SoK: Tokenization on Blockchain

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ABSTRACT

Blockchain, a potentially disruptive technology, advances many different applications, e.g., crypto-currencies, supply chains, and the Internet of Things. Under the hood of blockchain, it is required to handle different kinds of digital assets and data. The next-generation blockchain ecosystem is expected to consist of numerous applications, and each application may have a distinct representation of digital assets. However, digital assets cannot be directly recorded on the blockchain, and a tokenization process is required to format these assets. Tokenization on blockchain will inevitably require a certain level of proper standards to enrich advanced functionalities and enhance interoperable capabilities for future applications. However, due to specific features of digital assets, it is hard to obtain a standard token form to represent all kinds of assets. For example, when considering fungibility, some assets are divisible and identical, commonly referred to as fungible assets. In contrast, others that are not fungible are widely referred to as non-fungible assets. When tokenizing these assets, we are required to follow different tokenization processes. The way to effectively tokenize assets is thus essential and expecting to confront various unprecedented challenges. This paper provides a systematic and comprehensive study of the current progress of tokenization on blockchain. First, we explore general principles and practical schemes to tokenize digital assets for blockchain and classify digitized tokens into three categories: fungible, non-fungible, and semi-fungible. We then focus on discussing the well-known Ethereum standards on non-fungible tokens. Finally, we discuss several critical challenges and some potential research directions to advance the research on exploring the tokenization process on the blockchain. To the best of our knowledge, this is the first systematic study for tokenization on blockchain.

CCS CONCEPTS

• **General and reference** → **Computing standards, RFCs and guidelines**; • **Information systems** → *Information systems applications*; • **Applied computing**;

KEYWORDS

Blockchain, Tokenization, Fungible Token, Non-fungible Token (NFT)

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1 INTRODUCTION

Blockchain technology has emerged as a critical facilitator for the implementation and advancement of distributed ledgers. It enables a group of participating nodes (or parties) that do not trust each other to deliver trustworthy and immutable services [57]. Initially, distributed ledgers were designed as tamper-evident logs to record data and share information. Independent parties typically maintain them without resorting to some centralized authorities [24]. Blockchain became popular because of its success in crypto-currencies, e.g., Bitcoin [40]. The technological advances and extending application domain of blockchain technology have publicly received tremendous attention from academia and industry, promising to change all aspects of digital business in the industry. It is believed that blockchain will have a profound impact and influence on existing Internet infrastructures and will promote the development of a decentralized Internet [57]. This is because all the information recorded on the blockchain can be considered as digital assets, and these assets with guarantees of authenticity in the blockchain are tamper-proof and cannot be changed.

Smart contracts deployed on blockchains enable the creation of new types of digital assets, called tokens, that can interact with each other [16]. In general, all kinds of digital information or assets can be customized in the form of tokens, whose process refers to tokenization. After digital assets are tokenized, they can be recorded on the blockchain. Different blockchains may have different tokenization processes. Currently, the most well-known guideline to create a token is a series of Ethereum Request for Comments (ERCs) [21], which describe the fundamental functionalities and provide guidelines that a token should comply with working correctly on the Ethereum network. Within ERCs, various types of tokens are defined regarding the features of assets, e.g., ERC-20 [20] for divisible assets and ERC-721 [19] for indivisible assets. Once a token representation of a digital asset is created on a blockchain, it can be traded via a process known as an Initial Coin Offering (ICO) [33], the online sale of created tokens [10]. From an economic perspective, this is one motivation to promote the rapid development of tokenization on blockchain in recent years.

Tokens can represent assets on the blockchain to facilitate transactions, whose representations, tokens, are roughly categorized into *fungible tokens (FT)* and *non-fungible tokens (NFT)*, based on the fungibility of assets. Fungible tokens are exchangeable and identical in all aspects and generally divisible, while non-fungible tokens cannot be substituted for other tokens even with the same type and are indivisible [30]. One classic example of fungible tokens is crypto-currencies [12], in which all the coins generated for crypto-currencies are equivalent and indistinguishable. On the other hand, non-fungible tokens are typically unique and specially identified, which cannot be exchanged in a fungible way, making them suitable for identifying unique assets. Furthermore, with the help of smart contracts on the blockchain, one can easily prove the existence and ownership of digital assets, and the full-history tradability and interoperability of blockchain assets make NFTs become a promising intellectual property protection solution [59]. Also, NFTs have gained remarkable attention from academia and industry communities to embody unique real-world assets.

Digital assets vary in terms of fungibility, which is a characteristic of a token that indicates whether assets can be entirely interchangeable during an exchange process. Fungible tokens of the same type are identical (like coins are identical), being divisible into smaller units (like coins of different values). And, non-fungible tokens have been employed to represent unique assets (e.g., collectables, certificates of any kind, any type of access rights, objects, etc.) [3] [22]. Thus, an NFT is unique, indivisible, and different from other tokens even with the same type. In literature, there exist several well-known crypto-tokens: crypto-coins, asset-tokens, and utility-tokens. From the perspective of fungibility, crypto coins typically belong to fungible tokens, and both asset-tokens and utility-tokens are non-fungible tokens. Crypto coins are commonly referred to as crypto-currencies, with the help of blockchain, which can be used as a medium of exchange of currencies without resorting to any centralized banks. Asset-tokens typically can be used to represent a wide range of assets beyond crypto-currencies, e.g., assets with physical existence (i.e., real properties) or without physical existence (i.e., stock shares). Utility-tokens are typically used to represent a unit of product or service, or tokens that enable future access to a product of service [31] [34].

