INVITED PAPER *Special Section on Cryptography and Information Security*

Token Model and Interpretation Function for Blockchain-Based FinTech Applications

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SUMMARY Financial Technology (FinTech) is considered a taxonomy that describes a wide range of ICT (information and communications technology) associated with financial transactions and related operations. Improvement of service quality is the main issue addressed in this taxonomy, and there are a large number of emerging technologies including blockchain-based cryptocurrencies and smart contracts. Due to its innovative nature in accounting, blockchain can also be used in lots of other FinTech contexts where token models play an important role for financial engineering. This paper revisits some of the key concepts accumulated behind this trend, and shows a generalized understanding of the technology using an *adapted stochastic process*. With a focus on financial instruments using blockchain, research directions toward stable applications are identified with the help of a newly proposed stabilizer: *interpretation function* of token valuation. The idea of adapted stochastic process is essential for the stabilizer, too.

key words: *FinTech, timestamp, blockchain, cryptocurrency, adapted stochastic process*

1. Introduction

ICT has great impacts on the financial sector, and a wide range of such technologies form FinTech [24]. Among them, blockchain is attractive due to its innovative aspect in accounting: a record of consensus with a cryptographic audit trail maintained and publicly validated by multiple nodes in a distributed autonomous system [54]. The first half of this paper (Sects. 2 and 3) overviews key concepts that contribute to this trend of blockchain. Blockchain is implemented as a protocol suite, and many important details can only be found in mailing lists, forum posts, blogs, wikis, and source codes. As a result, scientific documentation of them resorts to tutorial papers. This paper's approach is a generalized description of secure timestamping. The second half of this paper (Sects. 4 and 5) points out research directions with a proposal toward stable FinTech applications.

2. Secure Timestamping

The mechanism of blockchain is described in the Bitcoin's white paper in 2008 [49] as follows: "*The network timestamps transactions by hashing them into an ongoing chain of hash-based proof-of-work, forming a record that cannot be changed without redoing the proof-of-work.*" In fact, the use of hash chains for accounting purposes was well studied in secure timestamping before the birth of blockchain.

2.1 Linking Schemes

In the seminal work of cryptographically secured timestamping in early 1990s [27], linear linking schemes were proposed. Let us consider a cryptographic hash function which handles an arbitrary-length input x to produce a fixed-length output (called the *hash value* of the input) $h(x)$ which satisfies the following two properties:

One-wayness: Given an output of the hash function, it is computationally hard to find an input which brings the given output.

Collision-freeness: It is computationally hard to find a pair of different inputs which bring the same output.

Then a simple variant of the linear linking schemes is a digital signature of a TTP (trusted third party) on a tuple $(n, t_n, \mathrm{ID}_n, y_n, L_n)$ where n is the serial number of submitted documents, t_n is the time information claimed in the timestamp of the n-th document, ID_n is the identifier of the submitter of the n-th document, y_n is the hash value $h(X_n)$ of the n-th document X_n, and L_n for $n \geq 1$ is the *linking information* defined by a recursive equation

$$L_n = (t_{n-1}, \mathrm{ID}_{n-1}, y_{n-1}, h(L_{n-1})) .$$

Their initial values for $n = 0$ are not clearly defined in the original paper but we may think of, for example,

$$L_0 = (t_0, \mathrm{ID}_0, X_0)$$

where X_0 is an opening declaration at time t_0 by the TTP whose ID is ID_0. Depending on implementation requirements, the index of the time information and the ID of the submitter do not have to be explicitly included in the linking information and the tuple to be signed by the TTP.

Let us suppose that the hash value of (the concatenation of all the components of)[*] the tuple is publicized through a medium (e.g. newspaper) which has a secure public archive[**] instead of requiring the signature of the TTP that can be a single point of compromise as well as a performance bottleneck. Thus we consider a less trusted entity called TSS (timestamping server) who handles submitted documents and publicizes the hash values through a medium. If the

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[*] Actual implementations may use a more complicated way of accommodating multiple input factors to a hash function.

[**] Major newspapers are archived in major libraries where we can assume integrity protection and public access.

medium is published too infrequently (e.g. at most twice a day in the case of newspaper), publicizing for just one document each time may not satisfy the demand of submitters. In order to solve this problem, we can repeatedly use a hash function and integrate the documents submitted during a period. For efficiency reasons, a tree structure (e.g. $h(h(h(X_1)\|h(X_2))\|h(h(X_3)\|h(X_4)))$) is better than a linear structure (e.g. $h(h(h(h(X_1)\|h(X_2))\|h(X_3))\|h(X_4)))$) for the integration.

