

# Web3: A Decentralized Societal Infrastructure for Identity, Trust, Money, and Data

J.W. Bambacht and J.A. Pouwelse

J.W.Bambacht@student.tudelft.nl, J.A.Pouwelse@tudelft.nl

Distributed Systems, Delft University of Technology

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**Abstract**—A movement for a more transparent and decentralized Internet is globally attracting more attention. People are consciously more privacy-aware of their online identities and data. Web2 is mainly focused on companies that provide services in exchange for ownership of personal user data. Web3 aims to place the users at the center of their data using decentralization and zero-server architectures. Ownership of identities is generally with governments. Many opportunities emerge by moving the ownership of self-sovereign identities to citizens. Banks could profit from one of the many advantages blockchain technology has to offer. Big-tech social applications are centralized in nature and regularly fail to deliver privacy to their users. Besides the storage of user data on their servers, the lack of authentic trust between participants of societal platforms is often misused or forged. Protection of data in storage and transit has proven to be essential, especially because of the increased amount of home workers due to the COVID crisis. The necessity for secure and private data transfer without leakage of any information grows. The overall challenge is to return the power to users and citizens again. A decentralized Internet will initially be an important step as it provides nobody but the owner full control over its data. This thesis is the first exploratory study into a decentralized societal infrastructure that integrates the use and ownership of governmental-issued identities to provide trust in online conversations, with a private and secure exchange of money and data. A fully operational infrastructure for Android has been developed that incorporates the P2P network overlay IPv8 [1], and TrustChain [2], a personalized blockchain. It contributes to a reformed tech and financial sector that is more efficient and effective in serving the wider economy, and more resistant to bad behavior of all kinds. Creating such an infrastructure that is decentralized and anti-fragile is seen as essential for the future.

## I. INTRODUCTION

The current digital infrastructure and financial system are unfit and structurally unfair to citizens. Citizens have no alternative to big tech monopolies, banking services, and their anti-competitive practices. Governments have failed to protect *consumer welfare* while keeping control over their citizens' personal identities. The WhatsApp messaging platform is a motivating example of market failure as it violates terms of service over a long period [3]. An update of their terms of service [4], providing mother company Facebook access to more user data, initiated a migration to other platforms. Competitors focused on privacy and openness, have barriers to market entry, no network effect, and compete against long existent closed protocols. Citizens and small(er) competitors [5] are powerless in this uncompetitive market.

The digitization of citizens' personal information by governments has highlighted privacy concerns. Government-issued documents of citizens are required for institutions and organizations, both online and offline. These documents have

been exposed numerous times by banks, insurance companies, hotels, employers, etc. Their owners have to rely on appropriate handling and storage. Governmental authentication mechanisms for digital identities are widely deployed by authorized institutions. Unfortunately, more personally identifiable information than required is stored on the organization's central server. Users, and governments, could benefit from the use of Self-Sovereign Identities (SSI). Users become in control over their own identities and can decide the exchange of their information. SSI's can also effectively be employed to enforce trust in online conversations to reduce phishing or impersonating attacks.

Governments, banks, and tax offices have insight into bank accounts and transactions of their citizens, often exploited using big-tech cloud services. Additionally, transaction costs are disproportional as debit card transactions range from about €0,05 to €0,20 per transaction [6], and even more for other online payment services like iDEAL [7]. The use of cash, which offers respectable privacy and also serves as a store of value, is (slowly) fading away [8]. Blockchain-based wallets, in combination with Central Bank Digital Currencies (CBDC), can positively impact both privacy and costs. Blockchain transactions are pseudo-anonymous, fast, cross-border suited, without requiring any costs.

A digitally oriented society negatively impacts people's privacy. The European Union started an ongoing effort into the General Data Protection Regulation (GDPR) [9] in 2016, targeting the misuse of privacy-sensitive data by companies. Big companies and platforms have failed to offer compliance to personal data protection, resulting in over 900 filed cases of GDPR complaints, valued over 1.3 billion euros [10]. Due to the GDPR in combination with intensive efforts of the EU and marketing campaigns, people raised awareness of the privacy of their online data and identities [11]. Commercial entities have an incentive to minimize spending on cybersecurity [12]. The storage of personal data and weak security mechanisms of platforms are both at the expense of the user. Users have to trust that the owner of the platform has the best intentions with their personal data. User data is often used as the product for company revenue and value, sold for personalized advertisement, and therefore form a challenge to rely on.

This research makes the following contributions: (I) design of a novel decentralized infrastructure that incorporates and uses a self-sovereign identity, (II) authentic trust enforcement between participants of communication, (III) generic transfer of money to other peers, (IV) generic transfer of data using a custom-designed P2P data transfer protocol.

## II. PROBLEM DESCRIPTION

The goal of this study is to design a novel societal infrastructure that incorporates a self-sovereign identity while facilitating the enforcement of trust between users and a private transfer of money and data in a permission-less fashion without the involvement of any centralized component. With centralization, even if the data is exchanged in encrypted form, an intermediary (the platform owner) is still able to see and collect your metadata. By removing these single points of failure, the violation of privacy and security of users is reduced.

One of the key aspects of our research is the application of citizens' self-sovereign identities. The definition of a self-sovereign identity is characterized by the ten principles of Allen [13, 14], that target the insurance of the users' control within its own SSI, with a balance between transparency, fairness, and protection. Although governments currently have ownership and control of these identities, various opportunities arise by moving the power to the user. Firstly, the user is the owner of their own identity and can view and decide what information to share. Secondly, as governments don't have control anymore, less personal data management is required, less bureaucracy, and a cost reduction for facilitating the heavily secured infrastructure and authentication mechanisms. And lastly, a minimum amount of personal data is stored on central servers or the cloud, reducing the possibility of data breaches and theft. Another opportunity is the replacement of visual identity document checks. Currently, identity documents are exposed upon request of some authority. Not only the requested piece of information is visible, but also the complete document. By using identity attestations, authorities are able to verify information of the identity without exposing the actual value. Age validation of a bouncer from the local pub is the perfect example of this. Communication channels lack trust in the authenticity of other participants' online identities. Since we have access to official SSI's, we can even apply this information for building trust. No social platform currently integrates government-issued identity information in such a fashion. Generally, online identities consist of a name, picture, phone number, or email, that altogether contribute to forming some trust in the authenticity of the user's identity. The problem with these attributes is that they are manually forgeable, and can be intentionally impersonated. Malicious actors try to make their fake identities look as genuine as possible to mimic someone's identity. Without these editable components and with automatic acquiring of information from the SSI, we can enforce authentic trust to other participants.

The global financial infrastructure is failing to provide real-time cross-border payments and is dominated by a select few monopoly players with high profits and near-zero innovation. Financial privacy is something that disappeared in the last decade(s). Governments, banks, and tax offices heavily supervise the bank accounts and transactions of users, albeit using automatic cloud services, removing the option to privately exchange money digitally. The transfer of money comes with disproportional costs, adverse cross-border payments in terms of speed and additional costs, and unwanted transparency.

Many of these issues can be solved by the use of blockchain technology, and specifically Central Bank Digital Currencies (CBDC). With (almost) zero costs, transactions are executed between wallets anywhere in the world in a matter of seconds. Even internal use of blockchain for banks themselves will save about 10 billion dollars globally [15]. Despite the openness of blockchain transactions to practically anyone, quasi-anonymity is maintained as the identity is not revealed.

The self-sovereignty of data, in any form, is also a fundamental issue of centralized platforms. The use of central servers is profitable in terms of availability and synchronization, but it stores the data and metadata of users. Although the data itself is often encrypted, the stored metadata contains an unnecessary amount of information (sender, recipient, time, location, .etc). WhatsApp is the most widely used messaging app [16] and promises its users end-to-end encryption. That does not withhold them to store a vast amount of metadata. Even though these platforms make us think they have prioritized security and privacy, not giving up their centralized nature is the primary reason for the existence of attacks [17].

The use of decentralization as part of a societal infrastructure emerges many opportunities and advantages. The user will be more respected in terms of their privacy, have control and ownership over their own data and self-sovereign identity, can provide authentic information to build trust with others, communicate with storage of useless metadata while reducing costs for the government and indirectly for the citizen as well. In the following sections, the design and implementation of the first user- and identity-centric infrastructure is presented in sections IV, V, and VI. Our custom-designed P2P data transfer protocol is analyzed and evaluated in Section VII.

## III. RELATED WORK

The application of SSI enables citizens to be in control of their own identity. Governments enable citizens to authenticate organizations and institutions to their identities, stored on their central server. DigiD<sup>1</sup>, the primary identity authenticator in the Netherlands, enables citizens to authenticate using their mobile phone. Personal data is transferred from the government's server to the organization's server. This requires a perfectly secure connection and infrastructure on both sides. Unfortunately, the citizen has no control over what information is actually shared. These authentication mechanisms are extremely expensive, especially during the COVID crisis due to scheduling of vaccination and test appointments, as €0,13 is credited for every successful authentication [28]. SSI's can be successfully applied to mobile applications that replace the necessity of authentication services like DigiD. A first example is IRMA<sup>2</sup>, an operational mobile platform that fetches the identity from the servers once and stores the SSI and other personal information locally on the phone. The authentication to organizations can be provided by the local SSI instead of the online authentication mechanisms. The user is in control and able to see the required information and what is actually shared. Sovrin Network<sup>3</sup>, a blockchain-based

<sup>1</sup><https://www.digid.nl>

<sup>2</sup><https://irma.app>

<sup>3</sup><https://sovrin.org>

TABLE I: Characteristics of competing platforms

	decentralized P2P	open source	E2E Encryption	metadata	requirements	attributes used for trust enforcement	wallet	maturity <sup>a</sup>	note
WhatsApp [18]	✗ ✗	✗	curve25519	✓	phone number	phone number, name, profile picture and status	✗	high	
FaceBook Messenger [19]	✗ ✗	✗	curve25519	✓	FaceBook profile	FaceBook profile, name, profile picture	✗	high	<sup>b</sup>
WeChat (QQ) [20]	✗ ✗	✗	✗	✓	phone number	phone number, name, profile picture and ID	money	high	
Telegram [21]	✗ ✗	✓	MTPROTO	✓	phone number	phone number, name, username, profile picture and status	✗	high	<sup>b</sup>
iMessage [22]	✗ ✗	✗	NIST P-256 curve	✓	Apple profile	phone number, name, email, profile picture	✗	high	
Signal Messenger [23]	✗ ✗	✓	curve25519, curve448	minimum <sup>c</sup>	phone number	phone number, name, profile picture and status	crypto	high	
Session Messenger [24]	✓ ✗	✓	curve25519, curve448	minimum <sup>c</sup>	✗	name, profile picture	✗	medium	<sup>d</sup>
Status.im [25]	✓ ✓	✓	curve25519	minimum <sup>c</sup>	✗	username, profile picture	crypto	high	
Sylo [26]	✓ ✓	✗	curve25519	✓	✗	name, profile picture	crypto	high	<sup>e</sup>
Berty [27]	✓ ✓	✓	curve25519	minimum <sup>c</sup>	✗	name, profile picture	✗	medium	
<b>Our design</b> (Section V)	✓ ✓	✓	curve25519	minimum <sup>c</sup>	official Identity	identity name and verification status, profile picture	crypto	medium	

<sup>a</sup>the current state of development in terms of completeness and usefulness

<sup>b</sup>E2E encryption not enabled by default

<sup>c</sup>no storage of metadata, only required for routing

<sup>d</sup>fork of Signal Messenger, onion routing for metadata anonymity, undelivered messages stored one of the distributed service nodes

<sup>e</sup>everyone can set up node and will be rewarded in crypto token SYLO

ecosystem that enables other developers to build their own SSI application on top, shares the same methodologies. Some situations require the possibility to revoke the self-sovereign identity, for example when the identity is lost or stolen. Both IRMA and Sovrin apply the concept of (centralized) authorities that handle the revocation. This is a violation of the principles of SSI as it should be an authority-free system. The work of Chotkan [29] incorporates a distributed attestation revocation for SSI's. Offline verification is more privacy-aware and offers a more robust solution for digital attestations.

