Turing-complete transaction script. Programs encapsulate the business logic and can for example transfer a value from one address to another only if some conditions are met.

A virtual machine allows Turing-complete code to be run on a Blockchain as smart contract (e.g. Ethereum virtual machine).

Not every Blockchain supports Turing-complete programming languages and virtual machines (e.g. Bitcoin is not Turing-complete[2]).

Nodes

A node is an active entity which stores a copy of the blockchain and can perform and/or valide transactions (following a consensus protocol, e.g. the Proof of Work).

Consensus in Blockchain

[2]It however supports smart contracts

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