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Universal and scalable infrastructure for digital asset management

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UniCon: Universal and Scalable Infrastructure for Digital Asset Management

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ABSTRACT

Non-Fungible Tokens (NFTs) leverage blockchain technology to certify and transfer ownership of digital assets to individuals. NFTs on the Ethereum blockchain have garnered significant attention recently, with a trading volume of over $2 billion in Q1 2021 only. At the same time, established NFT solutions have low flexibility, limited scalability, and high transaction fees. These deficiencies make them impractical to use at a larger scale to manage digital assets.

We present UniCon, a universal and scalable infrastructure for digital asset management. The key idea of UniCon is to track asset ownership in a *tracking blockchain* while making minimal assumptions on the capabilities of this blockchain. UniCon enables the exchange of asset ownership in *any* digital currency, unlike current NFT platforms. We devise a system architecture and build a prototype of UniCon. We use a scalable distributed ledger that is highly suitable for the tracking of asset ownership. Our prototype enables a decentralized ecosystem to manage and trade assets.

CCS CONCEPTS

• **Applied computing** → **Media arts**; • **Computer systems organization** → **Peer-to-peer architectures**.

KEYWORDS

Non-fungible Tokens, Blockchain, Content Management, Content Middleware

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1 INTRODUCTION

Recently, there has been a surge in the popularity of Non-Fungible Tokens (NFTs). An NFT is a digital description stored on a blockchain ledger that certifies the uniqueness of a digital asset and can be sold to others [1].[1] In 2021, an NFT that represents ownership of the first tweet ever on Twitter has been auctioned for $2.9 million [2]. Even though NFTs have been around as early as 2014, they have only gained traction in 2021, with an impressive trading volume of $2 billion dollar in the first quarter of 2021 only [3]. At the same time, established NFT platforms are by far not flexible nor scalable enough to host the ever-increasing amount of digital assets such as artwork, songs, and movies.

The dominant platform used for the creation and exchange of NFTs is Ethereum [4]. Ethereum allows developers to devise decentralized applications (DApps) that run on a blockchain. At the time of writing, almost 2'000 DApps are deployed on the Ethereum blockchain.[2] These DApps span many application domains, including digital coins, marketplaces, games, and NFTs. Ethereum uses the EIP-721 standard to create and exchange NFTs [5]. This standard describes an API to host NFTs on the blockchain within a smart contract and provides the critical functionality to track and transfer ownership of NFTs.

Current NFT platforms, however, have various deficiencies that limit the usage of NFTs at scale (also see Section 2). In particular, many NFT platforms are built on top of a particular blockchain fabric and provide little flexibility, i.e., NFT payments can often only be conducted in a currency native to the hosting blockchain platform. Other deficiencies include scalability limitations and high transaction fees, introducing economic barriers to enter NFT ecosystems. These concerns have motivated the search for alternatives for the Ethereum-based architectures, as shown by a $3 million investment to develop a Solana-based NFT auction platform [6]. Nevertheless, these alternatives still depend on a particular blockchain architecture and have limited flexibility.

We argue that a fundamentally different design is needed to achieve large-scale management of digital assets. We present UniCon, decentralized and scalable infrastructure for the universal management of digital assets. At the core of UniCon is a *tracking blockchain* that include digitally signed records with asset metadata. This blockchain hosts a tamper-proof, public history of modifications to assets, e.g., ownership changes. By including payment information on the tracking blockchain when selling assets, any user can verify the authenticity of a sale, and users can conduct payments in any currency. UniCon requires participants to link their digital identity to a real-world persona, raising the barrier to commit fraud.

In summary, we make the following three contributions:

(1) We present UniCon, *scalable and universal infrastructure* for the creation, transfer, and management of digital assets (Section 3).

[1] In this work, we particularly focus on non-fungible assets, i.e., assets that represent something unique.

[2] See https://www.stateofthedapps.com.

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(2) We outline *the UniCon protocol* and describe the process of creating, managing and transferring digital assets (Section 4.1 and 4.2).
(3) We build *a prototype* of UniCon as a mobile application, showcasing the feasibility of our approach (Section 4.3).