In general, a token is affected by four operations in its life-cycle [30]. The issuer (often as a seller) first creates the token (e.g., via smart contracts). If traded on a trading market, the buyer then bids upon the token, at which point agreement, the seller transfers the token's value to the buyer. Finally, the new owner (e.g., the buyer) of a token can redeem the value of the token [30]. This description describes a general model of a token life-cycle. However, within this cycle, it may have some challenges and risks to overcome, e.g., legal disputes or limitations on smart contract [9]. When a token is created on a blockchain, e.g., public blockchain, everyone can see how it was developed and linked to the underlying right or asset. Due to the anonymity or pseudonymity of blockchain, when legal disputes arise from the creation and use of digital assets, it is not enough to match these assets with the real-life owner or creator of the token, which makes the verification process of assets difficult. Most existing tokens are required to operate with smart contracts to verify their ownership and manage their transferability. Fulfilling the requirements of smart contracts may be a potential issue, e.g., a transaction be carried out in a written form requires to include signatures of the parties. And, not everything about the token can be coded in a smart contract. For instance, if the seller of a token wants to introduce some contractual terms (e.g., prohibiting buyers from using the represented token for commercial purposes), such a term typically cannot be enforced by smart contracts.

Tokenization creates many opportunities to apply and adapt blockchain to real-world applications. By tokenizing digital assets, assets can be easily represented and recorded on blockchains. Although tokenization on a blockchain is promising, it still faces many challenges, and it would be better for system designers to know these potential issues and challenges. Even though some media reports on some special blockchain use cases (e.g., NFTs for Ethereum), there are no systematic level studies on a general tokenization process. As such, a systematical-level study of tokenization on the blockchain is required. This paper presents a comprehensive and systematic study of tokenization on the blockchain, mainly from the perspectives of functional and conceptual components. According to current works of literature, we classify tokens into different categories regarding these fungibility of represented digital assets, namely, *fungible tokens*, *non-fungible tokens*, and *semi-fungible tokens*. For each category, we present the state-of-the-art literature works in that category and provide some discussions. As a systematization of knowledge on tokenization, we also provide some research challenges and research directions, which may help interested readers explore more in this area.

The rest of the paper is organized as follows. Section 2 introduces some preliminary information on the blockchain, transactions, and general tokenization on blockchain. Section 3 discusses the classification on blockchains' tokens. Section 4 details existing solutions on crypto-tokens and provides a detailed discussion on opportunities and risks on NFTs. Section 5 shows some potential research directions, and section 6 concludes this paper.

2 PRELIMINARIES

This section provides some preliminary information for tokenization on blockchain.

2.1 Blockchain and Transaction

Blockchain is a publicly known distributed ledger technology underlying many digital crypto-currencies, such as Bitcoin [40]. In a broad sense, blockchain can be roughly explained as an immutable, decentralized, trusted, and distributed *ledger* based on decentralized (e.g., peer-to-peer (P2P)) networks [50]. Essentially, blockchain is a distributed data structure and is labelled as a "*distributed ledger*" in its applications, functioning to record transactions generated within a network [53]. In general, crypto-currency is only one application of record-keeping functions, and distributed ledger technology has great potential to be adapted to other application scenarios as long as data exchanges exist. The key idea behind blockchain technology is decentralization, which means blockchain technology does not require any trusted central point or party to control or manage the participating nodes.

As a distributed and decentralized ledger, the essential component of blockchain is data, alternatively called transaction. The transaction information can be considered a token transferring process occurring in a network or any data exchange. Atomicity Consistency Isolation Durability (ACID) provides general principles for transaction processing systems, e.g., blockchain. A transaction in an ACID system should have the following features for a blockchain system [51]: (a) a transaction (or a transaction block consisting of multiple transactions) is executed as a whole or not at all (e.g., enabling the feature of "all or nothing"); (b) each transaction transforms the system from one consistent and valid state to another, without compromising any validation rules and data integrity constraints; (c) concurrent transactions are executed securely and independently, preventing them from being affected by other transactions; and (d) once a transaction has been successfully executed, all changes generated by it become permanent even in the case of subsequent failures. Thus, ACID is crucial to a blockchain transaction. However, different applications may require different transaction structures to represent the represented information or assets. For instance, some indivisible assets would require strong atomicity on the contained information, e.g., as one piece, while others (e.g., most crypto-currencies) can be dividable. Thus, we need some schemes to digitally denote the states of these assets so that they can be processed more efficiently on blockchain, and tokenization is an ideal candidate to signify these different kinds of transactions. And, smart contracts will assist the tokenization process on blockchain.

