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A systematic framework to understand central bank digital currency

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Abstract The ongoing research and development of digital fiat currency (DFC) have triggered attention of policy makers, regulators and the industrial and academic communities. But there is not yet a clear idea and blueprint of what DFC looks like. This paper establishes a systematic framework to analyze the essence and connotation of DFC from four dimensions: currency value, technical aspects, means of implementation and application scenarios. It is argued that DFC is a credit-based currency in terms of value, a crypto-currency from a technical perspective, an algorithm-based currency in terms of implementation and a smart currency in application scenarios. Compared with existing private digital currencies and electronic currencies, DFC will be equipped with brand new and higher qualities. The goal of Chinese DFC is to contribute to more stable value, more secure data, more powerful regulation, stronger empowerment of individuals in payment activities and smarter application. Chinese DFC should have qualities that enable it to provide better service for the public, to offer effective tools for macroeconomic control and to lay a solid foundation for RegTech development.

Keywords digital fiat currency, credit-based currency, crypto-currency, algorithm-based currency, smart currency, central bank digital currency

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1 Introduction

In recent years, digital currency has become a hotspot because of its rapid development. In particular, R&D of digital fiat currency (DFC) has triggered interest among policy makers, regulators, the industrial community and the academia. Currently, central banks around the world pay more attention to the application of distributed ledger technology (DLT) in real-time gross settlement (RTGS) for wholesale market. There is not yet a clear idea and blueprint of what exactly a DFC should look like.

In 2015, DFC was defined by the Committee on Payments and Market Infrastructures (CPMI) [1] as crypto-currency. Zhou [2] proposed in 2016 that DFC could be either account-based or non-account-based. After Broadbent [3] came up with the idea of central bank digital currency (CBDC), Fan [4] argued that CBDC fell into the category of cash (M0). Furthermore, Yao put forward the concepts of account-based digital currency and wallet-based digital currency [5], and proposed a design in which bank account and DFC wallet coexisted in different layers [6] to integrate DFC into the traditional "central bank-commercial bank" binary system so as to reuse the existing mature financial infrastructures and to

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avoid the consequence of narrow banking. Similarly, Koning [7] distinguished from CBDC the concept of central bank digital account (CBDA) that was based on central bank account. Bordo and Levin [8] classified DFC into CBDC accounts and CBDC tokens. Bech and Garratt [9] came up with the idea of central bank crypto-currencies (CBCCs) and analyzed CBCCs' characteristics from four perspectives, namely the issuer (central bank or other), currency form (electronic or physical), scope of circulation (universal or limited) and circulation mechanism (centralized or decentralized).

The concepts and definitions of DFC mentioned above bear both similarities and slight differences. To figure out what DFC looks like, we have to be more imaginative and visionary because it is indeed an unprecedented thing. Unlike previous research, this paper tries to establish a systematic framework to analyze the essence and connotation of DFC from four new dimensions, namely currency value, technical aspects, means of implementation and application scenarios. This paper argues that DFC is a credit-based currency in terms of currency value, a crypto-currency from a technical perspective, an algorithm-based currency in terms of implementation and a smart currency in application scenarios. The ideal DFC should have a set of brand new qualities that enable it to excel over existing private digital currencies and electronic currencies.

2 DFC is credit-based currency in terms of value

DFC is a form of currency that is issued by central bank and delivered with specific digital crypto-technologies. It is presented in a different technical form but contains the same intrinsic value as physical fiat currency. By its nature, DFC is still central bank's liability against the public with its value supported by sovereign credit, which gives it two unconquerable advantages over private digital currencies.

First, DFC has anchor of value that enables it to perform functions of money effectively. Compared to the function of medium of exchange, unit of account is a more fundamental function of money, which means that stability of value is of critical importance. This is even truer when it comes to the function of store of value. Value anchor is important for money to perform its functions effectively.

If we look back in time, we will find that all currencies have anchor of value regardless of the forms they take. Commodity currency and metal currency had their value anchored to the intrinsic value of the physical objects that they were carried with. Under the gold standard, fiat money of all countries took gold as anchor of value. After the collapse of the Bretton Woods system, fiat currency was no longer pegged to gold but instead had its value supported by sovereign credit, a form of highest trust that continued to remain in the age of DFC.

But if we look at Bitcoin, a decentralized quasi-private digital currency, we have to ask the question where does its value come from? Does it come from the almost utopian affection of the liberals who advocate for the "non-nationalized" issuance of currency? Does it come from the computing resources used to support the mining activity? Does it come from the expectation of the market toward blockchain technology in the future? Or does it come from the temptation of speculative returns in the short run? Based on current situation, it seems that speculation plays a bigger role. From the perspective of public economics, Bitcoin and other private quasi-digital currencies cannot provide public products such as "payment service" and "accounting unit value stabilization service", nor do they offer significantly lower transactions charges. These defects make it difficult for Bitcoin to become real currency [10].