2 THE SHORTCOMINGS OF NFT PLATFORMS

NFT platforms provide the necessary functionality to create and manage digital assets using blockchain technology. We consider, however, existing NFT platforms impractical for the management of different types of assets at scale. We identify the following four shortcomings of current solutions.

Shortcoming I. Platform dependency. All existing NFT platforms are built upon a particular blockchain architecture, with Ethereum currently being the most popular platform to host NFTs [7]. This approach creates a critical dependency on the underlying blockchain and reduces flexibility. In particular, by deploying an NFTs marketplace on the Ethereum blockchain, end-users are now required to pay NFT sellers in a currency native to the Ethereum ecosystem. In the fragmented landscape of digital currencies, the requirement to buy NFTs with a specific currency raises the barrier for users to enter a particular NFT ecosystem. Instead, we argue that an ecosystem for digital asset management should allow users to pay for assets using *any* digital currency.

Shortcoming II. Limited scalability. Scalability limitations are an inherent issue of blockchain technology and can result in high transaction latency. In 2017, the NFT-based Cryptokitties project was deployed on the Ethereum blockchain, allowing users to breed and trade virtual kittens [8]. Cryptokitties became so popular that they clogged the Ethereum network, causing a stark increase in transaction fees and degrading the network's performance. This event hints that Ethereum is not suitable for managing digital assets at scale, for many types of assets and by many users. Although Ethereum 2.0 is projected to increase the throughput of the Ethereum network, its full deployment is not expected to be completed soon. For these reasons, multiple NFT projects are looking into layer-two technology where transactions are made off-chain [7].

Shortcoming III. Transaction fees. Besides scalability limitations, popular NFT marketplaces experience high transaction fees, posing an additional obstacle in transforming current NFT marketplaces towards generic frameworks to manage and exchange multiple types of assets. For example, the number of transactions in the global art market in 2019 summed up to 550'000 transactions, 90% of which were under $20'000 [9]. With an average Ethereum transaction fee ranging between $60 and $100 at the time of writing, the fees would make up 5% of the total transaction volume if all these transactions were included on the Ethereum blockchain. Exorbitant high transaction fees pose an economic barrier to artists who create assets and buyers interested in buying particular assets.

Shortcoming IV. Fraud. Due to the pseudonymous nature of blockchain platforms, a user could illegitimately sell assets it has not authored or does not rightfully own. Current NFT markets allow users to sell assets without any form of identity verification. It is estimated that in NFT marketplaces, more than $150'000 worth of assets has been published under a fake identity [10]. The *lack of verified identities* provides a getaway for illegal activities. Along with verifying the identity, we foresee the importance of maintaining the ownership attribution and paying royalties to the original authors when assets are re-used.

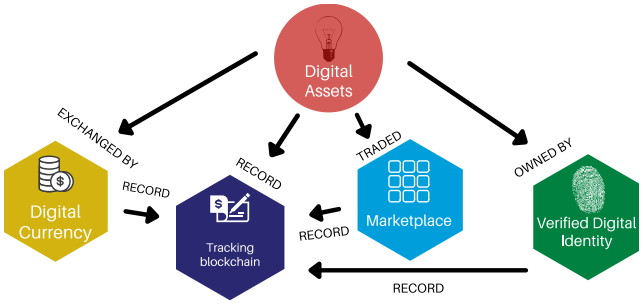


Figure 1: The four pillars of UniCon, our infrastructure to manage digital assets. The tracking blockchain maintains a tamper-proof history of digital assets.

Given these four shortcomings, this work focuses on the following question: *How can we build a secure, universal and scalable ecosystem for the management of digital assets?*

3 SOLUTION OUTLINE

We now outline the main ideas of UniCon, our universal and scalable infrastructure for digital asset management. UniCon is based on four pillars, visualized in Figure 1. These pillars include (1) a tracking blockchain, (2) digital currencies, (3) a decentralized marketplace, and (4) verified digital identities. The pillars of our solution do not work in isolation but cooperate to enable decentralized asset management. Digital assets such as songs or videos are not stored on the tracking blockchain but are persisted in an external storage backend for efficiency reasons. The tracking blockchain includes a pointer to these assets, e.g., using a hash.