Based on the above considerations, two-layered binary linking schemes were proposed in 1998 [12] where *two-layered* means *integrate-and-then-publicize* and the integrated hash value is used as y_n in the linking information. We will refer to the integrated hash value as a *root hash value*, and the hash value of the tuple as a *super root hash value*, in the following. The repeated use of a hash function in a tree structure was studied well for digital signature in 1980s [44], and the optimal structure for timestamping was explored around late 1990s and early 2000s [12], [36].

2.2 Generalization

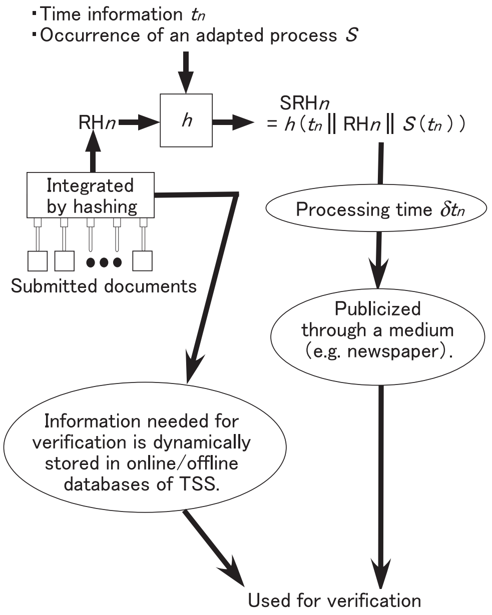
Secure timestamping is designed to ascertain whether a digital document was created at a certain *point* of time. Signing on or publicizing the hash value of a document X_n only implies that the document was created *before* t_n. By appending the linking information, we may try to claim that the timestamp was created *after* the linking information was computed. An ideal feature for this purpose can be captured by a stochastic process in finance. An *adapted stochastic process*, or an *adapted process* for short, (informally)[†] represents observable numerical values of a system randomly changing over time whose perfect prediction is impossible but whose realized values (called *occurrences*) are never changed. Examples include stock prices and exchange rates of currencies.

By using a process with such features, let us consider a generalized timestamping scheme described in Fig. 1 where the root hash value and the super root hash value of the n-th period are denoted by RH_n and SRH_n, respectively, and the processing time required for publicizing SRH_n is denoted by δt_n. One of the schemes in [12] can be viewed as an instantiation of this generalized scheme if we define a stochastic process $S(t)$ as follows.

$$S(t) = \begin{cases} h\left(S_0\left(t\right)\right) & (t < t_1 + \delta t_1) \\ \mathrm{SRH}_n & (t_n + \delta t_n \le t < t_{n+1} + \delta t_{n+1} \text{ for } n \ge 1) \end{cases}$$

where $S_0(t)$ is a popular process such as an exchange rate between particular major currencies. The workflow of this scheme can be summarized as follows.

Generation of a timestamp for documents submitted in the n-th period. Not documents but hash values of them are submitted if we need to do so due to privacy requirements or bandwidth restrictions.



・Time information t_n
・Occurrence of an adapted process S
h
RHn
SRHn
= h (t_n || RHn || S (t_n))
Integrated by hashing
Submitted documents
Processing time δt_n
Publicized through a medium (e.g. newspaper).
Information needed for verification is dynamically stored in online/offline databases of TSS.
Used for verification

Fig. 1 A generalized description of secure timestamping.

1. TSS integrates the submitted documents, and computes RH_n.
2. TSS derives $S(t_n)$ either from the public archive or from his database, and computes the super root hash value as
$$\mathrm{SRH}_n = h\left(t_n \| \mathrm{RH}_n \| S(t_n)\right).$$
3. TSS publicizes SRH_n through a medium.
4. TSS sends the following materials to each document submitter. If needed, his signature on the materials is appended.
   - SRH_n.
   - An appropriate subset of the intermediary hash values computed during the integration.
5. TSS updates his online/offline database. Typically, the online database stores recent records, and the offline database stores all of the past records composed of the submitted documents, the intermediary hash values, the root hash values, and the super root hash values.

Verification of the timestamp. If needed, the document submitters verify their timestamps on receiving the necessary materials from TSS.