2.2 Tokenization for Blockchain

A token is typically a digital representation of an asset available in the physical or virtual worlds [36]. In the blockchain domain, a token can be used to represent some crypto-currencies, such as Bitcoin or Ether [32]. Technically, a token is implemented by an algorithm defined in a smart contract on a blockchain. And smart contracts are essentially computer programs that verify or implement a contract by automatically carrying out a pre-defined set of terms in a trackable and irreversible manner without the involvement of a third party [56]. The output of a smart contract can be literally considered as a token. For instance, the Ethereum platform can be used to create arbitrary smart contracts, whose tokens (aka. Ethereum tokens) can be used to represent various digital assets [15]. These tokens can represent anything from both physical objects and virtual objects. They can use them for a variety of purposes, e.g., recording transactional data information or paying to access a network. The mapping process between a token and its representative asset is initially purely fictitious. The token contains the asset model that is certified by a smart contract to guarantee the uniqueness of data. In general, tokens will not depend on operating systems and do not include physical content within, and via the smart contract, it is easy to verify the validity of a token.

Tokenization is the transformation process of data/assets into a random digitized sequence of characters (aka. a token) [39]. It simplifies the process of representing physical/virtual assets and provides some protection on sensitive data, e.g., by substituting non-sensitive data into a token. The token serves merely as a reference to the original data or assets for blockchain applications but cannot be utilized to determine those values. A token itself does not include some economic value information in it, and the "monetary" value of a token typically is assigned by the market. Thus, we can consider a token as a symbol that is validated by smart contracts of the target blockchain system. As long as validated by the smart contract, the token can be used in numerous applications or be traded in the market. Tokenization of real-world assets is a trend that generates much interest in blockchain research [47]. Tokenization on the blockchain provides many advantages. For instance, tokenization eliminates most financial, legal, and regulatory intermediaries, resulting in significantly lower transaction costs. However, the tokenization process on the blockchain is still in its early stage, and there are many challenges and risks to overcome, including regulatory and technical challenges, to fully realize the potential of tokenization on blockchains[55]. For example, the lack of regulatory clarity for tokenized assets becomes a significant obstacle for the wider implementation. And, from a technical perspective, there lacks a trusted way to ensure consistency between the on-chain assets and the underlying off-chain assets. In this paper, we focus on representing the physical/virtual off-chain assets and digital on-chain assets from the features of fungibility. Specially, we roughly classify tokens into three categories: fungible tokens (FT), non-fungible tokens (NFT), and semi-fungible tokens (SFT).

3 CLASSIFICATION ON BLOCKCHAIN TOKENS

In the tokenization process for blockchains, there indeed exist many types of tokens for various applications. Instead of discussing these specific application-based tokens, according to the fungibility of assets on blockchains, we roughly classify them into three well-known tokens: fungible tokens (FT), non-fungible tokens (NFT), and semi-fungible tokens (SFT).

3.1 Tokens

In the blockchain domain, tokens can be used to represent digital assets. However, the concept of a token is not exclusive to the blockchain. Historically, tokens were used to secure digital transactions, e.g., banking transactions [9]. Nowadays, tokens are regarded as one of the critical uses of blockchain technology, and tokens are described as "central to most social and economic innovations developed with blockchain technology" [26]. From a technical perspective, tokens are a piece of digital information, e.g., lines of computer code, which details what the token represents. While, from a legal perspective, tokens can represent digital assets that can virtually specify any value that has been agreed on and secured by cryptographic protocols, e.g., crypto-currencies. Also, some rights, such as access rights, can be represented in the form of tokens. And assets from both the real world (e.g., real estate, collectables, commodities, and even company shares) and the virtual world (e.g., crypto-currencies, lottery tickets, or even character skills in online games) can all be tokenized for further processing.

In literature, there exist different kinds of classifications for digital objects. These digital objects typically carry a state of information that helps to bridge the gap between the physical and digital world [28]. Following the ways on how to represent digital objects or the tangibility [43], digital objects can be roughly categorized as tangible and intangible objects. Tangible objects refer to the assets with physical existence, and they are typically unique. For example, a tangible object in a blockchain represents an asset with both physical existence and its digital form. On the other hand, intangible objects refer to the assets that do not have a physical nature, such as services or virtual objects, which can be represented as abstract objects within its targeting system. Also, from the fungibility of assets, digital objects can be classified into fungible and non-fungible objects. Table 1 shows a classification of digital objects with their key features.

From an application perspective, there is little internationally recognized categorization for tokens, and different countries may endorse different types of tokens. In literature, there are indeed

Table 1: Classification of Digital Objects

	Object Class	*Key Features*
Tangibility	Tangible	Physical existence
	Intangible	Virtual existence or service
Fungibility	Fungible	Exchangeability
	Non-fungible	Uniqueness

having some classifications based on their functionalities: payment tokens, utility tokens, and alternative tokens (e.g., asset, security, equity, or investment tokens) [9]. The most evident example for payment tokens lies in the digital payment domain, e.g., in the form of crypto-currencies. Utility tokens typically are used to provide digital access to some applications or services, and this type of token typically requires some supporting infrastructures to function fully. Alternative tokens have different purposes, e.g., asset tokens digitally represent assets, and security tokens grant their holders some rights as certificates. Even though various names are attached to tokens, from its essential perspective, they are used to digitalize the information of represented assets (e.g., goods, services, rights, etc.). And, from the fungibility perspective, these tokens can be classified into three types: fungible tokens, non-fungible tokens, and semi-fungible tokens.