The cardinal idea of UniCon is to track the history of digital assets on a *tracking blockchain*. These records include metadata on the creation, (re)sell, and modification of assets. By storing this information on the tracking blockchain, users can always verify the legitimacy of information and detect fraudulent behaviour, e.g., when a buyer has not paid for some assets. UniCon enables payments in any digital currency, as long as the payment can be publicly verified. We elaborate on the main functionality of each pillar and outline how our infrastructure addresses the shortcomings mentioned earlier.

Pillar I: Tracking Blockchain. The tracking blockchain maintains a tamper-proof history of digital assets. The only requirement for the tracking blockchain is that it can securely store data elements, making UniCon blockchain-agnostic.

For our prototype, we leverage an existing distributed ledger that is optimized for tamper-evident data accounting, named TrustChain [11, 12]. In TrustChain, each user maintains their *personal ledger* in which records are stored. A record contains an application-specific payload. Furthermore, a record is digitally signed by its creator, links to its previous record in the personal ledger, and optionally links to other records, e.g., to record a bilateral agreement between two parties. Each record includes a type field to distinguish between

different record types. TrustChain allows system designers to write custom validation logic that assesses the validity of a particular record in the context of a particular application, as we will further describe in Section 4.

Unlike conventional blockchains, TrustChain chooses to detect fraud instead of preventing it. Fraud in TrustChain manifests as creating two records at the same position in a personal ledger and is similar to a double-spend in cryptocurrencies. It involves a malicious user trying to rewrite the records in its personal ledger. The consistency of incoming records is checked against stored records to detect this fraud. Users continuously share known records in the network and also request random records from other users. Through the collective effort of users in the network, this approach can quickly reveal fraud. The TrustChain ledger is highly scalable, and experiments have demonstrated that fraud can be detected in seconds, even for networks with thousands of users [13].

Pillar II: Digital Currencies. The second pillar of UniCon are digital currencies. Unlike existing NFT platforms, we allow asset buyers to remunerate sellers in any desired currency and store the payment details on the tracking blockchain. Given the highly fragmented field of digital currencies, with over 4'000 cryptocurrencies [14], we argue that this is an essential requirement for digital asset management at scale. When assets are sold, the buyer and seller first create a trade agreement digitally signed by both parties. This agreement is stored on the tracking blockchain. Then, the buyer pays the seller and includes payment information on the tracking blockchain. Any user can now verify whether the buyer adhered to the trade agreement.

Pillar III: Verified Digital Identities. A verified digital identity uniquely links a digital identity to a real-world persona. Identity verification is a common practice in many digital marketplaces and raises the barrier to commit fraud. Verified digital identities are an integral pillar of UniCon. The main problems that this pillar addresses are the possibility for users to publish stolen content, use the platform for money laundering, or conduct other illegal activities hidden under the anonymity of the network. UniCon enables external auditors to link fraudulent behaviour to a real-world identity in case of illegal conduct.

We argue that emerging identity solutions, particularly Self-Sovereign identities (SSI), are highly suitable for implementing this pillar in UniCon. SSI is a decentralized identity management system that allows individuals to fully own and manage their digital identity and aims to increase control over our identity and our data [15, 16]. In an SSI system, a user, or *subject*, can make a claim (e.g., "I am over 18 years old") that then is attested by an *issuer* using a digital signature. The subject can then hand over the attested claim, i.e. an *attestation*, to a *verifier* (e.g., a liquor shop). An attractive property of SSI is that users can selectively disclose certain information. This concept of identity ownership diverges from established identity management solutions in which centralized authorities store and control the identity data of their users. In UniCon, a user stores an attestation that verifies their digital identity on the tracking blockchain. A user can now verify that another participant participates in the system under a verified identity.

Pillar IV: Decentralized Marketplace. UniCon includes a decentralized marketplace that asset creators can leverage to sell ownership of their assets to others. All market information is stored on the tracking blockchain, and users can reconstruct the current offerings by requesting records from other users. This pillar also includes protocols for exploring the current offerings and completing a trade.