As mentioned before, this paper presents a *novel* decentralized infrastructure as it incorporates a government-issued identity within a messaging platform. Many other platforms exist, both centralized and decentralized, that apply at least some of the key points of this paper. In Table I a (non-exhaustive) list of significant and related competitors in the market is portrayed. The difference in characteristics between the centralized and decentralized platforms shows a clear clustering. The centralized platforms all have a privacy-sensitive asset as a requirement for its use and many different attributes are shared with contacts for identification and trust enforcement purposes. The decentralized platforms are examples of Privacy by Design [30] implementations as they try to minimize the leakage of privacy-sensitive information. There are no explicit requirements and the trust attributes are limited to manually chosen names and profile pictures.

WhatsApp [18], Facebook Messenger [19], and specifically WeChat [20], are all fully centralized platforms that store metadata of their users. All platforms but WeChat have integration for commonly-used E2E encryption curves, due to their performance in terms of speed and secrecy, and only Telegram

[21] applies their self-designed protocol. WeChat, which is monitored by the Chinese government, incorporates strong censorship and interception protocols for data exchanged by its citizens. Luckily, this degree of violation is not present in any other (centralized) platform. Also, these centralized platforms are often obliged, also because of their infrastructure design, to provide information in the form of metadata to governmental instances or apply censorship in some situations, all upon request. Signal Messenger [23], which is centralized but specifically designed with privacy in mind, does not store any personal information. Central servers, however, are deemed necessary for routing and functionalities like account recovery using the same phone number or email. Account activation is validated using the users' phone number or email address. Characteristically, most of the centralized platforms don't provide full transparency and rather do not share the structure of their platform openly.

Decentralized infrastructures try to realize anonymity by reducing the metadata in the network as much as possible. Session Messenger [24], a *decentralized* fork of Signal Messenger, attempts to provide anonymity and preservation of privacy using a technique called onion routing [31]. It makes it nearly impossible for any intermediary (node) to derive both the sender and receiver of the message. It is not possible to apply this technique in a (fully) P2P network as peers only know a limited number of other peers and do not (necessarily) communicate with nodes. Status [25], Sylo [26], and Berty [27] are decentralized, P2P, secure, minimize leakage of privacy-sensitive information, and provide the most preferable features, apart from the absence of self-sovereign identity integration. Status is developed on the Ethereum

network and incorporates their own utility network token that fuels their network and provides (paid) features to users. In a similar fashion to Session Messenger, undelivered messages are stored on nodes that obtain your IP address to deliver at a later moment. This is not a desirable characteristic as this contradicts the principles of privacy. Sylo is a fully operational platform that cannot withstand the leakage of information in the metadata and does not provide full transparency to its users. Berty has all potential as it is secure and transparent, minimizes leakage of privacy-sensitive information in terms of metadata and requirements, but is currently underdeveloped.

As we've seen, there exist many different implementations that are designed on similar characteristics. The idiomatic platform is decentralized and P2P with no temporary storage of messages on nodes (as convenient as they are), incorporates trusted curves for E2E encryption, does not require and apply the use of metadata, and has no useless identifiable requirements. Our design additionally and uniquely incorporates a self-sovereign identity as a requirement, providing various functionalities. Trust enforcement attributes should be limited to not only manually forge-able components as it achieves higher trustworthiness. Furthermore, the platform must contain private and secure mechanisms for data transfer and transfer, and store, of digital money.

#### IV. INFRASTRUCTURE

The prominent problem of leading societal platforms is their centralized nature. Decentralization targets the many weak spots of centralization, such as providing a private and secure storage of data in a distributed way. Even a decentralized network allows data to traverse many other nodes on its path to its destination, possibly allowing them to store metadata. A P2P network makes it possible to communicate directly between peers without any intermediary. As no intermediary is able to act as a middle-man or adversary, an extra layer of protection is provided. Nobody other than the participants is able to store or share metadata, or even sell metadata to third parties. The communication itself can only be sufficiently secure if the message, or data, is encrypted. We also require a component to store and exchange data in a distributed manner. In distributed systems, one of the requirements is full synchronization across many independent nodes. This is difficult to realize for systems that include peers are not connected at all times. To enable the transfer of (digital) money, the infrastructure is required a persistent and decentralized store of data that does not require continuous synchronization. The blockchain is often applied to store transactions between two individuals in a permanent and uneditable manner. Every transaction on the blockchain is entangled to its previous block, making it a reliable 'chain' of tamper-proof assets. This very basic form of storage is a fast, lightweight, and structured alternative to conventional storage. Every transaction can be back-traced to create a well-organized overview, which is well suited to serve as a wallet. In Figure 1 a low-level overview of our infrastructure is portrayed.

Peers in the network are constantly looking (and updating connectivity status) for other peers in the network as no central server or node monitors the online activity of participants.

A certain degree of anonymity is required as it is not desirable to spread personal information to (unknown) peers in the network. The infrastructure desperately requires some sort of anonymous form of peer identification. To ensure a completely secure communication channel, the principles of the CIA Triad [32] must be in place. The objectives of a secure system include *Confidentiality*, *Integrity*, and *Availability*. Confidentiality is achieved by encryption as it ensures that data is only accessible to authorized parties. Digital signatures ensure the integrity of the data by providing proof that it is originated from the sender and has not been altered by any third party. The availability is slightly more difficult to ensure in decentralized systems, especially in P2P networks, due to the dependence on the connectivity of individual peers (or nodes).

A commonly-used mechanism for secure communication is public-key cryptography [33]. Not only does it provide a confidential exchange of messages and data, but it is also a way to identify peers without exposing any private information. Each peer is provisioned with a so-called public-private key pair. A private key is generated at once and should be known to its owner only. The private key performs the decryption of encrypted data. A public key is mathematically derived from the private key and may be publicly disclosed to others without damaging its security, as it is computationally infeasible to derive the private key from the public key. A public key serves multiple purposes. Firstly, it provides a way to find and identify other peers. Secondly, encryption of data is performed using the public key of that receiver. Even the peer that encrypted the data for another peer is unable to read the contents anymore. And lastly, digital signatures provide proof of authenticity of a piece of data, which can be verified with the public key of the signatory.

##### A. Networking Layer

To be able to communicate with other peers we need a networking layer that handles all outgoing and incoming communication. This can be achieved with IPv8 [1], a P2P networking layer that provides authenticated and privacy-aware communication between peers. IPv8 is developed as a possible successor of IPv4, in an attempt to overcome IPv4's weak characteristics and increasing problems. The objective of IPv8 is to provide communication in a zero-server infrastructure, equal status and power within the network for everyone, and to provide perfect secrecy with E2E encryption. IPv8 is capable to establish connections to other peers, even for devices that are connected behind NAT or a (strong) firewall. Customized NAT traversal techniques, e.g. UDP hole-punching, are effectively applied to provide connectivity with increased privacy. The endpoints of the networking layer are independent of any central infrastructure.

The aim is to reduce the exposed metadata to an absolute minimum. It requires that data packets are not widely broadcasted on the network, hoping other peers are able to deliver the packet to the intended recipient. Some P2P systems employ distributed nodes that enable the delivery of data to peers that are currently not connected to the network. These

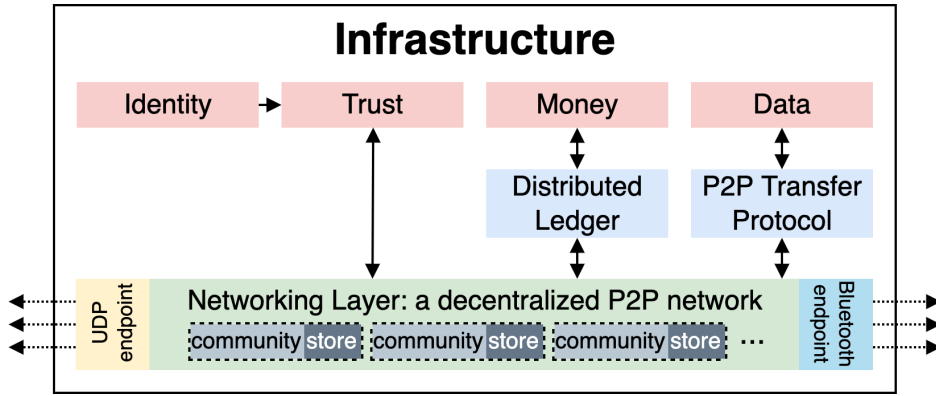


Fig. 1: General overview of the infrastructure

nodes temporarily store the data and metadata of the message until it has been successfully delivered. Although this feature addresses the availability property of the network, it also risks the leakage of metadata. The metadata of a packet should, ideally, only contain information about delivery, that is, the receiver’s public key or IP address, as additional metadata could be encrypted with the data. The risk of exposing privacy-sensitive information in our P2P network is minimized as peers directly communicate without any intermediary nodes or peers. As peers come and go, it may happen that peers change connectivity status or change their network address. In these situations the peers announce their new address to all previously connected peers. This may sound contradicting in terms of privacy. Hence no personal information, including intentions and communication histories, can be deduced as peers also connect to random peers to increase their network reach.

IPv8 applies the concept of the so-called network overlay or *community*. This enables developers to build applications on top of the base networking layer by creating their own community. The base community includes all functionality in regards to peer connectivity, communication, data serialization, and encryption. One could argue that the IPv8 networking layer actually combines multiple layers together, as it handles various functionalities in the OSI model [34]. Every community may have a different list of connected peers, based on the peers that chose to join the community or hasn’t been connected (yet). Every community that requires the storage of data is in need of a service that handles the interaction with a database, or *store*. A specific discovery community handles the discovery and the connection with (new) peers that are present in the same community. The communication between peers in the network and community is handled by endpoints/sockets. IPv8 provides support for both online and offline communication using UDP and Bluetooth endpoints. The support for offline communication increases the reliability and applicability of the platform.