Before introducing these tokens, we first need to know the concept of fungibility. A fungible asset can be interchangeable with other assets of the same category or type [41]. Fungibility refers to an asset's capacity to be interchanged with other assets of the same or similar types. In other words, fungibility is one kind of property of a token that specifies whether objects or quantities of a similar type can be freely interchangeable during a trade or utilization [5]. In general, in the finance domain, fungible assets simplify the exchange and trade processes, as fungibility implies equal value among the involved assets. Currency (or crypto-currency) is an excellent example of fungible property, e.g., $1 bill can be easily and equally convertible into four quarters or ten dimes with the same value [25]. In the token domain, some of them are purely equal (aka. perfectly fungible tokens), while others possess distinct characteristics which ensure their uniqueness (aka. non-fungible tokens) [52]. For example, if we consider physical assets, such as uniquely identified real estate or collectables, as tokens, they are non-fungible.

3.2 Fungible Tokens

The fungibility of a token refers to the fact that the token has the same or similar content compared to other fungible tokens. Thus, fungible tokens are interchangeable/replaceable with, or equal to, another asset of the same category. For example, A fungible token can be readily substituted by other assets of the same or equivalent value that may be divided or exchanged. They are identical to one another and can be divided into smaller units, which does not affect their values [5]. Furthermore, fungible tokens typically are not unique. For example, a payment token is always fungible, which is exchangeable, divisible, and not unique in nature. As Glatz stated [26], "From a technical perspective, a fungible token is implemented as a list of blockchain addresses (user accounts) that have a number (quantity) associated with them, together with (1) a set of methods used to manipulate that list, such as 'transfer *n* tokens from address *a* to address *b*', and (2) rules to determine who can manipulate that list in which way." Under applications of the Ethereum blockchain, ERC-20 (or Ethereum Request for Comments #20) is an example of fungible tokens. It is a specification established upon by the Ethereum community (a community that endorses ERCs) that specifies certain fundamental functionalities and provides criteria for a token to comply with performing correctly on Ethereum blockchains [10]. An ERC-20 token is a token that follows ERC-20 guidelines. They have some inherent feature that makes one token identical to another token in terms of type and value. For example, an ERC-20 token functions similarly to ETH on the Ethereum blockchain, in that one token always have an equal value to all other tokens [20]. Besides, the ERC-20 standard specifies a common interface for fungible tokens that are divisible and not distinguishable, which further ensures interoperability among the Ethereum blockchain community [57]. However, applying the ERC-20 token type to other blockchain scenarios still has a long way to go.

One limitation to fungible tokens is that many valuable assets, such as artwork, real estate, cannot be effectively divided and replaced from the nature of these assets. And, these assets are typically unique assets that are required to keep track of the ownership, which needs non-fungible tokens to represent.

3.3 Non-fungible Tokens

A non-fungible token (NFT) is a cryptographically unique, non-replicable token, which can be used to keep track of the ownership of individual assets. Non-fungible tokens differ from fungible tokens in terms of interchangeability, uniformity, and divisibility. A non-fungible token cannot be divided in nature, in which each one contains some distinctive information and attributes to identify itself from others uniquely. This feature makes NFTs impossible to interchange with each other [5]. In general, each non-fungible token is unique and differs from others. The ERC-20 standard provides the technological framework and best practices for fungible token creation under Ethereum blockchains. Similarly, the ERC-721 standard [19] did the same for non-fungible tokens, which allows the developers to create a digital asset representation that can be exchanged and tracked on the blockchain. The establishment of this new standard was prompted by the fact that there exists a significant difference between fungible and non-fungible tokens in nature. For example, the notion of *fungible* commonly describes the capacity of each piece of a commodity to be interchanged with other pieces of the same or similar commodity. For example, two individuals could swap the same amount of assets without any gain or loss, and even if these assets are in different forms, the values should be the same. While the non-fungibility is opposite as each token is unique and cannot be divided into small pieces or merged with other pieces into a large piece. For example, the ERC-721 defines that each NFT token must have a universally unique identifier, whose ownership can be identified and transferred with the help of metadata [45]. In general, the ERC-721 standard specifies an interface that each smart contract on Ethereum that wants to create ERC-721 tokens has to implement.