In summary, our four pillars provide the necessary primitives to create, manage and sell digital assets while addressing the shortcomings stated in Section 2. Since our architecture is blockchain-agnostic, we avoid dependencies on a particular platform and address shortcoming I. Since UniCon can run on more scalable blockchains, e.g., TrustChain, our infrastructure addresses shortcomings II and III. By adding support for verified identities, we address shortcoming IV.

4 UNICON PROTOCOL AND IMPLEMENTATION

We will now present the UniCon protocol, outline how records are validated, and discuss our prototype.

4.1 Protocol Description

Our protocol provides the core functionality for the management of verified identity, the creation of digital assets, and the exchange of asset ownership. The protocol uses six TrustChain record types, which are listed in Table 1. We also show the organization of TrustChain records with UniCon in Figure 2. This figure shows two personal ledgers of two distinct users, both containing records used by UniCon. We now explain the four steps of the UniCon protocol.

Step I. Identity Verification. UniCon requires users to participate under a verified digital identity. When a user wishes to join UniCon, it has to acquire an attestation from a trusted third party such as a government. The user then creates a TrustChain record with type `identity` that includes the attention in its payload. The record is appended to the personal ledger of the user and shared with other users. Figure 2 shows the `identity` record in the personal ledgers of users a and b. As long as a user has not included a valid attestation in its personal ledger, all TrustChain records of this user will be considered invalid by other users, and not processed.

Step II. Creating and Tracking Assets. After identity verification, a user can proceed to manage assets with UniCon. First, a user persists its assets in an external storage backend, e.g., on a web server or in the decentralized IPFS network. Then, the user creates a TrustChain record with the `create` type. This record includes the type of the external storage backend in which the assets have been stored (e.g., "IPFS") and also contains a pointer to the assets in the appropriate backend as a URI (e.g., a URL or an IPFS address). After

Record type	Description
`identity`	Includes an identity attestation.
`create`	Start tracking assets with UniCon.
`sellable`	Put up assets for sale.
`wallet`	Contains a wallet address.
`agreement`	Includes a trade agreement.
`payment`	Includes trade payment details.

Table 1: TrustChain record types used by UniCon.

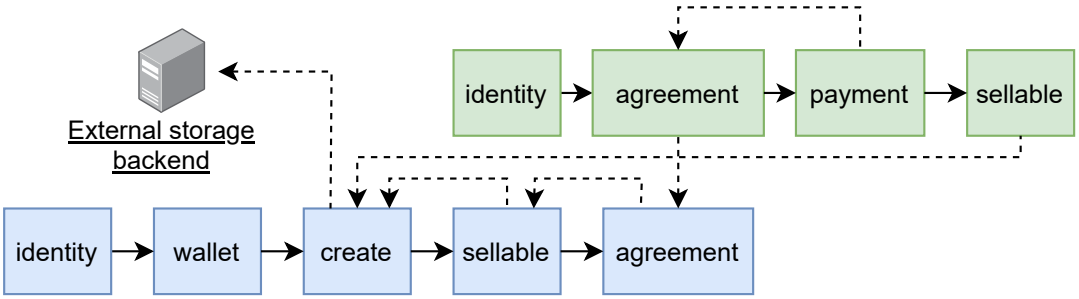


Figure 2: The personal ledgers and UniCon records of user a (in green) and user b (in blue). Solid arrows are pointers between records in a personal ledger and dashed arrows are pointers included in the record payload. Both users have their digital identity verified with an `identity` record. User b includes some assets in UniCon (with a `create` record) and puts it up for sale (with a `sellable` record). User a buys asset ownership created by b and puts it up for sale again.

creating the `create` record, it is appended to the personal ledger of the creator and shared with other users in the UniCon network.

Step III. Selling Assets. A user can offer to sell its asset ownership to other users by creating a `sellable` record. This record includes a `price` field, indicating the desired selling price of the assets, and also includes a pointer to the `create` record associated with the assets being sold (this is also shown in Figure 2).

The decentralized marketplace in UniCon lists all assets that has a `sellable` record and has not been sold yet. To streamline the trading process, a seller can persist `wallet` records on the tracking blockchain that includes information on the wallet of a buyer. A `wallet` record includes an identifier of the currency this wallet contains (e.g., Bitcoin) and an address (e.g., a Bitcoin address). This information is used by a buyer when initiating a payment to a seller.