### B. Distributed Ledger

The ecosystem requires a distributed ledger that provides the transfer of money and storage of transactions. TrustChain [2], a permission-less scalable distributed ledger, is already

integrated as a community on top of IPv8 and is therefore a proven candidate. TrustChain has the capability of sending and receiving trusted transactions between peers. The blockchain-based data structure is a tamper-proof immutable chain of transactions. There is no central control over the transactions. Every peer implements a personalized chain that only contains blocks that are either sent or received by the peer. TrustChain has three basic functionalities: sending/receiving of blocks, blocks broadcasting, and crawling of chains. The send and receive process merges both parties in one transaction, see Figure 2. The initiator ( $p_0$ ) signs and sends a *proposal block*

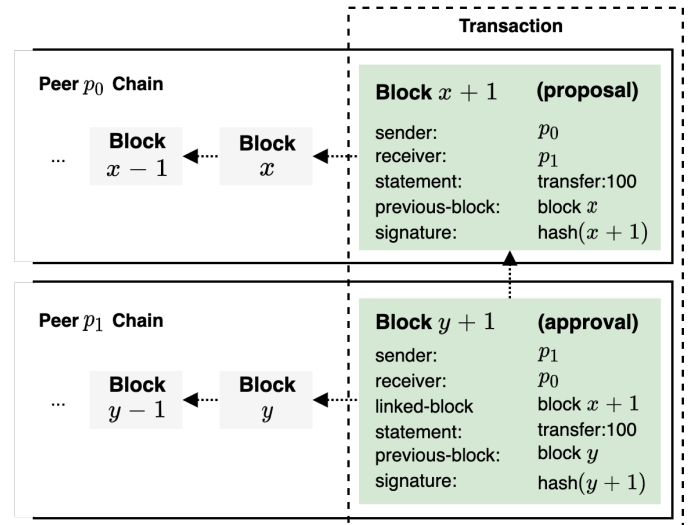


Fig. 2: Transaction in the ledger

(a half block) to the counterparty ( $p_1$ ). On receipt of the *proposal block*, ( $p_1$ ) creates, signs, and sends the *agreement block* back. During the process, the integrity of the received block is validated and both parties add the half blocks to their chains. The half blocks are linked by the public key of the counterparty. The transaction is considered complete when both parties received and signed both half blocks. Not only is it possible to send a block to a specific peer, the broadcasting of a block will send the block to all currently connected peers. The crawl functionality is nothing more than retrieval of a peer’s chain using its public key.

## V. DESIGN

The design of the platform can roughly be divided into four main elements: identity, trust, money, and data. These elements are integrated within the infrastructure of Section IV to create an ecosystem that combines these elements seamlessly. The elements, described in the following sections, are required to satisfy the requirements and functionalities that are deemed necessary for a self-sovereign, secure, and privacy-aware communication platform.

### A. Identity

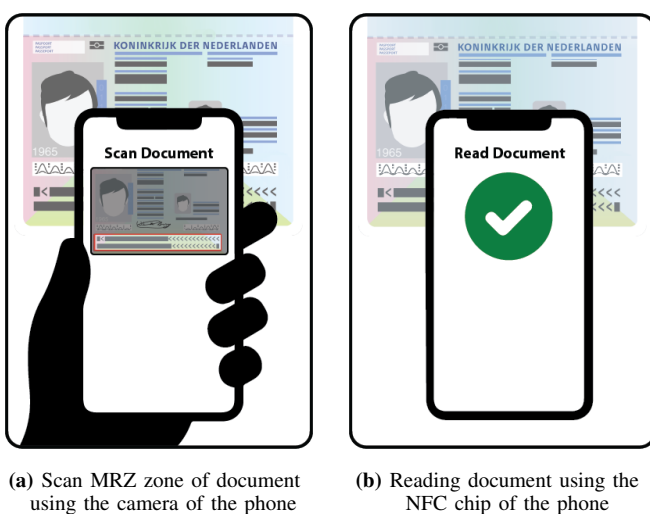
The identity is an integral part of citizens when it comes to ownership over their (self-sovereign) identity. Integration of their legally valid government document in a self-sovereign manner introduces various new opportunities. One of these purposes is the authentication of online institutions. The owner controls the exchange of its own information to organizations instead of the conventional governmental authentication that blindly transfers every piece of information. Authentication can only serve its purpose if the information within the self-sovereign identity is authentic. IRMA, application mentioned in Section III, achieves authenticity by fetching the attributes from the government's central servers once. This is not a suitable option in our system as we desperately want to eliminate the use of central servers. Every (adultery) citizen is obliged to possess a physical government-issued travel document in the form of a passport or identity card. These documents contain (visually) the exact same identity information in the machine-readable zone (MRZ) as on the government's servers. The identity document onboarding process is executed in two consecutive steps. The first step consists of scanning the MRZ zone of the document using the camera of the phone, see Figure 3a. A combination of AI and check digits embedded in the MRZ zone ensure that the required attributes for the second step are valid. These attributes are stored on the phone after a successful scan. The second step is executed in combination

of the phone. This step is extremely important as it proves the authenticity of the document in digital form. Without this validation step, there is no way to determine the correctness of these attributes. The phone has to be placed with its back to the document to make contact, see Figure 3b. The chip communicates with the NFC chip to fetch all attributes digitally from the document. Before these attributes can be transferred to the phone, a connection has to be established. The authentication requires three valid attributes (document number, date of birth, and date of expiry) to successfully establish a connection and exchange the document attributes to the receiving phone. The application stores all document attributes on the phone in the form of the self-sovereign identity. This process is deemed authentic and secure because (I) a physical document is required and the attributes displayed on the card must match the content in the chip of the card, and (II) the biometric document is widely applied for governmental purposes and international traveling, without excessive vulnerabilities [35]. It is important to note that it's not possible, and possibly never will, to revoke access to a stolen or lost document without online knowledge from a central server. The SSI will be valid, just like official documents, until the expiration date of the document.

A different situation arises when the phone has no support for the NFC chip, defectively or physically. There does not exist an (offline) method to obtain the identity authentically by only scanning the document. As the chip performs the validation of the document, a malicious actor can forge any detail in the MRZ zone to its preference. No identity-related functionalities can be trusted to contain truthful and authentic information. There is no other option to either disable all these functionalities for these devices or to be dependent on the government's central servers to obtain the identity.

In real-world situations, it is sometimes mandatory to show or even make a copy of your physical identity document to verify some details or to serve as insurance. The authority is not only capable of unnecessarily viewing the requested attribute(s), but also other attributes on the document. This directly violates your privacy and can even cause identity theft or misuse of a person's authenticity. People are forced to trust this authority to handle and store your identity secure and with care. Self-sovereign identities introduce the opportunity to use verifiable claims. Verifiable claims are claims about pieces of information that can be verified using attestations. Chotkan [29] designed a framework that incorporates revocable verifiable claims without revealing the actual requested piece of information using zero-knowledge proofs. To apply variable claims in a trustworthy manner, the information from the self-sovereign identity must, again, be authentic.

The focus should not only be on data in transit, but also on data at rest. In the latter, the data is stored somewhere without anyone currently accessing it. The data is often stored as a file or in a database. In our case, the identity must be secured significantly without risking identity theft. As mentioned before, our design applies public-private keys for encryption. The storage of the identity can easily be encrypted using the private key of the user, while only allowing the application to decrypt when absolutely required. That means that no one is able to



**Fig. 3:** Step of identity document onboarding process

with the documents' built-in biometric chip and the NFC chip

access the contents outside the application environment, as long as the private key is insusceptible. Biometric protection (face recognition or fingerprint), or the use of passcodes, can effectively be applied as another layer of protection for unauthorized access of sensitive data. It can also serve as confirmation for irreversible actions like the transfer of money or exchange of sensitive information.

### B. Trust

Platforms have to deal with multiple types of trust. The first natural form is trust in a system or platform, especially for a centralized platform. As a user, you want to have faith that your personal data is handled and stored with care. This is often one of the primary problems with centralization. As all user data is stored on the platform's servers, you must have confidence that the data, including metadata, is protected with the highest security standards, exchanged in encrypted form, and not sold to any third parties. If no good alternative platform exists, or because no friends use other platforms, the user has to decide whether to continue to use the platform and neglect the privacy-related issues, or not use the platform anymore. Often the first choice is selected as people value the use of the service more than their own privacy. Decentralization (almost) completely eliminates this trust, or distrust, as there is no central component or authority that decides over you and your data. Also, a platform that is open source is generally better trusted as there are no hidden surprises due to experts evaluation. We must take notice that in some networks, malicious actors actively crawl metadata in order to gain knowledge about confidential information. Communication in P2P networks, in the form of network packets, is directly sent to the network address of the recipient, making this problem almost redundant.

In messaging and societal applications another form of trust arises: the trust in the authenticity and identity of the other participant. The confidence in the authenticity of the contact is determined based on the (online) identity of the contact, the (dis)similarity in the way they communicate, and the discussed topics. The style of writing and difference in for example punctuation and the use of capital letters can also play a role in recognition. Unfortunately in most applications, personal information can easily be forged or stolen from people's (real) online identities. If we again look at Table I, most attributes for trust enforcement of centralized platforms are forgeable. Spear phishing [36] is for example an attack in which individuals are targeted with the explicit use of personal information with the goal to gain knowledge or access to (more) sensitive information. In applications like WhatsApp, it is possible to migrate from one phone to another. As this is a convenient feature in case you got a new phone, it also exposes risks as hackers are able to take over your account on their phone and communicate with your contacts instead. This has the deficit that hackers, within the context of (spear) phishing attacks in messaging platforms, are able to use these accounts to steal confidential information or money from trusted unsuspecting contacts. These hackers try to mimic as much confidential information of the hacked person to not arouse suspicion and

to gain trust with new victims. Fortunately, this type of attack does not exist in our design as migration is not possible.

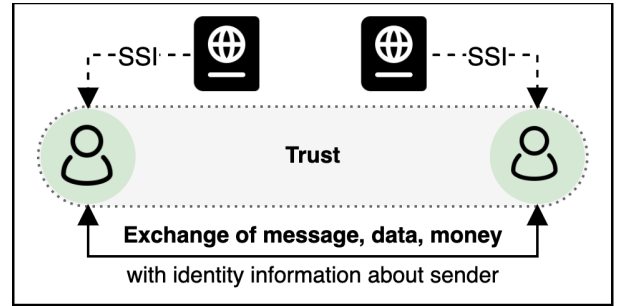


Fig. 4: Building trust using the self-sovereign identity

The challenge is to exchange just enough trust to the recipient of your message, without exposing an unnecessary amount of private information. In the initial phase of the conversation, especially if the users are connected in some online way, trust (or mistrust) plays a major role. As valid SSI's are incorporated in our design, we can access and apply this authentic information. In a normal, physical first meeting, one would introduce themselves by their (first) name, and indirectly with facial expressions, the sound of their voice, and the overall atmosphere. These aspects are not available in a digital world. The only identifiable information that we can exchange is a person's name and photo, as embedded in the SSI. These attributes can provide the authenticity that our system requires by sending it to the other contact. To provide proof of its authenticity, we can include the identity verification status. The verification status formally denotes the trustworthiness of the name and photo, while it actually denotes the use of the NFC chip. Users which not have been able to use the NFC chip, and thus unverified, are able to choose their own name and photo to allow them access and use of the platform. The contacts will in turn be notified of the unverified status, implicating they should act cautiously.

TABLE II: Trust enforcement combinations for identity name

Combination	Example
I {First Name}	Timothy John
II {Last Name}	Berners-Lee
III {First Name} {Surname[0]}	Timothy John B.L.
IV {First Name[0]} {Surname}	T.J. Berners-Lee
V {First Name} {Surname}	Timothy John Berners-Lee

The next step is to decide on the contents of the exchanged name, as we basically have access to the full official name. The transfer of too much confidential information can lead to malicious misuse against them or their contacts. Various combinations of the given and last name exist that aim to provide trust, see Table II. While combination I is too general and unidentifiable, the use of the last name in II provides more specificity but may still be too general in most cases. The use of the full name in V, as embedded in the SSI, is an easy source for malicious actors to take advantage of. The combinations III and IV include both the first and last name in a modified form, and provide a more personal and identifiable view without overdoing it. The identity of a person

is more decisive by its last name due to its uniqueness, and combination IV therefore fits our aim best for the use as the trust enforcement attribute.