1. A verifier computes RH_n by using the document of concern and the intermediary hash values either presented by the document submitter or obtained from the database of TSS.
2. The verifier derives $S(t_n)$ and SRH_n from the public archive(s).
3. The verifier checks if the following equation holds.
$$\mathrm{SRH}_n = h\left(t_n \| \mathrm{RH}_n \| S(t_n)\right)$$

[†] Readers may consult financial literature (e.g. [7]) for the formal definition.

2.3 Digital Publicizing

If we use a paper-based medium, the resolution of the timestamp has a serious limitation due to the infrequency of the publicizing. In order to alleviate this problem, the use of a digital medium such as digital-TV broadcasting was proposed in 2004 [48]. The resolution realized by a paper-based medium is insufficient for many of financial transactions. Higher resolution realized by digital publicizing is much better, and blockchain deploys a witness-based approach over the Internet for this purpose as well as for the purpose of achieving a more distributed mechanism of trust.

3. Blockchain

3.1 Protocol

As a design philosophy, blockchain does not have a TSS. Therefore, we expect that someone would not only witness the submitted documents but also compute the root hash values and super root hash values. In addition, the online/offline databases of TSS are replaced with replicated and shared ledgers maintained by distributed autonomous nodes. In order to realize such a distributed trust infrastructure, we need answers at least to the following five questions:

Question 1: How can we distribute submitted documents among those who may play the role of witnesses?
Question 2: How can a verifier obtain an authentic set of data required for the verification in a timely manner?
Question 3: Who stores the authentic set of data?
Question 4: How can document submitters know that their documents are correctly processed?
Question 5: How can we incentivize untrusted parties to witness the submitted documents?

Let us see the answers basically in the original setup for the Bitcoin-style blockchain. In doing so, we will gradually change terminologies of timestamping schemes into those of blockchain. First, we say *transactions* instead of documents since the primary application of blockchain is a cryptocurrency. Then the answers to Questions 1–4 are the development of a peer-to-peer communication network which has the following stakeholders.

Ledger nodes: Distributed autonomous parties who store the authentic data regarding past transactions as a form of an append-only database. The database is called a distributed ledger, and fully replicated at the ledger nodes. The set of data appended at the same time is called a *block*. A ledger node regularly checks whether recent updates are missing by communicating with other ledger nodes, and performs missing updates if necessary.
Transaction originators: Those who submit transactions by broadcasting them through a ledger node in the neighborhood.
Miners (block generators): Those who witness and integrate submitted transactions to generate a new block as an evidence. The transactions are received from a ledger node in the neighborhood.
Viewers: Those who view the ledger.

The communication protocols among the above stakeholders are well summarized (though not really detailed) in survey/tutorial papers such as [2], [10], [26], and [55]. Briefly speaking, they are best-effort protocols for broadcasting, synchronization, and trouble-shooting which are similar to what we can see in the Internet protocol suite.

Finally, the answer to Question 5 is a reward. This answer raises another set of questions:

Question 6: What is the reward?
Question 7: We should not allow any cheating regarding the reward. How can we secure the rewarding mechanism?
Question 8: Who will receive the reward if more than one miners do the work to receive it? That is, how can we determine the result of the competition among them?

The answer to Question 6 is simple: the reward is a certain amount of the cryptocurrency based on the blockchain itself. A miner originates a special transaction which will realize a reward, and integrates it together with the other transactions.

The answer to Questions 7 and 8 is the development of a *consensus protocol* where the Bitcoin implementation uses a *Proof-of-Work (PoW)* mechanism. In the PoW, an evidence of having done a cryptographic task is needed to achieve the reward. The idea of enforcing a carefully controlled or embedded workload on a client can be used to discourage attackers who try to flood a target resource. Security papers based on this idea were published in 1990s and early 2000s. Examples of such works include an anti-spam mechanism [21], plug-in or protocol countermeasures against Denial-of-Service (DoS) attacks [29], [30], and DoS-resistant key-agreement protocols [28], [39], [40]. The actual cryptographic task for the PoW in Bitcoin is a partial hash inversion used in Hashcash [3].