Step IV. Buying Assets. Our ecosystem should detect the situation where an asset owner sells the same asset to multiple users simultaneously. In existing NFT platforms, this is checked and prevented by smart contract logic. In UniCon, interested asset buyers verify whether an asset seller currently holds ownership over the assets and whether this seller is currently not engaged in another trade for these assets. We describe this process further in Section 4.2.

When the buyer has verified that it is "safe" to proceed with the trade, the buyer creates an `agreement` record. This record contains a pointer to the latest `sellable` record associated with the assets (note that this record includes the price of the assets). It also contains the preferred currency that the buyer wishes to use to complete the payment and the source wallet address used. The interested buyer sends this `agreement` record to the seller. If the seller agrees with the conditions of the buyer, it creates another `agreement` record that contains a reference to the `agreement` record of the buyer. This structure is also shown in Figure 2. The seller needs to be online to verify the buyers' agreement.

After persisting the trade agreement on the tracking blockchain, the buyer should initiate a payment to the wallet address of the seller (this address is specified in the `wallet` records created by the seller). The buyer then creates a `payment` record, which includes a reference to the payment, e.g., in the form of a transaction identifier. Any user that verifies the history of an asset and can verify the legitimacy of the payment, i.e., by checking the source and destination wallet addresses and by checking whether the payment amount is in accordance with the asset price specified in the `sellable` record. Only when the payment is valid, the buyer is considered the new owner of the assets.

4.2 Record Validation

Algorithm 1 shows the validation logic of the record types mentioned in Table 1. These procedure are invoked when receiving a record from the network and are used to track the verified users, wallets, current owners of assets, and the list of sellable assets in the variables on lines 1-4. We left out the procedure invoked when receiving a `agreement` record since this procedure does not affect the aforementioned variables. Instead, the validity of `agreement` records is checked during the validation of a `payment` record (line 27). The `verified` variable maintains all users with a verified identity, `wallets` contains all the different currency wallets for each user, `contentOwners` tracks the current owners of content, and `sellableAssets` is a list of all assets currently up for sale. We also invoke methods that assess whether records contain the expected fields, e.g., using the `isCreateValid` method. The `lookup` method first looks for the record in the local database and if it is not available, queries the network. The `sellableAssets` variable is updated when receiving `sellable` and `payment` records. When receiving an incoming `identity` record, the `isValidAttestation` method is invoked that checks whether the attestion is valid. The exact implementation of this method depends on the SSI protocol used.

We remark that TrustChain does not guarantee that records arrive in the same order as they are organized in a personal ledger and our validation logic therefore should handle out-of-order record delivery. Also, for presentation clarity, we do not show the implementation of all methods. We refer the interested reader to the source code of our prototype.

Detecting Asset Ownership Violations. A seller can misbehave by attempting to sell the same assets to multiple users simultaneously. This would violate the UniCon system rules since an asset should always have a single owner. This violation can be detected by other users, e.g., when a single seller has created multiple `agreement` records that point to the same `sellable` record. Asset buyers should verify whether the assets are currently owned by the

Algorithm 1 UniCon record validation logic.

```
1:  verified ← []
2:  wallets ← {}
3:  assetsOwners ← {}
4:  sellableAssets ← []
5:
6:  procedure onIdentity(R)                    ▷ R is the incoming record
7:      if isValidAttestation(R.payload.attestation) then
8:          verified.append(R.pubKey)
9:
10: procedure onWallet(R)
11:     if R.pubKey not in verified or not isValidWallet(R.payload) then
12:         return
13:     wallets[R.pubKey][R.payload.type] ← R.payload.address
14:
15: procedure onCreate(R)
16:     if R.pubKey in verified then
17:         assetOwners[R.payload.asset] = R.payload.owner
18:
19: procedure onSellable(R)
20:     if R.pubKey in verified then
21:         create_record = lookup(R.payload.create)
22:         if isCreateValid(create_record) then
23:             sellableContent.append(create_record.payload.pointer)
24:
25: procedure onPayment(R)
26:     if R.pubKey not in verified then
27:         return
28:     ag = lookup(R.payload.agreement)
29:     if isAgreementValid(ag) then
30:         if isPaymentValid(ag.buyer, ag.seller, ag.price) then
31:             sellable = lookup(R.payload.sellable)
32:             asset = lookup(sellable.create)
33:             assetOwners[asset] ← R.payload.buyer
34:             sellableAsset.remove(asset)
```