The name and photo attributes of the peer's identity are sent along with every message, obviously in an encrypted manner. Upon receipt, the system compares the information with the currently stored state and detects differences. Initially, the state is empty. The recipient of the first message will be notified in a recognizable manner that the identity of the contact has been determined. For every other message, if at some point the state changes, the user will receive similar notifications stating that the information has been updated. This mechanism makes sure the user always has knowledge of the sender's formal identity. It is, however, impossible to notice alteration of the identity in case a phone is stolen or unauthorized accessed. To provide on device authorization, it is desirable to apply biometric protection. As long as biometric protection is in place, it should be difficult to impersonate. Also, a mechanism that requires the user to regularly verify its identity using their physical document could help to reduce misuse. Both options are currently not part of our initial design but serve as improvements on authentic communication. It is equally important to not only focus on building trust but to preserve the privacy of the receiver as well. The platform will *never* share identity information without having sent a message or transaction first. This reduces the risk of malicious actors purposely fetching names and photos linked to the particular public keys.

### C. Money

As the need for financial privacy grows, many Web3 applications integrate the transfer of some sort of value in the form of cryptocurrencies or NFT's. Governments of countries and unions are currently exploring the economic and technical feasibility of Central Bank Digital Currencies (CBDC) [37, 38, 39, 40]. Money in the form of digital currencies that reflect on their native currency, often also referred to as stable coins, could provide a fast, cheap, and private exchange between participants. Other cryptocurrencies are not suited for this purpose as they appear to be extremely volatile, lacking the consistency for a safe store of value. CBDC offers three main characteristics: it is a digital currency, it is issued by a central bank, and it must be universally accessible. As these currencies will be legally recognized and backed by their governments and central banks, their introduction and effect on the financial system are heavily tested. If somewhere in the future, countries decide to become cashless, these currencies must be creditable to replace coins and banknotes. China, which is already in the advanced stages of the development of its CBDC, is currently testing the implementation of its digital Yuan wallet in a pilot [41]. The Bank of China will still include regulation for larger transactions and seek only to collect personal information that is legally required. Compared to the principle of cryptocurrencies, which strives for pseudo-anonymous transactions, China doesn't make an effort to give up its (financial) regulation.

Currently, many external services or banks provide the functionality to create payment requests. Its creator shares a

link to all participants that redirects to a payment portal of the service. This not only creates an additional dependency on the use of a centralized (paid) service but also opens abusive opportunities for malicious actors. Many fraud cases [42] using payment requests make the service vulnerable, specifically for unsuspecting persons or the elderly. P2P digital payments can solve this problem by eliminating the dependence on the middle-man. The transaction or payment request is instead directly sent to the other peer, in an online or offline fashion. This not only makes it faster and cheaper but also offers a more private exchange of value.

Governments, banks, and tax offices shouldn't have implicit insights into transactions of CBDC's. The privacy of the users will be preserved up to a certain level. As most ledgers and blockchains are transparent, transactions on the chain are visible to others, and can even view or make an attempt to trace back the wallet balance. Blockchain still provides pseudo-anonymity because participants of transactions are often identified by a public key only. No further personal information is attached to transactions, apart from the sender and recipient, and some unidentifiable transaction contents, statistics, and possibly some other (encrypted) data. Governments will not attempt to regulate and gain insight into these transactions because it is simply not feasible to do so. If we compare blockchain transactions with the current digital payment solutions, it is definitely a step forward, while conventional cash remains the most private and anonymous form of payment and store of value. Not only would the use of CBDC's contribute to new innovations and direct accessibility of money without any external dependence, but it may also even serve some of the fundamental financial primitives (lending, borrowing, liquidity, etc.) as well.

Our design incorporates the use of an offline-capable CBDC called EuroToken [43], in combination with the distributed ledger TrustChain [2] that builds upon the technologies of IPv8 [1]. The EuroToken protocol tries to offer a scalable, privacy-aware, and cheating-resistant system for the exchange and storage of transactions. TrustChain implements the ledger and communication over the IPv8 network. Every block stored on the ledger contains a single transaction that states the transfer of funds from one to another. A block is cryptographically linked to its predecessor, preserving a chain of chronological and valid blocks. TrustChain is not only limited to financial transactions and can basically serve any purpose. Transactions are settled within seconds, depending on the connectivity status of the other peer.

One of the aspects of a tokenized system is the acquiring of tokens. There must be at least one option to buy and sell these tokens for the system to be useful. EuroToken incorporates a central exchange portal that allows users to exchange money on their bank account with EuroTokens, in both directions. The user that wants to exchange money announces itself, in the form of their public key and the amount, to the portal. The portal creates a request to the user that is automatically handled and stored by the protocol. Although it is not desirable to integrate centralized components in the system, it is considered a requirement for the system to be functional.

After the initialization of the application, every wallet is



ready to send and receive tokens. A balance is required to be able to send tokens. A balance is either acquired using the exchange portal or received by other peers. The balance is determined and validated using the blocks on the chain. Our design fully integrates and stimulates the transfer of tokens between peers. It is possible to transfer tokens to a peer directly from the wallet or indirectly from within a chat. The integration of payment requests conveniently enables a peer to request tokens from another peer.

#### D. Data

One of the key aspects of secure and private communication is the transfer of data in a decentralized and P2P manner. Data is the collective name for everything that can be expressed in the form of human-unreadable blobs, a Binary Large Object. These blobs can in turn be deserialized into a format that may be readable for humans, e.g. images or text documents. Messages, and even transactions, can thus be classified as data as well. The current implementation of IPv8 already contains a data transfer protocol. This protocol is able to send small and large blobs to other peers, containing metadata and data. However, the protocol has proven to be limited in terms of performance and unreliability. For the proper use of our platform, it was deemed necessary to design a custom protocol that has a decent performance, provides a reliable exchange of data, in a secure and private fashion. The default data transfer functionality of IPv8 is fast and reliable enough for data in the form of text messages and small text attachments.

The designed data transfer protocol aims to provide reliable and optimal performance for everybody in a *progressive* and *adaptive* fashion. The protocol is fully integrated into IPv8 and available to every community if necessary. Due to limitations, IPv8 (currently) only allows one concurrent transfer between two peers. The protocol is based on the principles of TFTP [44], the Trivial File Transfer Protocol. TFTP is a simple and connection-less data transfer protocol, with the consequence that no authentication and security mechanisms are provided. The transfer of confidential data in (external) networks is unsafe, and therefore not recommended. In P2P networks it is difficult to maintain established connections, and therefore a protocol design based on the connection-oriented TCP protocol is not suited. For a connection-less protocol, the application of the User Datagram Protocol (UDP) [45] is an obvious choice. The question is how to effectively integrate the unreliable UDP in the design of a reliable data transfer protocol. For some purposes, for instance live video streaming, the loss of single packets does not impact the result as single video frames or pixels are simply skipped. In the case of our platform, the loss of packets would have the deficit of unusable data. Our protocol must therefore handle and keep track of unreceived packets and request retransmission if necessary. The operation of the protocol is very basic and only consists of four different payload types. The contents and metadata of the payloads are encrypted and only decryptable to the receiver of the packet. The normal operation of the protocol is showcased in Figure 5. The sender of the transfer first has to request to write data, including all transfer-specific details, by sending a

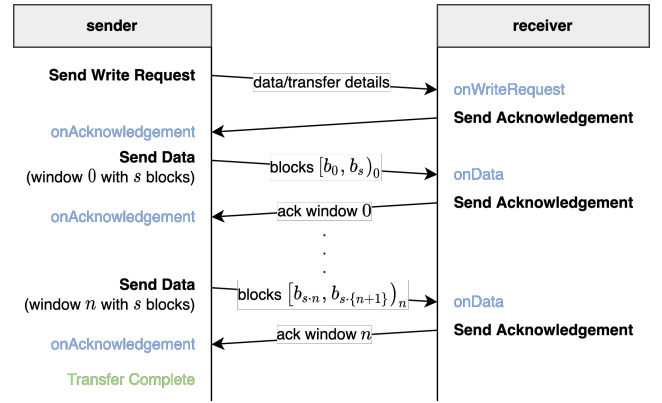


Fig. 5: Normal operation of the data transfer protocol

**WriteRequest** payload/packet to the receiver. The receiver confirms this request by returning an **Acknowledgement** packet. Upon receipt of an acknowledgement, the sender will start the transmission of data with **Data** packets. This data cannot be sent in one piece for multiple reasons. Firstly, the maximum UDP packet size is strictly limited to 1500 bytes due to the MTU (Maximum Transmission Unit) of the Ethernet [46]. The IPv8 protocol additionally requires a header of approximately 177 bytes to each block for routing, identification, and security purposes. Our **Data** payload header also requires identifiable information in the form of a block number and nonce. This means that the data inside the packet can be roughly somewhere between 1200 and 1250 bytes. Secondly, since UDP is unreliable and packets are not guaranteed to be delivered, the transmission of the data at once (if technically feasible) would be too much of a gamble to arrive, especially for large files. The protocol is required to split the data into small(er) pieces to fit the packets, creating so-called **blocks**. Each of the blocks has a particular **blockSize** in bytes. To reliably transfer data from one to another, we have to confirm the receipt of the data packets by again sending an **Acknowledgement** packet. To not unnecessarily wait for a confirmation and delay the transfer, the acknowledgement (and any other packet) must be received within a certain time, the **retransmitInterval**, before the previously sent packet is retransmitted. The principle of windowing allows multiple packets to be sent at once without requiring an acknowledgement for every single packet. This increases the performance majorly as most of the idle time of the sender is spent waiting for confirmation. The **windowSize** defines the hard limit on how many bytes or, equivalently, the number of blocks if we take the **blockSize** out of the equation, can be sent in every window without intermediate acknowledging. After the last block of the window has been received, the protocol sends an **Acknowledgement** to the sender. It does not mean that all blocks within that window have been received, as some arrive later and some will not be delivered at all. In that acknowledgement, the receiver includes the block numbers that have not been received (yet). The protocol could decide to only send individual packets and wait for the confirmation of receipt. This, however, has several disadvantages. Firstly, the transfer speed is significantly decreased as extra transmit

and acknowledge stages are added, including waiting time. Regularly UDP packets arrive late or not at all, meaning that for a good part of the windows the unreceived blocks have to be retransmitted, even for single unreceived blocks. Secondly, by staying at the current window, it may occur that some of these packets have trouble being delivered, and the transfer may not progress further for a long period (in terms of transfer time). To account for these drawbacks, the protocol will always try to *progressively continue* its normal operation. This means that these unreceived blocks will piggyback with the next transfer window in the hope to be delivered without overall delay. For every next window that passes, the confidence in these blocks being delivered increases. If all windows are sent, it may occur that there are some unreceived blocks left. In this case, the protocol will remain in the transmit phase of the last window until all unreceived blocks have been confirmed. The transfer is considered complete, for both the receiver and sender, after receipt of the last block (receiver) and acknowledgement (sender).