Figure 2 illustrates generation of a new block in the resultant blockchain mechanism. After receiving the submitted transactions in the n-th period, a miner verifies that each transaction is correctly formed, and integrates them to compute RH_n by using a hash function in a tree structure. The miner then tries to find a random number r_n called nonce which satisfies the following inequality:

$$\mathrm{SRH}_n \equiv h\left(t_n \| \mathrm{RH}_n \| S(t_n) \| r_n\right) < T \qquad (1)$$

where T is a *target value* of this task and controls its difficulty. In particular, for $n \geq 2$, the miner derives t_{n-1}, RH_{n-1}, $S(t_{n-1})$, and r_{n-1} from the ledger, and computes $S(t_n) = h\left(t_{n-1} \| \mathrm{RH}_{n-1} \| S(t_{n-1}) \| r_{n-1}\right)$. Then the miner randomly generates r_n, and checks if the inequality (1) is satisfied. If unsatisfied, the miner randomly generates r_n again, and repeats the same until the inequality (1) is satisfied.

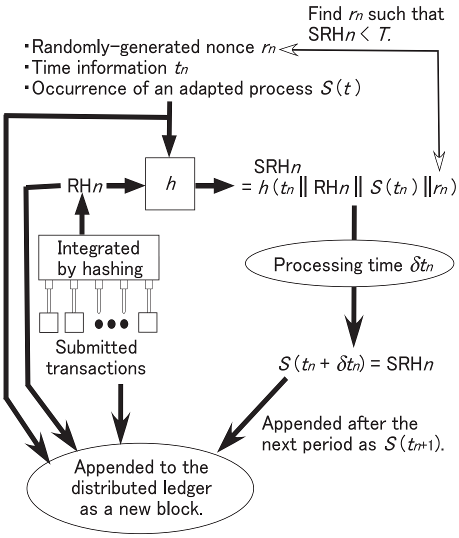

Find r_n such that SRHn < T.
・Randomly–generated nonce r_n
・Time information t_n
・Occurrence of an adapted process $S(t)$
RHn
h
SRHn = $h(t_n \| \mathrm{RH}n \| S(t_n) \| r_n)$
Integrated by hashing
Submitted transactions
Processing time δt_n
$S(t_n + \delta t_n)$ = SRHn
Appended after the next period as $S(t_{n+1})$.
Appended to the distributed ledger as a new block.

Fig. 2 Generation of a new block in blockchain.

A simple way of controlling the difficulty of the task is to change the target value. The change needs an additional protocol by which all of the participating nodes are notified. Variants of finer controls include a mechanism which allows different miners use different target values depending on their past achievements, present stakes, and so on [6]. Such variants contribute to finer control of incentives as well. If the flexible target values can be determined by the information included in the ledger, the notification protocol can be easier because stakeholders often view the ledger anyway.

Now that the nonce is successfully found, the miner broadcasts a request to achieve the reward through a ledger node in the neighborhood. The request includes a tuple $(t_n, \mathrm{RH}_n, S(t_n), r_n)$ and the pointers which identify the transactions and their order used to compute RH_n.

On receiving a new request, a ledger node verifies its validity; RH_n and $S(t_n)$ must be consistent with the past blocks and the transactions in the current period, the internal verification items (e.g. the transaction originator's signature) of each transaction must be valid, and the nonce r_n must satisfy the inequality (1). If everything is valid, the ledger node forwards the request to other ledger nodes. Once a certain quorum of the ledger nodes agree to accept the request, the new block is appended. This means that a certain amount of processing time (denoted by δt_n in Fig. 2) is needed for finalizing the consensus. If the request comes from different miners, the winner is determined based on a rule (for example, the miner that processed the largest number of transactions will win). The change of $S(t)$ is the same as that in the secure timestamping scheme.

3.2 Transaction

A transaction in the Bitcoin-style blockchain contains an array of *inputs* and an array of *outputs*, as well as other operational information such as version number and *locktime*. The locktime indicates the block number or timestamp at which the transaction is locked. The entire transaction is hashed, and the resultant hash value serves as its globally unique transaction ID.

Suppose that Alice is originating a transaction TX_A by which she wishes to spend her coins C_j whose amount is c_j $(j = 1, 2, \cdots, m)$. Suppose that Bob is going to receive a coin whose amount is c_0 by TX_A[†]. Those amounts must satisfy the following:

$$\delta c \equiv \sum_{j=1}^{m} c_j - c_0 \geq 0. \tag{2}$$

If unsatisfied, TX_A will be rejected; in other words, miners and ledger nodes check if the condition (2) is satisfied. If $\delta c > 0$, then Alice can pay this amount to herself as a *change*. The change is embedded as one of the outputs in the current transaction TX_A itself.