Second, DFC can play a part in credit creation and has real economic impact. In the age of non-credit-based currency, to the public money is meaningless. Classical economists such as David Ricardo, Carl Menger and Léon Walras tend to argue that non-credit-based currencies, such as commodity currency and metal currency, are economically neutral and have no real impact on economy except for causing price fluctuation.

However, in the age of credit-based-currency, money itself represents credit as it is by nature the securitization of the credit of currency issuer, and therefore the creation of money comes with the creation of credit. Keynesians, the Monetarists, the believers of the rational expectation theory and the financial accelerator principle have argued for the key role of currency in economy by elaborating from various

perspectives on the non-neutrality of money in terms of micro and macro mechanisms.

Facts tend to suggest that credit creation is critical to modern economy, in particular actions such as liquidity assistance during financial crisis contribute greatly to preventing risk contagion and promoting economic recovery. After the eruption of financial crisis in 2008, the Fed invented multiple liquidity instruments and reached out to not only commercial banks but also non-banking financial institutions, financial market and enterprises, which helped to prevent the crisis from spreading and deteriorating. This is the key to make the United States one of the first countries recovering from the crisis.

The emergence of centralized entity from a totally free market is the result of market evolution. Yet it is a sarcasm that the market fundamentalists who live by the principle of free market refuse to accept the choice of the market. The production of Bitcoin, according to its algorithm, is reduced by half every four years with a ceiling of 21 million. This is actually a throwback to the time of commodity currency and metal currency that only help to address the inconveniences of barter without having any real impact on economy. In the current credit-based economy that is becoming increasingly complex, to use Bitcoin as currency would definitely be disastrous.

In addition to the above-mentioned advantages, DFC has another merit to make the value of fiat money more stable.

Fiat money, with its value supported by sovereign credit, is viewed differently by different groups of people. Some believe that fiat money is backed by utmost trust and some argue that it is just a tool for redistribution of interests. For example, the liberals advocate to abolish the monopolistic power of government as the sole currency issuer and to have free issuance of currency and full competition as they believe that government always has motivation to monetize its budget deficit, an action that may easily lead to inflation. Moreover, the 2% inflation target usually set by central banks in monetary policies is often interpreted as a tendency to inflation.

The first problem can be addressed by enhancing central bank's independence as in the case of countries with well-established governance mechanisms that help to contain monetization of deficits. As for the second problem, solutions can be found in DFC to make the 2% inflation target no longer necessary. In a DFC environment where negative effective interest rate is possible, central banks may not need the 2% buffer anymore and theoretically can lower the inflation target to 0%. From this perspective, DFC may help to stabilize the value of fiat money.

3 DFC is crypto-currency from technical perspective

DFC is the cornerstone of the development of digital economy. Digital economy in the future will definitely be an encrypted digital economy rather than a plaintext digital economy. In this regard, DFC should be crypto-currency from a technical perspective. Cryptographic technology is the key to the technical security and credibility of DFC.

To be specific, cryptography should be used in the design of DFC presentation format to ensure that it can be circulated and stored and cannot be forged, double-spent or repudiated. The transaction of DFC requires the use of cryptography, DLT, trusted cloud computing and secure element (SE) to ensure peer-to-peer security in order to prevent the DFC from being stolen, tampered or imitated [11]. In terms of DFC user experience, while peer-to-peer payment service different from traditional electronic payment is provided to users, privacy protection technology and DLT should be integrated to ensure safety of user data and to prevent leakage of sensitive information without compromising usability. In terms of DFC regulation, since DFC adopts the mechanism of "voluntary anonymity at front-end and real-name at back-end", security and privacy protection technologies can be used to manage data access, so as to make best use of RegTech such as big data analysis [12].

Theoretical innovation and practice of crypto-currency have burgeoned in recent decades with relevant theories becoming increasing mature. Chaum [13] was the first to propose an anonymous and untraceable e-cash system. Dai [14] presented an anonymous distributed e-cash system called B-money, and Jakobsson and Juels [15] brought up the concept of POW. Szabo [16] invented Bit-Gold. In 2008, Nakamoto [17]

published the classic paper of Bitcoin: a peer-to-peer electronic cash system where he proposed a decentralized e-cash system completely based on peer-to-peer technology. In fact, the DLT adopted by Bitcoin was an integration of the latest achievements of various crypto-technologies at that time.