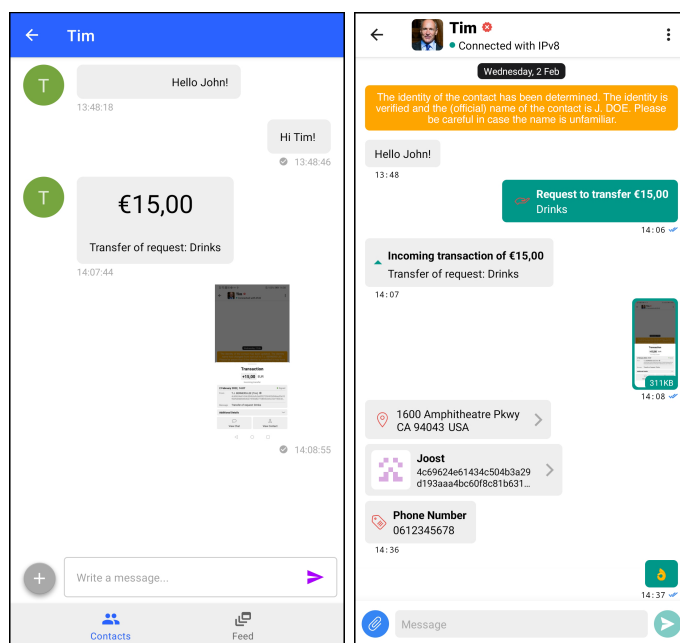
The receiver may not be able to adhere to the write request because either the data does not comply with the allowed size between zero and `binarySizeLimit`, or both peers try to start a transfer at the exact same time. In these situations an **Error** packet is returned, containing the reason of refusal. Both the sender and receiver will terminate the transfer. During the transfer, it regularly happens that sent packets receive no response. Both the sender and receiver use their own `retransmitInterval` and `retransmitAttemptCount`. A retransmit is scheduled if the time between the last transmit with the allowed interval is exceeded. We don't want the protocol to retransmit infinitely while the other peer is for example disconnected. The attempt count prevents that by only allowing a maximum number of *consecutive* retransmits. If after retransmission the other peer suddenly responds, the count is reset and the protocol continues normal operation. If the peer appears to be unresponsive, and the number of consecutive retransmits exceeds the retransmit attempt count, the transfer is considered timed out and will be terminated. In worst-case scenarios, often where the connection is unreliable or slow, the transfer of packets and response of confirmation take too much time. A transfer may timeout once, or even multiple times. These connections could benefit from a lower window size as fewer blocks have to be transmitted and confirmed within the same time. The protocol *adaptively* lowers the window size of a transfer after every timeout to give slower connections a better chance of success. The protocol must be suitable to everyone but without sacrificing performance to most of the normal operations, due to an (extremely) small number of failures. The default parameters of the protocol are therefore chosen to provide *optimal* performance, as analyzed in Section VII.

## VI. IMPLEMENTATION

In Sections IV and V the infrastructure and design of the main components that form the basis of our novel platform have been discussed. The use of both IPv8 and TrustChain has proven to be a perfect fit for our infrastructure. The

already existing implementations are applicable to a certain level as they have primarily been developed to serve as isolated proofs-of-concept. These implementations lack refinement and general cooperability and applicability with the other functionalities. In this section, the contributions to our complete infrastructure are discussed, as well as the changes to the existing implementations, and how they are integrated into our platform to provide a well-designed and functioning platform. The implementation of the platform is also concerned with the UX and UI design. The platform has been integrated within the TrustChain superapp<sup>4</sup>, an Android application developed in Kotlin. The data transfer protocol is integrated into the IPv8 stack<sup>5</sup> and is available to every community.

The platform consists of five main views that can all be navigated to using a navigation bar. The initial view, the wallet overview, as in Figure 9b, provides a widget-like overview of the identity, exchange, and chats components. For each of the widgets there is a separate view that includes all related aspects. It is important to not densely pack these widgets with information to overload the user.



(a) Original PeerChat implementation (b) Our chat implementation

**Fig. 6:** Difference between old and new implementation

The base functionality of the designed platform is the societal component. The implementation of a simple chat functionality is present in the form of PeerChat [47], implemented as a community of IPv8. Its core functionality is the exchange of text messages and photos over the P2P network. Many more functionalities had to be implemented to be able to compete with the big-tech platforms. The ability to exchange files, locations, contacts, identity attributes, money, and payment requests has been integrated. Most of these attachments are previewed in chats with the corresponding peers. By clicking

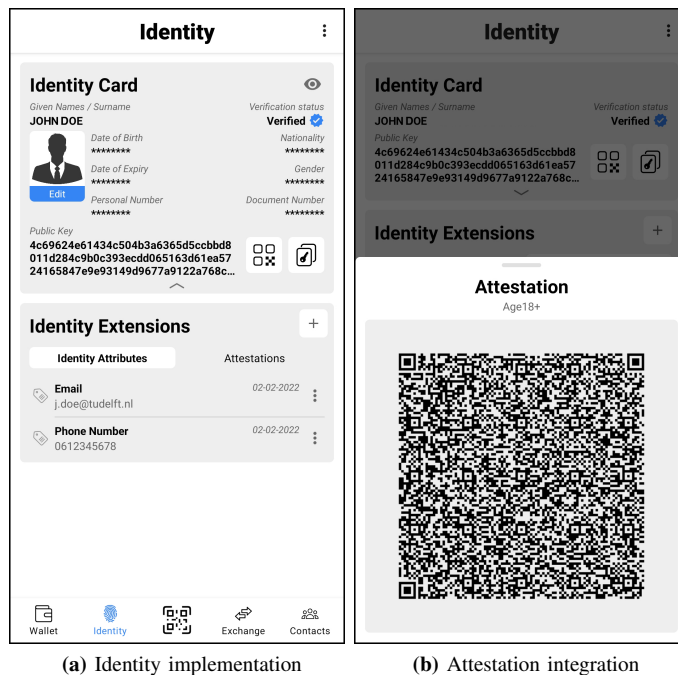
<sup>4</sup><https://github.com/Tribler/trustchain-superapp>

<sup>5</sup><https://github.com/Tribler/kotlin-ipv8>

on the attachment in the chat, most of the attachments display a more detailed view. The addition of chat-related features like searching and filtering, muting, archiving, or blocking, attempt to improve the usability. Unwanted spam is discarded as communication with blocked peers is no longer accepted. Large attachments, photos and files, are exchanged using our designed data protocol of Section V-D, while the other attachments are embedded in the packet with the message, and can be delivered using the IPv8's default method. It may happen that the recipient of the message (or data) is not connected and cannot be delivered. To determine the status of delivery for sent messages, every received message must be acknowledged. That enables the community to periodically check every 30 seconds if there are unacknowledged messages, and retransmit if the peer is connected. In a P2P network (without intermediary nodes) it regularly happens that messages can't be delivered as there is no central component storing the message temporarily until delivered. As a consequence, it may happen that two peers are unable to communicate if they are never connected at the time.

In Figure 6 both the existing PeerChat implementation and our implementation are displayed. Our implementation is not only equipped with many more functionalities, in the design of the layout the user experience and ease of use play a prominent role. So have we for instance provided our platform with full integration and support for QR-codes, offering tons of possibilities. A lot of information can be embedded in these code without having to worry about human errors. Inter-platform and offline communication still enable users to exchange information, even when disconnected from the (online) network. These codes can provide direct navigation within the platform using the contents of the scanned code. The use of QR-codes improves the user experience as less time and effort is required from the user. By creating or scanning the QR-code, the platform lets users also share their public key, create unspecified payment requests for any user, and set up the initial communication with the exchange portal by announcing their public key (and transfer amount). Currently, all QR-codes contain unencrypted data as no sensitive data is embedded. Other future functionalities may include for instance the exchange of information from the self-sovereign identity and are therefore required to encrypt the contents. QR-codes are suitable to embed encrypted data as well but requires initial knowledge of the recipients public key for encryption.

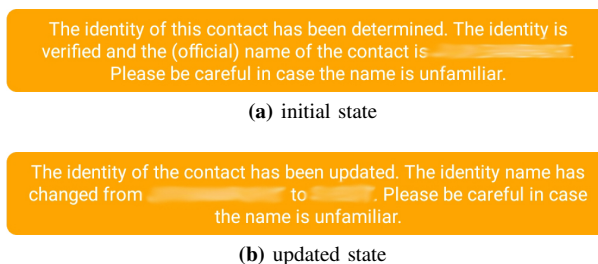
The integration of the identity component had to be designed from scratch. The `IdentityCommunity` handles anything related to the functionalities of the self-sovereign identity, including its storage. The platform requires its users to onboard their identity in order to use it. Any device with NFC support is required to verify its identity document, as it reduces misuse and provides authentic trust to other users. Compared to many other communities, the identity community does not include support for communication over the IPv8 network. There is currently no need to additionally share identity information, and it may only form a privacy vulnerability. The identity is onboarded as explained in Section V-A and stored in the database. An extra layer of protection makes sure that the identity details are not visible for eavesdrop-



(a) Identity implementation (b) Attestation integration

Fig. 7: Implementation of self-sovereign identity

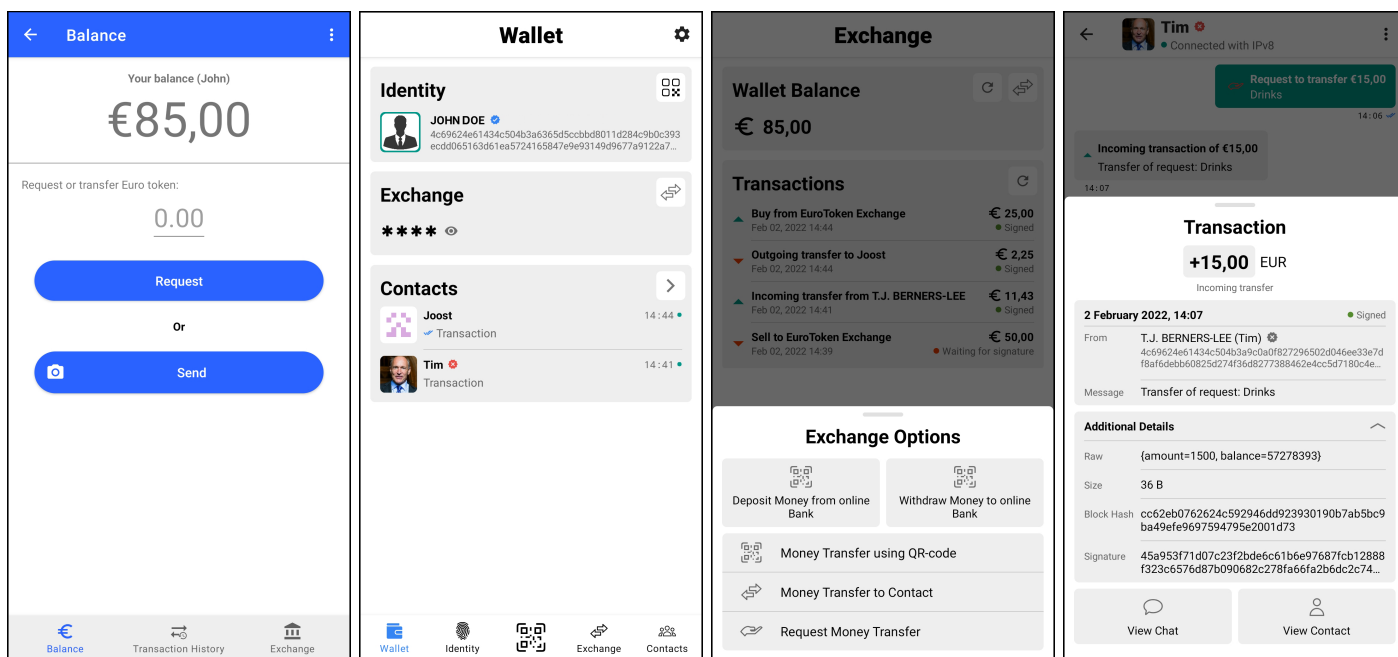
pers, see Figure 7a. Apart from the SSI itself, `identity` attributes and `identity` attestations have been integrated as well. Identity attributes are convenient pieces of information that serve as an unofficial extension to the SSI. These attributes are for example a phone number, email address, or home address. These attributes are shareable with other peers and solely extend the use of the SSI. The identity attestations are incorporated in unmodified form using the `AttestationCommunity`, as result of the work of Chotkan [29], and a QR-code of an example attestation can be seen in Figure 7b. Currently, only the age-related attestation types obtain the value of the age directly from the SSI. Future attestation types could embed more confidential information from the SSI as it may additional purposes.