Each input tells which coin is going to be spent by TX_A, and each coin is identified by

(i) the ID (i.e. hash value) of the past transaction which brought the coin to Alice as an output, and
(ii) the hash value of her public key used as one of the recipients' addresses[††] in the past transaction.

In order to avoid being spent by someone else, each transaction is signed by Alice.

Each output tells who is going to receive a coin, and how much. The recipient, Bob, is identified by an address defined as the hash value of his public key. In addition, an output has some *scripts* which can define a wide variety of operations associated with the transaction. The scripts enable us to design a *smart contract*; based on the idea of forming a protocol suite including cryptographic protocols, a smart contract was proposed in 1997 as a cryptographically enforceable agreement of a formalized workflow [53], and blockchain is a realization of this concept. The components of a smart-contract transaction may include multiple numeric values with different financial implications (e.g. unit price regarding a fee paid to a miner, amount of currency transferred by the transaction, and so on).

The construction of transactions is well summarized in papers on *wallets* (e.g. [4]). A wallet is a module by which a stakeholder (in the above example, Bob) receives a coin, consisting at least of a public/private key pair.

3.3 FinTech Applications

With the help of scripts in outputs, blockchain can be used to implement a wide variety of applications as well as cryptocurrencies [57]. In fact, based on a comprehensive survey of more than 200 blockchain startups and projects, at least seven classes of applications are recognized [22]. An updated description of the seven classes is as follows.

[†] Although this example considers just one recipient, multiple recipients can be accommodated in a single transaction.

[††] The idea of using a public key as a privacy-preserving address or digital pseudonym can be found in a paper in 1981 [14].

Underlying infrastructure: Underlying protocols, decentralized application ecosystems, IoT architecture, and so on (e.g. Ethereum, [11], [15], and [31]).

Currency: Payment services, internal currencies, utility tokens, and so on (e.g. Bitcoin and [45]).

Financial services: Asset management, investment trading, crowdfunding, and so on (e.g. [47]).

Proof-as-a-service: Notaries, registers and attestation, supply-chain management, credit management, and so on (e.g. [16], [56])

Property and ownership: Digital rights management, copyright and ticketing services, and so on (e.g. [32]).

Identity management: Self-sovereign digital identity, authentication, and so on (e.g. [20]).

Distributed Governance: Voting services, distributed autonomous organizations, coordinated human interaction, and so on (e.g. [33]).

Currencies and financial services are clearly FinTech applications. However, since fees can be embedded in a transaction, the other five classes also have an aspect of FinTech.

4. Token Models

The structure of a transaction is the key for the design of blockchain applications. Although there is no rigorous definition, each transaction output can be called a token [10], [22]. A complication of blockchain is the fact that each transaction can have multiple inputs and multiple outputs which share several components such as locktime and that each input/output intuitively represents a different coin.

In this paper, in order to have a better fit for financial engineering, a token corresponding to a transaction output is modeled by extracting and interpreting some information from the block where the transaction is integrated. This idea comes from a security token model studied in early 2000s [41]–[43] which considered a cryptographically secured and timestamped token with contents.

4.1 Security Token

In order to model not only purely financial digital materials but also general digital commodities, a security token was originally defined as follows [41].

Definition 1 (Setok): A *security token* or *setok* is a digital material which contains the following attributes:

- *contents* which may include MAC (Message Authentication Code), digital signatures, or other security-related control sequences if necessary,
- a non-negative *explicit price* (denoted by $\bar{S}$) which is paid when the setok is purchased,
- a set of non-negative *explicit values* (denoted by $\bar{V}_1$, $\bar{V}_2$, $\cdots$, $\bar{V}_m$ where m is referred to as the *dimension* of the explicit values) which represent some qualities of the contents in a way that larger values of each element imply better qualities regarding the feature represented by the element when the setok is purchased, and
- a *timestamp* which indicates when the setok is purchased,

and is associated with

- a non-negative *implicit price* (denoted by S) and
- a set of non-negative *implicit values* (denoted by V_1, V_2, $\cdots$, V_n where n is referred to as the *dimension* of the implicit values)

in the following way.