Essentially, an NFT can be seen as a piece of digital information (token) that is stored on a ledger system and, due to uniqueness, it can be interchangeable with other digital assets in nature, even with the similar digital assets [11]. Practically, real-world assets may be tokenized with the aid of NFTs. However, NFTs, unlike standard crypto-currencies or ledger-based tokens, are not interchangeable and replaceable, as they include their own information or other characteristics that make them unique and irreplaceable [54]. The key characteristic of NFTs is that they symbolize ownership of digital or physical assets, which can encompass a wide range of assets. This distinguishes NFTs and allows for individual tracking of their ownership [49]. Furthermore, with the help of blockchain, the NFT, as a token, provides the essential verifiable immutability and authenticity, as well as other characteristics like delegation, transfer of ownership, and revocation [42]. Also, the NFT plays a key role in scaling the ability of Ethereum to process a high number of transactions using stable channels [13].

3.4 Semi-fungible Tokens

Tokens standards on fungible and non-fungible assets typically facility distinct contracts for each token type, which may place some redundant bytecodes on blockchain and limit certain functionality by the nature of separating each token contract. Semi-fungible tokens are a new class of tokens, which have the features of both fungible tokens and non-fungible tokens. SFTs provide more flexible interfaces to represent some complex assets or processes. In literature, ERC-721 is not the only token standard that exists for NFTs. The Ethereum ERC-1155 standard (Multi Token Standard) [18] is another notable Ethereum variant that offers "semi-fungible" options and the potential to represent both fungible and non-fungible assets. This offers an interface to denote an NFT in a fungible way. For instance, an ERC-1155 token extends the functionality of token identification (aka. *tokenId*), which can offer configurable token types. This type of token may contain customized information, e.g., metadata, timestamp information, supply, and other attributes [59]. In general, the ERC-1155 token is a new token proposal standard to create fungible and non-fungible tokens in the same contract. Currently, there is neither too much information on the standard of ERC-1155 tokens nor much information on semi-fungible tokens.

In general, semi-fungible tokens can hold and represent the features of both fungible and non-fungible assets. Thus, semi-fungible tokens may be more efficient to create and bundle token transactions (without requiring a mandate unique token contract for each token created). For example, the ERC-1155 token offers some level of flexibility over the ERC-721 token, e.g., creating flexible, re-configurable, or exchangeable tokens with non-fungible features [54]. Accordingly, the token structures and interfaces of SFTs will also be more complex.

4 EXISTING SOLUTIONS ON CRYPTO-TOKENS

4.1 Crypto-tokens

Blockchain technologies give birth to a new cryptographic form of assets, crypto-assets, or crypto-tokens, which can be represented in different forms and used in different application domains. In general, the concept of fungible tokens can be directly adapted to blockchain-powered financial systems. When integrating FTs into the blockchain, one of the important applications is crypto-currencies, which are typically considered divisible crypto-assets. And the exploration and use cases of semi-fungible tokens are still in the concept stage. This section presents some existing solutions and uses cases on some commonly referred crypto-tokens. Specially, we discuss three well-known crypto-tokens: crypto-coin, asset-token, and utility-token [43]. The crypto coins typically belong to fungible tokens, and both the asset-tokens and the utility-tokens are non-fungible tokens.

Crypto coins are commonly referred to as crypto-currencies; with the help of blockchain, they can be used as a medium of exchange of currencies without resorting to any centralized banks. They are typically used as payment currency or trading currency where payments or trades can be made for goods, services, and fiat currencies. However, crypto-coins highly rely on their underlying blockchain systems and protocols. For example, Bitcoin and Ethereum, as crypto-coins, are based on different blockchain systems, and each system runs its own independent ledger. Therefore, they are not directly exchangeable between other systems, but they can be traded via some trading platforms. In general, crypto coins are modelled to represent some intangible and divisible assets. However, they also can be designed for some special purpose, e.g., assigning a unique number or value for each coin.

Asset-tokens typically can be used to represent a wide range of assets beyond crypto-currencies, e.g., assets with physical existence (i.e., real properties) or without physical existence (i.e., stock shares). These kinds of tokens are commonly implemented and verified via smart contracts. With the help of blockchain, it makes accessing and managing digital assets more efficient. Typically, asset-tokens are implemented as non-fungible tokens that are digitally unique to each other. There exist some well-known non-fungible use cases, such as CryptoKitties [22], copyright protection, supply chain tracking, software licenses distribution, to name a few. While asset-tokens can also be in the form of fungible tokens, they require that each unit of the asset be uniquely identified and hold the same characteristics within their representative systems. For example, Colored Coin [46], as a fungible token, describes a class of methods on how to represent and manage some specific types of real-world and physical assets, which enable them to be exchanged on top of a Bitcoin network. These kinds of asset-tokens would require some verification schemes (e.g., in the form of smart contracts) to verify the validity of fungibility.

Utility-tokens are typically used to represent a unit of product or service or tokens that enable future access to a product of service [31]. Utility-tokens are not like crypto-currencies that are designed for investment or made for exchange purposes, and they are designed as a service that can be purchased. However, in practice, some situations may exist in which the same product or service can be distributed to multiple users and allow them to exchange utility information with each other [43]. Typically, utility tokens belong to fungible tokens. For example, ERC-20 compatible tokens on the Ethereum platform are considered utility tokens. The utility tokens are generally valid between users within a network or community.