(a) initial state (b) updated state

Fig. 8: Detection of change in received trust attributes

The trust attributes, as explained in Section V-B, are directly deduced from the SSI. These attributes are automatically added to every form of communication with other peers. The user is unable to choose to communicate without sending the trust attributes along, as this exposes the integrity of our platform. Changes to the state as result of the received trust attributes are notified in the chat as in Figure 8. The verification status of the



(a) Old exchange implementation

(b) Our wallet overview (initial view) containing exchange widget

(c) Our exchange implementation and transfer options

(d) Our transaction detail view transaction

Fig. 9: Screenshots of implementation

contact is explicitly displayed in several different views with the sole purpose to draw attention and recognition, especially when unverified. A recognizable blue check star, similar to that of popular social media platforms, indicates successful verification and a red cross star indicates the peer is unverified. Both verification statuses can be found in Figure 9b.

An implementation to transfer digital money was already integrated in the superapp, see Figure 6a. The `EuroTokenCommunity` handles the transfer of the academic CBDC 'Eurotoken' [43] with other peers, while the `TrustChainCommunity` handles the storage-related functionalities of the transactions in the distributed ledger. In our platform, the wallet balance is displayed and protected from eavesdroppers by hiding the balance initially, in several relevant views, see for example Figure 9b. Various options to exchange money have been integrated as can be seen in Figure 6b. Firstly, QR-codes are used to deposit or withdraw tokens from and to the exchange portal. Secondly, users have the option to scan a QR-code payment request to transfer tokens, create a transfer to another contact, create and send a payment request to contact over the network or create an unspecified payment request using a QR-code. The latter three are accessible from the chat with the corresponding contact as well. An extra layer of protection, in the form of a 'slide-to-transfer' element as seen in Figure 10, withholds the accidental exchange of tokens. For convenience, transactions are not only accessible from within the exchange view, but also in the chat with the corresponding contact. Figure 9c shows a detailed view of a transaction, which may be convenient in some situations, that is displayed by clicking the corresponding transaction. Payment requests are attachments and not actual

transactions and therefore only included and visible in the chats.

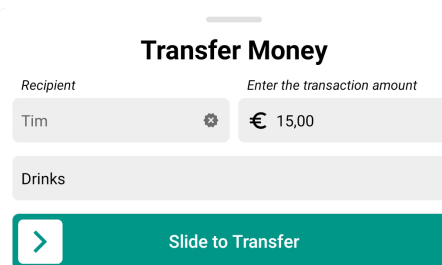
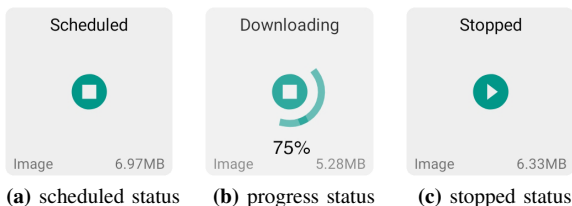


Fig. 10: 'Slide-to-Transfer' protection]

As mentioned before, the data transfer protocol handles the transmission of large data. The data transfer protocol contains an endpoint for peers to transmit data to another peer directly or to be scheduled to be transferred later. Scheduled transfers are periodically checked and started if the following requirements are satisfied: (I) the peer is connected, (II) there's no other current transfer with the peer, and (III) the size of the transfer does not exceed the maximum allowed size. The protocol exploits packet listeners to directly respond to the receipt of packets from other peers. Every packet type serves its own purpose and initiates certain actions. The `WriteRequest` packet announces the transfer and specific settings. As many different communities may employ the protocol, it is convenient to include the designated community. A nonce is used for the remainder of the transfer to distinguish the transfer from other transfers, enabling multiple concurrent transfers with different peers. Transfers can only be

successfully completed if both peers apply the same settings in the form of data size, window size, block size, and block count. The request is processed in the `onWriteRequest` listener and confirmed by sending an acknowledgement to the other peer. The **Acknowledgement** packet confirms the receipt of either a request or a data packet. Apart from the nonce, the confirmation of a request does not require any other information while the confirmation of a data packet requires the window that is being acknowledged and which blocks are missing (if any). The confirmation is received in the `onAcknowledgement` listener and invokes the transmission of the (next) window of data blocks until all blocks have been received. The **Data** packet obviously contains the data, the nonce, and additionally the block number to stitch all blocks together in the correct order. The data packets are received using the `onData` listener and only acknowledges the receipt of the window of blocks if the block is the last of its window. If after receipt of the last packet all blocks appear to be received, the transfer can be considered completed. If during, or before, the transfer sometimes goes wrong, an **Error** packet is able to report the error the other party, and additionally terminates the transfer on both sides.

To realize a quick response to the transmitted packets, the recurrent packets must contain the least possible information. The **WriteRequest** packet is only transmitted once and is therefore allowed to contain more information. The **Acknowledgement** and **Data** packets are transmitted frequently and profit from a quick response, and must therefore not contain redundant information.



**Fig. 11:** Download progress indicators in chat

To accommodate communities, and users, with useful information during and after the transfer, the protocol has built-in support for callbacks. These callbacks enable the execution of specific tasks after the transfer progressed to another state. These tasks are outside the scope of the protocol itself. The sender is able to execute code after the data has been successfully sent or upon receipt of an error. The receiver has access to the transfer progress, transfer completion, and erroneous updates. Specifically, the first two are important. Transfer progress updates enable the application to communicate the current download status to the recipient, see Figure 11. For convenience in certain situations, the user is able to (temporarily) stop and restart the transfer at a later time. The transfer complete update triggers the conversion of the raw binary data to the correct format, creates an external file on the phone storage, and embedding it in the chat. The protocol is dependent on many parameters that may have an impact on the performance. In Section VII these parameters are analyzed to obtain the optimal performance during *normal* operation.

## VII. EXPERIMENTAL ANALYSIS AND EVALUATION

In the previous sections, we have discussed the design and implementation of the designed data transfer protocol. In this section, an experimental analysis is performed to derive the optimal protocol settings. Additionally, an evaluation of a large-sized transfer, using the optimal settings, is executed to prove its contribution and applicability to our platform.

### A. Experimental Analysis

To exploit the best possible performance, the designed binary data transfer protocol requires its settings to be optimal. We define the protocol to be optimal if (I) the runtime, the time between the start and end of the start, is as low as possible, (II) the ratio of unacknowledged blocks (as explained in Section V-D) is as low as possible, and (III) the number of retransmits of windows of blocks (by the sender) and acknowledgments (by the receiver) is as low as possible. The latter two constraints should contribute to a lower runtime because no blocks have to be transmitted and there's no additional idle time waiting for an acknowledgment.

As mentioned before, the UDP packet size is limited due to Ethernet constraints. As two blocks with a payload of 500 bytes carry twice as much redundant information as one block of 1000 bytes, a transfer using a greater block size  $B$  is preferred and should theoretically result in a lower runtime. The maximum *data* size of UDP packets for IPv8 has been determined (through trial-and-error) to be around 1241 bytes. The exact size may depend on each peer, the chosen packet header options (encryption, signature, public key, etc.), and the *Data* packet metadata. To keep a safe margin we've decided to allow data of at most 1200 bytes in each packet. The window size  $W$  is defined as the number of bytes ( $n_{\text{blocks}} \times \text{blockSize}$ ) the sender can transmit without having to wait for an acknowledgment of receipt from the receiver. Theoretically, a higher window size would directly contribute to higher *transfer speeds*. A smaller number of acknowledgments has to be sent and received, reducing the idle time of both participants. Higher window sizes also increase the existence of late or lost blocks, specifically in imperfect or congested networks, with an increased number of block retransmits as a result. The importance of this analysis is to find the trade-off between a high window size and low delay due to undelivered blocks.

The other parameters do not have a direct impact on the performance, apart from the block and window size. The retransmit interval may affect the performance when it is either too tight or loose, but it will only play a role in a small part of the cases. A tight interval can force blocks or acknowledgments to be retransmitted while they are still in transit and may arrive shortly after. For a loosely set interval, the protocol may unnecessarily have to wait for a window or acknowledgment. The transfer timeout interval is less critical and will only affect the performance when a window or acknowledgment has been retransmitted and used for all retransmit attempts. The retransmit attempt count likewise has little influence on the performance.

**TABLE III:** Parameters that are being tested for optimal execution. The file size and number of executions have only been used for consistency. In total 80 combinations of parameters have been executed 5 times.

Parameter	Values	
Block size ( $B$ )	600, 700, 800, 900, 1000, 1100, 1200	[bytes]
Window size ( $W$ )	16, 32, 48, 64, 80, 96, 112, 128	[blocks]
File size ( $F$ )	5, 10	[MB]
Iteration	0, 1, 2, 3, 4	[-]

*Experimental Setup:* The experimental setup is equipped with two phones, a Xiaomi Redmi 9T with Android 10 and a Huawei P20 Lite with Android 9, both 4GB RAM. The phones have the same version of the app installed and are connected to the same WiFi-6 mesh network (NETGEAR Orbi RBK753). To obtain more accurate results, the experiments are repeated a total of five times. Also, to verify the independence of the file size of the transfer, the experiment is executed for a file size of 5MB and 10MB (and normalized to 5MB for comparison). Each important step of the protocol is captured in a log to be processed in Python. An automatic Kotlin script makes sure that every combination of parameters, the file sizes, and the five iterations are executed consecutively. Table III gives an overview of the analyzed parameter values.

*Experimental Results:* The optimality of the performance of the protocol can be determined in combination with the before mentioned requirements.