- The explicit price is specified as the occurrence of a *price-interpretation process* $Y(t)=y\ (t, S\ (t))$ at time $t = t_0$. Each occurrence of the price-interpretation process is called the *up-to-date price* at time t. The price-interpretation process is a non-negative process and also called the *up-to-date price process*. $y(t, s)$ is called a *price-interpretation function* and monotone increasing with respect to s.
- The explicit values are specified as the occurrences of *value-interpretation processes* $H_1(t)=h_1(t,\ V_1(t),\ V_2(t), \cdots, V_n(t))$, $H_2(t)=h_2(t, V_1(t), V_2(t), \cdots, V_n(t))$, $\cdots$, $H_m(t)=h_m(t,\ V_1(t),\ V_2(t),\ \cdots,\ V_n(t))$ at time $t = t_0$. Each occurrence $h_i(t, V_1(t), V_2(t), \cdots, V_n(t))$ is called the i-th *up-to-date value* at time t. The value-interpretation processes are non-negative processes, and also called the *up-to-date value processes*. $h_1(t, v_1, v_2, \cdots, v_n)$, $h_2(t, v_1, v_2, \cdots, v_n)$, $\cdots$, $h_m(t, v_1, v_2, \cdots, v_n)$ are called *value-interpretation functions*.

The price-interpretation function models the effects of taxes, transaction costs, regulation, and so on. The value-interpretation functions model the effects of security policies, regulation, editorial policies, transmission delay, evaluation of stakeholders (e.g. firms), and so on. The "up-to-date" processes, $Y(t)$ and $H_i(t)$ $(i = 1, 2, \cdots, m)$, are observable in the market and hence are adapted processes. Implicit processes often remind us of the world behind, whereas interpretation/up-to-date processes often remind us of the market.

The explicit values represent qualities of a setok, and depend on the implicit values. The bridge between them is the value-interpretation functions. Changes in the implicit values may be relaxed/exaggerated by interpretation.

The subsequent frameworks of setok include the definitions of refundability, tradability, online divisibility, and offline divisibility. Their applications include pricing theories regarding financial derivatives written on a setok. The pricing theories can help risk management because we can estimate risk parameters (e.g. probability of compromise) by solving inverse problems where the risk parameters are included in a pricing formula as independent variables.

4.2 Token Model for Blockchain

Inspired by the setok framework, I propose the following token model for blockchain-based Fintech applications. An implementation will be suggested in 5.2.

Definition 2 (Blockchain Token): Consider a transaction output TXO_A in a transaction TX_A originated by Alice. Let BLC_M be the block where TX_A is integrated by a miner M. A *blockchain token* corresponding to TXO_A is a token composed of the following attributes:

- *contents* which contains the scripts of TXO_A and the ID of TX_A[†],
- a non-negative *explicit price* (denoted by $\bar{S}$) which is the amount of the coin written in TXO_A,
- a non-negative *explicit value* (denoted by $\bar{V}$) which represents a quality (e.g. exchange rate to a popular fiat currency agreed over the blockchain network) of the coin, and
- a *timestamp* T_M which is indicated by the locktime of the youngest transaction in BLC_M,

and is associated with

- a set of non-negative *implicit values* (denoted by V_1, V_2, $\cdots$, V_n where n is the number of the transactions in BLC_M)

in the following way.

- Each implicit value V_j is the j-th transaction itself. The explicit value is the occurrence of a non-negative *value-interpretation process* $H_M(t){=}h_M(t, V_1, V_2, \cdots, V_n)$ at time $t = T_M$ where $h_M(t, v_1, v_2, \cdots, v_n)$ is called an *interpretation function* of values.

The interpretation function of values models the effects of implications of scripts (e.g. significance of the output, local exchange rate to a popular fiat currency, and so on), regulation, transmission delay, evaluation of stakeholders, valuation by stakeholders, and so on. Each implicit value reflects the local world where the corresponding transaction originator is active, whereas the interpretation process reflects a more global world realized by the blockchain network.

5. Research Directions

Academic researches of blockchain are still in their infancy, and hence there are so many immature research items. Rather than showing exhaustive list of such items, this section is focused on two research directions which are important particularly from the viewpoint of FinTech. Therefore, some major research items (e.g. scalability [37] and Sybil attacks [55]) are lacking here.

5.1 Empirical Analysis

In the economics of information security [1], it is usually hard to find rich empirical data for rigorous analysis. However, in principle, there is a full record of all public transactions in the history of Bitcoin. In addition, freely available datasets include the followings:

- Bitcoin price index (exchange rate between the US dollar and the Bitcoin).
- Total Bitcoins in circulation.
- Number of transactions excluding exchange transactions.
- Estimated output volume.
- Ratio of trade volume to transaction volume.
- Difficulty of the PoW.