In general, different digital objects can be mapped into different types of tokens, such as crypto coins, asset-tokens, or utility tokens. These types are not exclusive, and according to practical use cases and actual characteristics, one kind of digital asset can be classified into different categories. The above discussed three crypto-assets serve as some baseline for current or future emerging digital crypt-assets.

4.2 Opportunities of NFT

Most existing fungible tokens target crypto-currencies use cases that take advantage of divisibility, like fiat currency. And NFTs consist of unique features that make them easily accessible to other real-world use cases (besides crypto-currencies). This section presents some opportunities provided by NFTs on the blockchain, e.g., authenticity, ownership, and transferability [37].

4.2.1 Authenticity. The standardization of NFT, with the help of blockchain and smart contracts, makes each token uniquely identifiable and authentic, and the token information can be recorded in a blockchain which makes them immutable and trustworthy. Theoretically, there is no efficient way to copy or duplicate a unique token once the token is recorded in the blockchain, which helps prevent fraudulent items and protect intellectual property. Also, the transparency of blockchain makes it possible to verify and prove the authenticity of each NFT. Therefore, when NFT is equipping with blockchain, it can effectively prevent the counterfeiting and fraud problems in many industrial use cases, such as art and collectables.

4.2.2 Ownership. At the heart of NFT is uniqueness and ownership, and a token is required to prove its ownership of an asset. Ownership means that an NFT can only be transacted and transferred by the owner of the asset (not the owner of the issuer) due to the smart contracts and associated rights. Even the issuer of an NFT cannot replicate or transfer the NFT without permission from its owner. An NFT token on a blockchain can track ownership and, therefore, authenticity, undeniably proving ownership. For example, the ERC-721 standard defines the minimum interfaces, including ownership details, security, and metadata, and the ownership is assigned to the owner of the asset.

4.2.3 Transferability. NFTs recorded on a blockchain must be decentralized, and no centralized authority can regulate the movements of these tokens over the blockchain systems. In general, one NFT only belongs to one owner at any time, whose unique data structure offers a simple way to verify its ownership and to transfer the token among owners [14]. The owner of the creator can also store specific information inside them to clarify the ownership, making NFTs transferable. Also, the help of blockchain enables millions of people to have ready access to NFTs, and they can trade these NFT tokens for other cryptocurrencies.

Besides the above-mentioned features and inner natures (such as indivisibility and uniqueness), NFTs have other features, such as scarcity and indestructibility. For example, for scarcity, the total number of NFTs is currently pretty low, and they are quite rare, which makes them not only uncommon but also increases their values. For indestructibility, NFTs are typically managed and operated via blockchain, which increases assets' security. And this ensures that these NFTs cannot be removed or destroyed.

Due to easy transfer and proof of ownership, NFTs open a wide range of potential applications for real-world and virtual assets, e.g., the gaming industry, digital assets, identities, collectables, and certificates. Taking digital collectables as examples, NFTs are scarce, which fits the use cases in collectables and art. The collectors may readily verify the authenticity and ownership of corresponding assets with the meta-data included in the token, which protects an artist's work from being copied or misused. Also, NFTs are typically encoded with a unique collection of information on the represented assets. As such, NFTs are ideal for granting certificates, identities, credentials, and licenses. With the help of blockchain, the ownership information is appended in the blockchain in a decentralized manner, which makes NFTs traceable [7].

The tokenization process provides many benefits to existing blockchain systems [45]. A key benefit of NFTs is that their uniqueness is better than existing blockchain-based use cases, and via smart contracts, it makes digital assets programmable. Even for some assets with certain fungible features, we can still use NFTs to differentiate between assets. NFTs enable new use cases and have the potential to improve existing blockchain systems by providing unique and exchangeable assets. For individual assets (other than fungible assets), NFTs provide two distinguishable properties: 1) NFTs can guarantee authenticity and uniqueness when tokenization of these assets; 2) NFTs ideally represent physical assets in the digital sphere. With the help of blockchain, tokenization increases the transparency of ownership benefits regulators, which bridges the gap between the physical and digital worlds.

4.3 Risks Associated with NFT

Although NFTs provide many opportunities to digitalize assets, NFTs, as digital objects over the Internet, do have some risks to consider [2]. Most existing NFTs in literature are still in the form of software codes following predefined and standardized rules, like smart contracts, deployed and executed on the blockchain network. Thus, the integrity and security of NFTs are highly reliant on their underlying blockchain systems [45]. For example, most NFT-related projects are currently enabled by the Ethereum blockchain. And the Ethereum blockchain has its own limitations, e.g., scalability and decentralized autonomous organization (DAO) attacks on Ethereum. Another challenge is the privacy issues on permissionless blockchain, e.g., the mechanisms to preserve some sensitive information of digital assets locally.

Even though many ICO (Initial Coin Offering) projects are available, it is still a challenging proposition to purchase an NFT. In general, NFTs offer a new marketplace for customizing blockchain applications and are even different from the new crypto-currencies market. However, there is no guarantee that demand for digital assets will be comparable for distinct applications. If there is no market for trading NFTs, the customer may pay an exorbitant price for some digital assets that depreciate or is just unsaleable. The creators can even create their own NFTs. Again, however, there is no guarantee to find a customer respective to the digitized asset. Thus, market research is necessary before engaging in creating, issue and investing NFT tokens. Also, NFTs typically lack easy accessibility for users due to the nature of backend components and the lack of user-friendly interfaces.