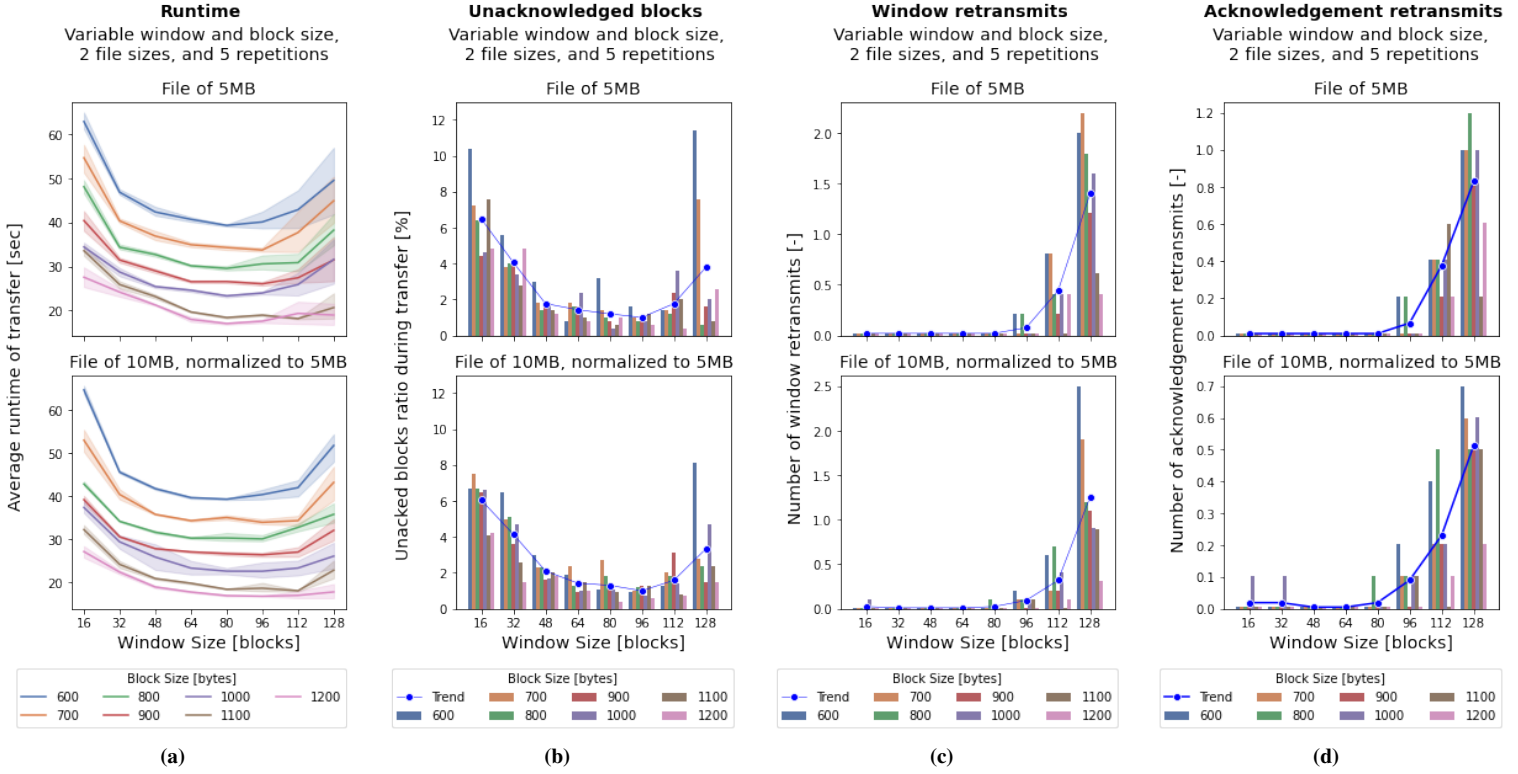
The first requirement, the runtime of the protocol, is displayed in Figure 12a. We can clearly see the effect of both the block and window size. An increasing block size results in a lower runtime. The difference in runtime becomes less significant for higher block sizes, indicating that if we could neglect the maximum packet size, the optimal block size would expectantly be not much greater than  $B = 1200$  bytes. The window size follows a parabolic curve and the runtime is optimal for a window size  $W = \{64, 80, 96\}$  blocks. We cannot yet distinguish the optimal value for the window size as these values are very similar and are less pronounced than the block size. To decide on the optimal sizes, we have to include the requirements as well.

The second requirement, the ratio of unacknowledged blocks during a transfer, is visualized in the plots of Figure 12b. The block size shows a decreasing pattern and overall contains the lowest number of unacknowledged blocks for higher block sizes. There is no consensus on the block size *within* each window size, as there are small deviations and no consistent decreasing or increasing pattern. The trendline, a combined average of all block sizes within each window, shows a minimum for the same three window sizes of the first requirement, but slightly favors  $W = 96$  blocks. For window sizes higher than  $W = 96$  blocks the number of unacknowledged blocks again increases. The protocol is behaving more unreliable as more unacknowledged blocks have to be added to the next window. Every unacknowledged block will cause the runtime to increase as more blocks have to be delivered. The aim is to reduce these undelivered blocks as

much as possible. Especially for more unreliable connections, unacknowledged blocks may have a big impact on the transfer.

The last requirement, the number of retransmits of windows and the number of retransmits of acknowledgments, are combined as it takes both the sender and receiver in the equation for the same transfers. In Figure 12c and 12d the results for the sender and receiver are visualized, respectively. Both diagrams show the same pattern. The optimal block size shows, again, no notable preference within each window size. The results for the window sizes are a strong indicator that we don't want them to be too high. The number of window and acknowledgment retransmits is of neglectable proportion for a window size smaller than  $W = 112$  blocks, or even  $W = 96$  blocks if we would be really strict. As the protocol has to wait for a full `retransmitInterval` for every retransmit, it has a big impact on the overall performance. It is crucial to reduce the number of retransmits to an absolute minimum. For the largest three window sizes, a small experiment was executed that verifies if the large increase of retransmits were the result of a too loosely set `retransmitInterval`. The interval was increased majorly, just for verification purposes, and only served for analysis of the third requirement without including the results of the other requirements (yet). The results showed that the number of retransmits slightly improved, but the pattern was equally in place. It was deemed unnecessary to investigate it further.

We must take into account that the experiments have been performed under somewhat optimal circumstances: phones only running system services and the platform itself, and both connected to the same local WiFi network. From this, we could argue that if conditions worsen, the runtime and the number of retransmits of windows and acknowledgment would logically increase. We can summarize our findings based on the results of the experiments and analysis. The performance of the runtime (continuously) increase with higher block sizes, with the optimal block size of  $B = 1200$  bytes. For the other requirements, the difference in block size was less definite. The runtime found an inconclusive optimal for window sizes of  $W = \{64, 80, 96\}$  blocks. The second requirement showed similar results, although slightly in favor of  $W = 96$  blocks. Both types of retransmits for the third requirement indicated an increase of retransmits for higher window size, specifically above  $W = 80$  blocks. To obtain the optimal performance, in combination with a reduction of retransmits and unacknowledged blocks, we can conclude that a window size of  $W = 80$  blocks is optimal. The optimal window size based on our findings is  $W = 96000$  bytes or 96kB. We've executed the experiments using two file sizes to verify its independence on the file size. As all diagrams provide an almost equivalent view without any differences in trends, it is fair to say that the file size has no impact on the performance. We've also concluded that an increase of the `retransmitInterval` does not necessarily give a significant overall reduction of the number of retransmits, and therefore not contributes to a better performance.

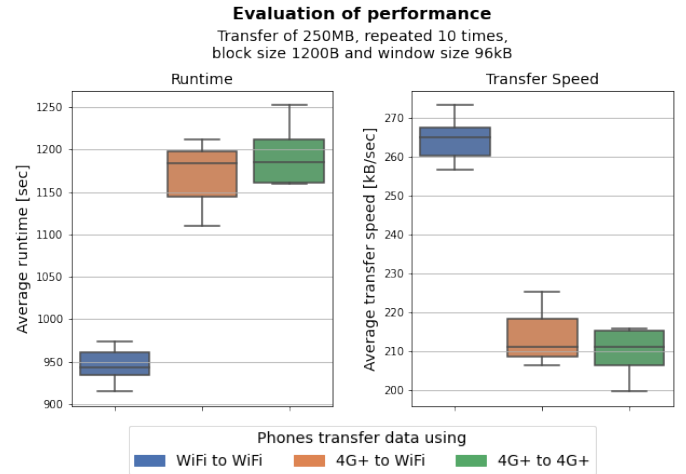


**Fig. 12:** The results of all executed tests for each window size and block size. Each experiment is executed for a file size of 5MB and 10MB, normalized to 5MB, and is repeated a total of five times and averaged for results.

### B. Performance Evaluation

Now that we've determined the optimal parameters for the protocol, we want to see how it performs in the wild, for a large-sized transfer of 250MB. This enables us to evaluate the performance more consistently over a longer period of time. In most cases, phones are not connected to the same local WiFi network. We have to consider three commonly used situations: WiFi to WiFi, WiFi to 4G+, and 4G+ to 4G+. For the connections of 4G+, we use the telecom providers Vodafone and KPN on the same phones as before. Our evaluation includes the same requirements as in the experimental analysis, focused on the performance and delays. Instead of finding the optimal parameters, we this time evaluate the applicability and the difference between the three situations. Each experiment is executed 10 times to provide more consistent results. We obviously expect the first situation to offer the most performance and least delays, as the packets are only exchanged within the local network.

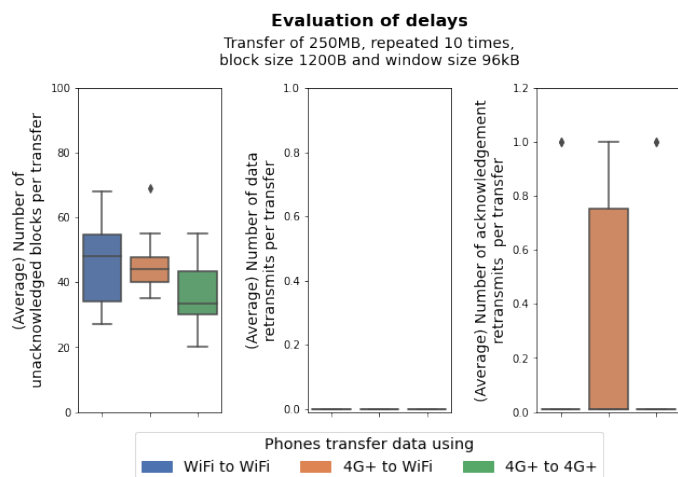
The performance results for each of the connection types are portrayed in Figure 13. The diagrams show a clear division in performance. The runtime, and equivalently the transfer speed, is least and most for the inter-WiFi transfer, with an average transfer speed of about 260kB/s. The other two connection types offer almost equal speeds, of about 213kB/s and 210kB/s, respectively. The transfer speed of the inter-WiFi transfer is executed on a local network and would theoretically be lower, and possibly be similar to the other situations. It's a good indication that there is no extreme performance



**Fig. 13:** Evaluation of the performance of a transfer of 250MB

difference between an exchange that uses one WiFi-connected device and a complete mobile network exchange. We do however notice that the complete mobile network exchange has a bigger spread in terms of lower speeds. If we look at the absolute speed, we must conclude that our protocol is nowhere near the download speeds we experience today. The exact reason for this is unknown, but it is expected to be some limitation in IPv8.

In Figure 14 the evaluation of the delays is showcased. Unexpectedly, the number of unacknowledged blocks per



**Fig. 14:** Evaluation of the delays of a transfer of 250MB

transfer is on average larger for an inter-WiFi transfer in comparison with the other two situations. In absolute numbers, we can conclude that the total loss of about 50 blocks in a transfer of over 200.000 blocks, equivalent to every fifty windows containing one unacknowledged blocks, is neglectable. Surprisingly, the retransmit diagrams conclude that no window retransmits and almost no acknowledgment retransmits were encountered as a result of unresponsiveness. This proves that our protocol has been performing at the absolute top of its abilities, leaving almost no room for errors.

During the experiments, it was noticed that larger-sized transfers couldn't continue due to memory allocation issues on the phones. Currently, the protocol stores the sent and received data in memory for reconstruction purposes. The current maximum file size has therefore been limited to 250MB, but can differ from phone to phone.

### VIII. TIME MANAGEMENT

The research, design, implementation, analysis, and documentation have been an effort of one person in roughly nine full-time months. The research phase required about two months to study the literature and existing platforms, including the basics and characteristics of IPv8, TrustChain, and the other components. The design and implementation phase were entangled as the scope of the research became wider several times along the way. You could say that it was a repeating process of invent-design-implement for most of the features. An initial layout of the application was designed and implemented to provide a basic platform that slowly evolved to the current state. This included familiarizing the style and coding within the `Trustchain` superapp. The design and implementation of features were not only concerned with the features themselves, but also the UX and UI design of the platform. In total, about six months have been allocated to the design, implementation, and analysis of the platform. The data transfer protocol is the only component that has additionally been analyzed as part of experimental analysis and evaluation. Of these six months, about one month of work was required to optimize and analyze the data transfer protocol.