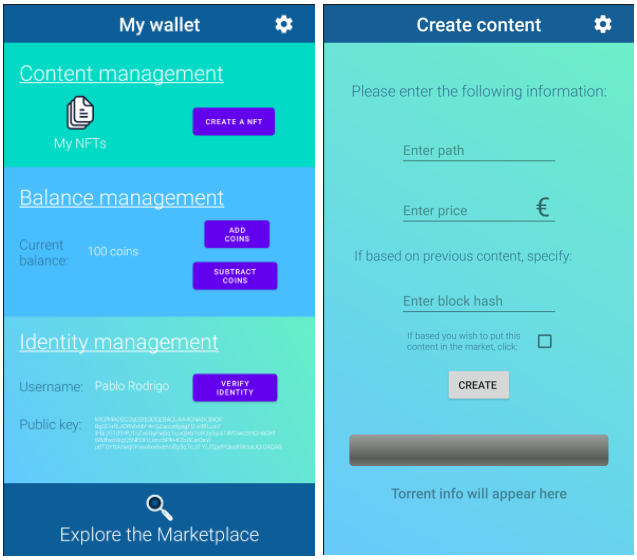
seller by requesting and inspecting records. When misbehaviour is detected, the set of records that prove the misconduct should be broadcast to other users in the network.

4.3 Prototype Implementation

We have implemented UniCon as a mobile Android application. Our prototype currently supports the decentralized BitTorrent protocol as external storage backend. Using the BitTorrent protocol, users can share assets without dependency on a trusted third party. We leverage the `jlibtorrent` library[3] to persist and share assets. The UniCon source code has been published on GitHub.[4]

In Figure 3 we show the user interface of the UniCon app. The main menu of UniCon is visualized in Figure 3a and is the entry point for the end-user to manage assets, their digital identity, and

[3]See https://github.com/frostwire/frostwire-jlibtorrent.
[4]See https://github.com/prodrigovalero/trustchain-superapp/tree/UniCon.



(a) Main menu **(b) Creating assets**

Figure 3: The user interface of our UniCon prototype.

integrated wallets. From this menu, users can also access the decentralized marketplace. Figure 3b shows the user interface for adding assets to UniCon. In this screen, a user can link to local files and optionally enter a price for the assets when the user wishes to put them up for sale. When clicking on the "create" button, a torrent will be created and the user starts seeding this torrent. The torrent infohash is included in the `create` record.

The UniCon implementation is a separate module in the "SuperApp" [17]. The MobileApp is our research vehicle for decentralized mobile systems. This application includes a peer-to-peer networking library and an implementation of the TrustChain ledger. Our mobile application includes a large number of decentralized applications, including a peer-to-peer social network, messaging application, and a decentralized music sharing platform. UniCon currently supports payments in Bitcoin and Ethereum tokens.

5 RELATED WORK

Digital data management in a decentralized manner is a well-explored research area. Already in 1999, Napster proposed a semi-decentralized approach to manage musical digital content [18]. Similarly, Tribler is a fully decentralized file-sharing solution where users can create, download, and share content without supervised control [19]. We believe that UniCon can enhance existing decentralized content platforms such as Tribler by providing the notion of asset ownership and ownership transfers in the system.

The work of Wang et al. gives a systematic overview of the NFT ecosystem [20]. Some of the problems we elicited in Section 2 are recognized by the authors of [20], including high transaction fees and limited scalability. Additionally, the authors advocate for a redesign of the blockchain space, a proposition that closely aligns with the vision of UniCon.

Most literature related to NFTs presents methods to apply NFTs in different application domains. While virtual art items remain

the most popular NFT application, their usage is also considered in domains such as land management, wildlife conservation and ticket registry [20]. Several researchers adopt NFTs for the authentication and management of devices in an IoT environment [21, 22].