This situation suggests that there is a good chance of realizing deep empirical economic analyses regarding Bitcoin and possibly many of other alternative currencies (altcoins) which resemble Bitcoin; in fact, there have been published a lot of literature that show empirical analyses by using such rich datasets (e.g. [25], [34], [46]).

In blockchain, any stakeholder may misbehave. Double-spending attacks are by transaction originators, and malleability attacks are by recipients [18]. In addition, miners should be carefully marked since they may exploit the competition settlement mechanism in the consensus protocol and eventually replace an existing candidate of a new block (possibly created by themselves) with their selfish request [5]. Such malicious behaviors of miners imply that there is something fundamentally broken in the protocol's incentive structure [51], and empirical data can help us evaluate the effects of countermeasures.

5.2 Financial Engineering

Bitcoin's dollar value has been showing an extremely high volatility since its early years [59], which is considered one of the weakness origins of an ecosystem [58]. Volatility is a fluctuation measure of financial securities, and traditionally, it is shown that introducing financial derivatives can reduce the volatility of their underlying asset by promoting information dissemination and collection [13], [17], [19], [35]. In this regard, it is worth considering derivatives written on cryptocurrencies.

However, recent research trends include blockchain-based implementation of common derivatives [8], and the current state of the art is to tackle technical developments. We will next face financial risk management problems even after solving such development problems. In fact, a recent paper of financial derivatives using blockchain [23] mentions the followings:

- "*In a derivative where settlement is fully automated, either the underlying security (or a token representing it) needs to be on the blockchain already or the blockchain needs to be able to assign a value to the security.*"
- "*For derivatives on cryptocurrencies or more esoteric securities, models simply do not exist yet and are an open area of research.*"

The first sentence points out the necessity of a comprehensive marketplace based on blockchain, and there is a

[†] By using the transaction ID, one can read TX_A including the signature of Alice from the ledger.

view that its possibility is very likely [52]. Thus research efforts can be shared by those who have concerns about instability of cryptocurrencies and those who are interested in a decentralized e-marketplace of complex financial contracts.

The second sentence is included in a paragraph which states that the Nobel-awarded Black-Scholes model [9] had been influential in traditional markets with respect to financial risk management. The Black-Scholes model is based on stochastic theories using adapted processes. The setok framework [41]–[43] can be considered a corresponding model for an e-marketplace of digital commodities where we can assume adapted processes. The token model proposed in 4.2 may help thus upcoming research trends of financial engineering if the interpretation function is implemented in a way that the value-interpretation process can be regarded as an adapted process. Here is an example of starting points toward this direction.

Suppose that underlying cryptocurrencies may have very different exchange rates at different places. This situation may make it hard to use validation by a single stakeholder for stability and reliability reasons. In order to solve this problem, let us consider the following implementation of the interpretation function.

1. Transaction originators append their valuation of the token value to their transactions. Let u_j be the valuation result by the j-th originator ($j = 1, 2, \cdots, n$).
2. A miner uses u_1, u_2, $\cdots$, u_n as main inputs to the interpretation function of values. It may simply take the average. It may consider a weighted average based on other information such as scripts and locktime. The resultant explicit value is appended to the block. In this implementation, we use an interpretation function which does not depend on the miner. Therefore, in the following, the value-interpretation process is denoted not by $H_M(t)$ but by $H(t)$.
3. In the consensus protocol, the ledger nodes agree to the explicit value as well. The explicit value is recorded at the ledger.

$H(t)$ can be used in the design of financial derivatives. If the consensus algorithm is nicely implemented and $H(t)$ can be regarded as an adapted process, then theoretical studies on financial derivatives may become easier.

6. Conclusion

This paper overviewed an academic pedigree of blockchain where most of its technical components including secure timestamping schemes originated from the academic literature well before the Bitcoin's white paper. Nevertheless, as pointed out in [50], the system design of the Bitcoin's blockchain is more innovative than one might think. By using an adapted stochastic process to generalize the timestamping schemes, the potential of blockchain as a digital evidence technology can be more clearly recognized. This recognition helps us consider research directions toward more stable FinTech applications, and this paper proposed a blockchain token model as an example of starting points.

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