The last month, and also some days earlier in the process, was dedicated to documenting and finalizing this paper.

### IX. CONCLUSION

Ownership and exchange of sensitive or private data and information has never been a more eloquent topic, also due to the COVID crisis. This paper has presented a novel Web3 platform for identity, trust, money, and data. We performed the first exploratory study that shows the viability of the integration of a Self-Sovereign Identity in a social platform in a useful, secure, and private fashion. The application of SSI's has shown to be an effective mechanism in the provision of trust to other peers in the P2P network as well. Governments may change their mind in the near future about their identity management systems. Many of these centralized tasks can be replaced, providing their citizens more power and ownership over their data, while retaining authenticity and majorly reducing costs. Central banks have started to pursue the integration of Central Bank Digital Currencies globally. Our designed platform likewise incorporates the exchange of digital money in a private and informal way, similar to what cash once was. Data and personal information has been owned and managed by big-tech companies for far too long. Our designed P2P data transfer protocol enables peers to exchange messages and data securely and privately while reducing the leakage of metadata to an absolute minimum. Unfortunately, we cannot neglect some major disadvantages in our platform as well. Firstly, availability and connectivity of peers remains an open issue as it introduces lateness of delivery of messages and data, not something people are used to in existing platforms due to the use of central servers or nodes. Secondly, peers in a fully P2P network must keep themselves online by constantly connecting to other peers with the consequence of draining the phone's battery. This is something that probably can be improved, but will always be a weak spot of P2P-based systems. And lastly, the current EuroToken implementation is not reliable enough yet. Overall, we can conclude that we've designed a well-functioning platform that incorporates all aspects of our research in a valuable, private, and secure manner. There is still a lot to discover, but we are curious to see the directions big-tech companies, governments, and banks pursue in the near future.

### REFERENCES

- [1] Tribler. Ipv8 documentation. 2021. URL [https://py-ipv8.readthedocs.io/\\_/downloads/en/latest/pdf/](https://py-ipv8.readthedocs.io/_/downloads/en/latest/pdf/).
- [2] Pim Otte, Martijn de Vos, and Johan Pouwelse. Trustchain: A sybil-resistant scalable blockchain. *Future Generation Computer Systems*, 107: 770–780, 2020. ISSN 0167-739X. doi: <https://doi.org/10.1016/j.future.2017.08.048>. URL <https://www.sciencedirect.com/science/article/pii/S0167739X17318988>.
- [3] Nicolo Zingales. Between a rock and two hard places: Whatsapp at the crossroad of competition, data protection and consumer law. *Computer Law & Security Review*, 33(4):553–558, 2017.



- [4] The Guardian. Whatsapp loses millions of users after terms update. [Online] Available: <https://www.theguardian.com/technology/2021/jan/24/whatsapp-loses-millions-of-users-after-terms-update>, 2021.
- [5] "Wall Street Journal". Big tech braces for a wave of regulation. [Online] Available: <https://www.wsj.com/articles/big-tech-braces-for-wave-of-regulation-11642131732>, 2022.
- [6] PinDirect. Wat kost een pintransactie? [Online] Available: <https://pindirect.nl/kennisbank/uw-eigen-pinautomaat/wat-kost-een-pintransactie/>, 2020.
- [7] ZakelijkBankieren.nl. Vergelijk ideal kosten per aanbieder in nl. [Online] Available: <https://www.zakelijkbankieren.nl/kosten-ideal/>, 2021.
- [8] Dutch Payments Association. Facts and figures on the dutch payment system in 2020. [Online] Available: <https://factsheet.betalvereniging.nl/en/>, 2020.
- [9] Official Journal of the European Union. Regulation (eu) 2016/679 of the european parliament and of the council on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing directive 95/46/ec (general data protection regulation). [Online] Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0679&from=EN>, 2016.
- [10] Gdpr enforcement tracker. [Online] Available: <https://www.enforcementtracker.com>.
- [11] Aikaterini Soumelidou and Aggeliki Tsohou. Towards the creation of a profile of the information privacy aware user through a systematic literature review of information privacy awareness. *Telematics and Informatics*, 61: 101592, 2021.
- [12] ZDNet. The biggest data breaches, hacks of 2021. [Online] Available: <https://www.zdnet.com/article/the-biggest-data-breaches-of-2021/>, Dec 2021.
- [13] Christopher Allen. The path to self-sovereign identity. [Online] Available: <http://www.lifewithalacrity.com/2016/04/the-path-to-self-sovereign-identity.html>, 2016.
- [14] Quinten Stokkink and Johan Pouwelse. Deployment of a blockchain-based self-sovereign identity. In *2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData)*, pages 1336–1342, 2018.
- [15] "Computer Weekly". "blockchain technology will help banks will cut cross-border payment costs by \$10bn in 2030". [Online] Available: <https://www.computerweekly.com/news/252509262/Blockchain-technology-will-help-banks-will-cut-cross-border-payment-costs-by-10bn-in-2030>, 2021.
- [16] Statista. Most popular global mobile messenger apps as of october 2021, based on number of monthly active users. [Online] Available: <https://www.statista.com/statistics/258749/most-popular-global-mobile-messenger-apps/>, 2021.
- [17] Roman Zaikin and Oded Vanunu. Reverse engineering whatsapp encryption for chat manipulation and more. [Online] Available: , August 3-8, 2019.
- [18] WhatsApp. Whatsapp encryption overview. technical white paper. Nov 2021. URL <http://www.cdn.whatsapp.net/security/WhatsApp-Security-Whitepaper.pdf>.
- [19] FaceBook Inc. Messenger secret conversations. technical whitepaper. May 2017. URL <https://about.fb.com/wp-content/uploads/2016/07/messenger-secret-conversations-technical-whitepaper.pdf>.
- [20] WeChat. Wechat - free messaging and calling app. "[Online] Available: <https://weixin.qq.com>", Jan 2022.
- [21] Telegram. Telegram messenger. "[Online] Available: <https://telegram.org>", Jan 2022.
- [22] Apple. imessage security overview. "[Online] Available: <https://support.apple.com/en-au/guide/security/sec9764312f/web>", May 2021.
- [23] Katriel Cohn-Gordon, Cas Cremers, Benjamin Dowling, Luke Garratt, and Douglas Stebila. A formal security analysis of the signal messaging protocol. In *2017 IEEE European Symposium on Security and Privacy (EuroSP)*, pages 451–466, 2017. doi: 10.1109/EuroSP.2017.27.
- [24] Kee Jefferys, Maxim Shishmarev, and Simon Harman. Session: A model for end-to-end encrypted conversations with minimal metadata leakage. *CoRR*, abs/2002.04609, 2020. URL <https://arxiv.org/abs/2002.04609>.
- [25] Status. The status network. a strategy towards mass adoption of ethereum. June 2017. URL <https://status.im/whitepaper.pdf>.
- [26] Felix Schlitter, John Carlo San Pedro, Paul Freeman, and Callum Lowcay. Sylo protocol: Secure group messaging. 2020. URL <https://www.sylo.io/whitepaper/sylo-protocol.pdf>.
- [27] Berty. Berty protocol. "[Online] Available: <https://berly.tech/docs/protocol/>", Oct 2020.
- [28] Logius. Tarieven 2022 voor digid, digid machten en mijnoverheid. [Online] Available: <https://logius.nl/onze-organisatie/zakendoen-met-logius/doorbelasting>, 2021.
- [29] R. Chotkan. Industry-grade self-sovereign identity, on the realisation of a fully distributed self-sovereign identity architecture. Master's thesis, Delft University of Technology, 2021.
- [30] Ann Cavoukian. Privacy by design: The 7 foundational principles. May 2010.
- [31] M.G. Reed, P.F. Syverson, and D.M. Goldschlag. Anonymous connections and onion routing. *IEEE Journal on Selected Areas in Communications*, 16(4):482–494, 1998. doi: 10.1109/49.668972.
- [32] Wikipedia. Information security. "[Online] Available: [https://en.wikipedia.org/wiki/Information\\_security](https://en.wikipedia.org/wiki/Information_security)", 2022.
- [33] Whitfield Diffie and Martin E. Hellman. New directions in cryptography. Nov 1976. URL <https://ee.stanford.edu/~hellman/publications/24.pdf>.
- [34] International Telecommunication Union (ITU). Data networks and open system communications. open systems interconnection - model and notation. July 1994.

- URL [https://www.itu.int/rec/dologin\\_pub.asp?lang=e&id=T-REC-X.200-199407-1!!PDF-E&type=items](https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-X.200-199407-1!!PDF-E&type=items).
- [35] Keesing Technologies. Security vulnerabilities associated with e-passports. [Online] Available: <https://platform.keesingtechnologies.com/e-passport-security/>, Feb 2020.
- [36] Europol EC3. Spear phishing, a law enforcement and cross-industry perspective. Nov 2019. URL [https://www.europol.europa.eu/sites/default/files/documents/report\\_on\\_phishing\\_-\\_a\\_law\\_enforcement\\_perspective.pdf](https://www.europol.europa.eu/sites/default/files/documents/report_on_phishing_-_a_law_enforcement_perspective.pdf).
- [37] BOARD OF GOVERNORS OF THE FEDERAL RESERVE SYSTEM. Money and payments: The u.s. dollar in the age of digital transformation. Jan 2022. URL <https://www.federalreserve.gov/publications/files/money-and-payments-20220120.pdf>.
- [38] European Central Bank (ECB). Central bank digital currency: functional scope, pricing and controls. 286, Dec 2021. URL <https://www.ecb.europa.eu/pub/pdf/scpops/ecb.op286~9d472374ea.en.pdf>.
- [39] Bank of England. Central bank digital currency, opportunities, challenges and design. Mar 2020. URL <https://www.bankofengland.co.uk/-/media/boe/files/paper/2020/central-bank-digital-currency-opportunities-challenges-and-design.pdf>.
- [40] Working Group on E-CNY Research and Development of the People's Bank of China. Progress of research & development of e-cny in china. July 2021. URL <http://www.pbc.gov.cn/en/3688110/3688172/4157443/4293696/2021071614584691871.pdf>.
- [41] Reuters. China central bank launches digital yuan wallet apps for android, ios. [Online] Available: <https://www.reuters.com/markets/currencies/china-cbank-launches-digital-yuan-wallet-apps-android-ios-2022-01-04/>, Jan 2022.
- [42] Het Parool. Vier amsterdammers vast voor 'tikkiefraude' honderden mensen. "[Online] Available: <https://www.parool.nl/amsterdam/vier-amsterdammers-vast-voor-tikkiefraude-honderden-mensen~b33baf1a>", Nov 2020.
- [43] R.W. Blokzijl. A central bank digital currency (cbdc) with offline transfers. Master's thesis, Delft University of Technology, 2021.
- [44] Network Working Group. The tftp protocol (revision 2). June 1981. URL <https://www.rfc-editor.org/rfc/pdf/rfc/rfc783.txt.pdf>.
- [45] J. Postel. User datagram protocol. Aug 1980. URL <https://www.rfc-editor.org/rfc/pdf/rfc/rfc768.txt.pdf>.
- [46] Andrew S. Tanenbaum and David Wetherall. *Computer networks, 5th Edition*. 2011.
- [47] M. Skála. Technology stack for decentralized mobile services. Master's thesis, Delft University of Technology, 2020.