Some NFT solutions address the scalability issues of Ethereum by leveraging a blockchain with a different architecture, e.g., Hyperledger Fabric [23, 24] and EOS [25]. While some of these systems offer increased scalability or flexibility, they often depend on capabilities only offered by the respective blockchain architecture.

6 CONCLUSION

We have presented UniCon, universal and scalable infrastructure for digital asset management. Similar to blockchain-based NFT platforms, UniCon enables users to manage and track ownership of digital assets and to transfer ownership to other users. UniCon addresses several deficiencies of blockchain-based NFTs, including platform dependencies, limited scalability, and high transaction fees. The main idea of UniCon is to use a tracking blockchain to track modifications to assets. For this purpose, we leverage an existing, scalable ledger. We have described the UniCon protocol and validation rules, and implemented a prototype of our system as an Android application. Our prototype hints at increased flexibility and scalability, and is a first step towards a transparent, open, and decentralized ecosystem for asset management. Future work includes a deployment at scale and adding support for assets with joint ownership [26].

REFERENCES

[1] Bry. Non-fungible tokens – the art market's digital disruptor, 2021.
[2] Ledger Insights. Jack dorsey sells his first tweet as an nft for $2.9 million, 2021.
[3] Robert Frank. Nft sales top $2 billion in first quarter, with twice as many buyers as sellers, 2021.
[4] Gavin Wood et al. Ethereum: A secure decentralised generalised transaction ledger. *Ethereum project yellow paper*, 2014.
[5] Eip-721: Non-fungible token standard, 2018.
[6] Yogita Khatri. Solana-based nft project burnt finance raises $3 million in seed funding, 2021.
[7] Lennart Ante. Non-fungible token (nft) markets on the ethereum blockchain: Temporal development, cointegration and interrelations. *Available at SSRN 3904683*, 2021.
[8] Xin-Jian Jiang and Xiao Fan Liu. Cryptokitties transaction network analysis: The rise and fall of the first blockchain game mania. *Frontiers in Physics*, 9:57, 2021.
[9] The art market 2019. global assessment: strong and flexible demand, 202o.
[10] Valentina Di Liscia. Reports of stolen art on nft marketplace raise issues for crypto collectors, 2021.
[11] Martijn de Vos and Johan Pouwelse. Contrib: Maintaining fairness in decentralized big tech alternatives by accounting work. *Computer Networks*, 192:108081, 2021.
[12] M. et al. de Vos. Devid: Blockchain-based portfolios for software developers, 2019.
[13] Martijn de Vos and Johan Pouwelse. Contrib: Universal and decentralized accounting in shared-resource systems. In *DICG*, 2020.
[14] Raynor de Best. Number of cryptocurrencies worldwide from 2013 to 2021, 2021.
[15] Alexander Mühle et al. A survey on essential components of a self-sovereign identity, 2018.
[16] Quinten Stokkink et al. A truly self-sovereign identity system. In *LCN Conference*, 2021.
[17] Johan Pouwelse. Towards the science of essential decentralised infrastructures. In *DICG*, 2020.
[18] Bengt et al. Carlsson. The rise and fall of napster - an evolutionary approach. 12 2001.
[19] Johan Pouwelse et al. Tribler: a social-based peer-to-peer system. *Concurrency and computation: Practice and experience*, 2008.
[20] Qin Wang et al. Non-fungible token (nft): Overview, evaluation, opportunities and challenges, 2021.
[21] Omar Sghaier et al. Capability-based non-fungible tokens approach for a decentralized aaa framework in iot. In *Blockchain Cybersecurity, Trust and Privacy*, pages 7–31. Springer, 2020.
[22] Javier Arcenegui et al. Secure management of iot devices based on blockchain non-fungible tokens and physical unclonable functions. In *ACNS*, 2020.
[23] Mustafa Bal and Caitlin Ner. Nftracer: a non-fungible token tracking proof-of-concept using hyperledger fabric. *arXiv preprint*, 2019.
[24] Sangwon Hong et al. Fabasset: Unique digital asset management system for hyperledger fabric. In *ICDCS*, 2020.
[25] Wax project.
[26] Jaspreet Singh and Prashant Singh. Distributed ownership model for non-fungible tokens. *SSIS*, 2021.