With the help of blockchain technology, NFTs can be recorded in the blockchain, which establishes ownership. However, the marketplaces and platforms for creating genuine NFTs are still in some centralized authorities. If these centralized authorities and platforms stop working in any way, there is no promise that the end-user can still access the assets represented by NFTs [2]. This fact makes it less secure than real marketplaces. Also, current NFTs are not well regulated, and a high level of trust is necessary. For example, the represented assets must not have been duplicated elsewhere. Otherwise, it may risk a copyright issue. Furthermore, unlike fungible tokens, NFTs are not possible to create many tokens the right way, in which minting NFTs one by one is cumbersome and inefficient [45]. There also exist some risks in the process of approving transactions before the actual transactions can happen [17]. For example, suppose the ownership of a token is temporarily transferred out from its owner. In that case, this may pose some unexpected issues (e.g., modification on the token asset), and the security and the consistent status of blockchain may get compromised. In general, smart contracts can make token ownership transferring easy and efficient. However, different tokens on blockchain may adopt a different version of smart contracts, e.g., some earlier issued tokens may adopt an earlier version, and upgrading and updating existing smart contracts still bears many technical and operational risks.

Even the tokenization process enables new features to represent digital and physical assets digitally, there still exist many challenges and risks. Many of these risks can be enhanced by the terms/standardization of tokenization licenses and the platform's terms of service. However, the research of tokenization on the blockchain is still a developing area, and new issues and risks will continue to come up. Also, tokenization-based blockchain systems are not yet ready for a mass market for general use cases, demanding simplicity, user-friendly interfaces, and legal clarity. Furthermore, public knowledge about the tokenization process is still scarce. Nonetheless, tokenization on blockchain still has great potential to enable many more practical use cases.

5 POTENTIAL RESEARCH ON TOKENIZATION

The research for tokenization on the blockchain is still in its early stage, and there exist many challenges to facilitate the full tokenization on blockchain. By tokenization on the blockchain, we aim to achieve interoperable blockchain systems in which digital assets can be freely exchanged. This section presents some potential research efforts (rather than legal or market efforts) for tokenization on blockchain.

5.1 Interoperability

With the maturity of blockchain, more and more independent blockchains will come out for different applications (e.g., different digital assets), and both blockchain and tokens interoperability would become a fundamental issue that needs to be addressed. In general, tokenization will simplify the exchanging process of digital assets in the form of tokens. Blockchain interoperability would enable secure state information transitions across different blockchains, either homogeneous or heterogeneous, and create invaluable channels for connecting the decentralized Internet. Current researches on blockchain interoperability still concentrate on guaranteeing the ACID properties of atomic token exchanging process between blockchains (e.g., tokens from a source blockchain system to a target blockchain system) to remove the need for centralized exchanges [4] [35]. To establish an atomic process, the token transferring must take place in an autonomous and synchronized manner among the involved blockchains (mostly on crypto-currencies related blockchains). However, there is no universal interoperable protocol that works for any type of blockchain. Also, there is no efficient mechanism to fully replicate or duplicate the state and information of one blockchain to another, as different blockchains may have distinct meta-data [8]. An atomic swap is one technique that enables users of different blockchains to exchange their assets in an atomic and trustless manner [27] [58]. One of the most popular scenarios is the atomic token swap. However, atomic token swapping protocols [38] are not self-inclusive enough to complete tasks of cross-chain decentralized applications (*dApps*) because the "executable" components in those dApps may involve more complex activities (e.g., verifying against historical information) than pure token transfers. For example, the atomic swapping process typically cannot destroy a certain amount of assets (e.g., in the form of tokens) in the source blockchain and re-create the same amount of transferred tokens on the target blockchain [57]. In general, as its name implies, an atomic token swap offers only token exchanges rather than transfers. On the other hand, NFTs can help this atomic token swapping process change the ownership of assets since NFTs are a unique representation of digital assets. Thus, it suits well the token transferring process. Besides, this process always requires a counterparty (of another blockchain) who is willing to exchange these tokens [48].

5.2 Security and Privacy-preserving

When multiple blockchains work together, security and privacy are necessary considerations. In general, different blockchains may adopt different security primitives and token schemes to tokenize their digital assets, in which one security primitive is secure in one system but is not secure in another system. Security is still a major concern for the willingness to adopt token schemes among stakeholders. Therefore, it is highly recommended to develop security standards for scripting smart contracts and other blockchain primitives. Also, the privacy-preserving technologies in current blockchain systems are not robust enough. Ideally, privacy-preserving among distinct blockchain systems should be fully decentralized with the properties of obfuscation and anonymity by design [1]. Such solutions may need to consider different choices of blockchains, such as public blockchains or private blockchains. Also, most existing token schemes store data or assets off-chain and provide on-chain tags to link these assets. When storing data/assets into tokens, it requires to prevent the tokens from inaccessibility. For example, many NFT projects store a cryptographic hash as the identifier, instead of a copy of assets, into the tokens, which further are recorded on the blockchain. This may make the users suspect that NFTs might be lost, damaged, or even tampered with as the original asset. Even some distributed and decentralized storage schemes, such as IPFS [6] and StorJ [60], may help, however, relying on external storage is still vulnerable [59].

Privacy is crucial in any sensitive interaction (e.g., financial assets or health records) and thus in cross-chain communication. Practically, the data owner should have the ability to determine and observe what information and activities have been synchronized across blockchain networks [61]. However, in practice, different applications have different security primitives to guarantee secure operations, and it is hard, if not impossible, to make all applications adopt the same security primitive. When integrating them together, new data from an arbitrary process may go far beyond the outreach of any common security safeguard. This may make the data and services vulnerable. In the current stage, the research on anonymity and privacy of tokens is still understudied. And existing privacy-preserving technologies, such as zero-knowledge proof [23] and multi-party computation [44], have not been adopted to the tokenization schemes due to the complexity of these cryptographic primitives [59]. It requires a certain level of trade-off between privacy and public blockchains. For example, many researchers have demonstrated that privacy is not guaranteed. It is possible to make sure out of pseudonymous data on blockchains, as transparency and public access are key features of blockchains. Thus, security and privacy-assisted technologies are required to succeed in the tokenization on blockchain.

5.3 Usability

In general, usability is used to measure the users' effectiveness, efficiency, and satisfaction of designed schemes [59]. Current digital assets tokenization processes are closely coupled with their underlying blockchain platforms. As discussed earlier, many blockchain application scenarios require tokenizing their digital assets from finance to industry and economics. However, most existing assets tokenization solutions on the blockchain are still in theory (or some with prototype demonstration), and few have a real implementation. Even some of them have launched the ICO coin offering process; essentially, they are still crypto-coins, like Bitcoin. One reason for this is that the theoretical advances on blockchain tokenization have still not been agreed upon. Each organization may develop and deploy interoperable blockchain solutions based on its own requirements. For example, the most well-known ERC-20, ERC-721, and ERC-1155 are based on Ethereum, which does not fit other industrial use cases very well. This creates an isolated island and thus limits the achievement of theoretical efforts. Also, most existing token schemes are built on the Ethereum blockchain, which inevitably inherits the drawbacks of Ethereum. When considering tokenization on Ethereum blockchain, there exist two main challenges for usability, namely, slow confirmation and high transaction fee [59]. The underlying blockchain platforms typically have an extremely slow confirmation on the transactions (tokens if integrating tokenization system). Also, a high transaction fee involved by complex operations of blockchain will, in turn, limit the wide adoption of less valued tokens. A practical implementation needs to consider and evaluate different evaluation metrics, e.g., efforts to tokenization, cost, security, and privacy and would help speed up the development and deployment processes and the overall advancement of the blockchain tokenization process.

5.4 Standardization

There is currently no standard for establishing a compatible and universal token structure that suits most application platforms. Even though some standards are developed, they target specific application platforms (e.g., ERC-*xxx* for Ethereum), far from meeting the requirements of most existing industrial use cases. Without available standardization to regulate distinct digital assets, it is difficult or impossible to achieve a service agreement and thus an interoperable system on the integrated processes of blockchains. Moreover, each organization may develop incompatible standards among these partners. This further blocks the progress of tokenization on blockchain.

The current progress on digital assets tokenization is still in an early stage, and there is no simple agreements on what kinds of features or procedures should be included in tokens to formalize a de facto tokenization process on the blockchain, nor is there wide accepted agreement on how to create a reference architecture for tokenization on blockchain. Without it, independent developments would highly impact achieving the standardization process of tokenization on blockchain in the future. Two directions are possible to achieve standardization. The first is to publicly adhere to practices that have already gained widespread acceptance, known as industry or de facto standards [29]. The other direction is to create a platform (e.g., by international standards development organizations) to allow competing interests to interoperate in various jurisdictions. As these developments and implementations may have similar or overlapping functionalities by different organizations (or vendors), it is highly recommended to have some international organizations control these processes.

Tokenization on the blockchain is currently in its early stage, and many research efforts need to be done. It is no doubt that relying on a single party cannot resolve all the tokenization issues. Coordination between industry organizations and academic researchers is required to specify viable commercial solutions. Although many promising examples of tokenization efforts on blockchain systems are being achieved, most of these solutions are being carried out on and with specific blockchain platforms.

6 CONCLUSION

The research and progress of tokenization on the blockchain are still in their infancy stage. This paper presents a Systematization of Knowledge for existing efforts on these tokenization processes. According to fungibility, we classify existing tokens into three key categories: fungible tokens, non-fungible tokens, and semi-fungible tokens. For each type of token, we review and study the state-of-the-art solutions with detailed analysis. This paper serves as a starting point for exploring tokenization on blockchain. We discuss opportunities and challenges when tokenizing digital assets on the blockchain based on what we observed and learned. Finally, we present several potential research directions that can advance tokenization on blockchain.

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