The digital currency sector abounds with practical achievements. Ever since Bitcoin, alternative crypto-currencies have emerged one after another. By 2016, there have been all together more than 600 types of digital currencies. Those crypto-currencies have evolved based on Bitcoin by making further use of crypto-technologies, and many of those attempts have made impressive academic innovation.

The theoretical and practical achievements of crypto-currency have provided insights for exploration on DFC. At present, a number of central banks are experimenting on CBDC based on DLT such as Project Jasper of the Bank of Canada [18], Project Ubin of Monetary Authority of Singapore [19] and Lionrock of Hong Kong Monetary Authority [20]. The project Stella jointly initiated by ECB and Bank of Japan is focused on whether DLT has the potential to replace RTGS [21], which is still a conclusion too early to draw for the time being. Digital currency should be "untied" from blockchain technology [22]. It is important that the DFC makes flexible adoption of blockchain technology based on actual business demands. In this regard, the RSCoin initiated by Danezis and Meiklejohn [23] may serve as a valuable reference as it aims to implement, from a central bank's perspective, an extendable digital crypto-currency that is controlled by central bank and is not limited to blockchain technology [24].

It is significant when Koning [7] singles out two most important concepts, namely account and currency. If we look at their evolution paths, we will find that the issuance of CBDC is a process of moving from account to central bank token while the development of crypto-currency is a movement from token to account, marked by the emergence of private blockchain and consortium blockchain after public chain. In this sense, account, currency and token are actually intertwined with each other. Therefore, it may be prudent for central banks to pursue a path of CBDA+CBDC+CBCC for DFC issuance.

Speaking of token, one has to talk about tokenization, for example payment tokenization. As a technology put forward by EMVCo in 2014, payment tokenization replaces bank card number and valid date with identifiers, which prevents leakage of sensitive information once for all and lowers the possibility of fraud. It also applies domain control to put restrictions on transaction scenarios, such as transaction type, times of use, trading volume, valid date, payment channel, merchant name, so as to make payment more secure. To explore the representation method of Chinese DFC, it is definitely necessary to further study on the basic mathematic model of digital currency (including properties, issuer, owner, user permission, scope of use, digital signature, encryption, anti-counterfeit) and to build the identification and description models [12]. The balanced approach adopted by payment tokenization to ensure convenience, privacy and security as well as the design of domain control are something that we should draw upon when working on DFC.

As trusted cloud computing, secure element and privacy protection technologies are becoming mature, a user-centered administration of crypto-currency can be realized, which will cut intermediary links in currency operation. In this way, central banks are able to reach out to end users, offering a new way for economic control.

4 DFC is algorithm-based currency in terms of implementation

In real business, DFC is an algorithm-based currency. This is interpreted as follows. First, various encryption algorithms are applied in the design of DFC to ensure security and credibility (such as Hash functions, Fitzer algorithm, blind signature, ring signature) while special fields are also reserved for possible new algorithms in the future. Second, in terms of currency issuance, DFC design fully considers the executable script in a way that allows its issuance to be based on pre-installed and credible algorithm in the future. Speaking of issuance algorithm, it is natural that one thinks of Bitcoin's POW mechanism. The issuance of Bitcoin, which is based on "mining" algorithm, is bundled with transaction fees, compromising the flexibility of the issuance mechanism and making it unable to meet the demand of macroeconomic control. The algorithm supporting DFC issuance should be a set of smart rules that enable money supply

to fully adapt to the multi-variable environment of macro-economy under the prerequisite of maintaining stable currency value. Based on current technologies, this might be realized with a sophisticated AI model based on machine learning algorithms. Third, big data technology can be applied to conduct in-depth analysis of the issuance, circulation and storage of currency and to understand currency operation so as to provide data support for monetary policy, macro-prudential regulation and financial stability analysis.

Monetary economists have long engaged in extensive and in-depth studies on monetary policies and rules, trying to provide central banks with theoretical guidance on money supply. Various theories emerged, such as the Taylor rule, the Friedman rule and the monetarist ideas of the Chicago School of Economics, have gone beyond qualitative research to quantitative studies on methodology and have explored through econometrics and experimental economics to supply central banks with tools to understand modern economy. In this sense, the currency issuance models built by those economists can be regarded as preliminary AI models.

Yet it is a regret that these AI models end up playing a mere supportive role to central bank decision-making and have not been able to optimize and evolve based on merits of massive machine learning due to limitations of data collection, storage and computing. For example, model learning tends to be lack of knowledge, over parameterized and bear large error in forecast because the data is of limited dimension, low frequency and long time-lag. Due to limited computing capacity, it is difficult for a model to traverse all the possible policies, which leads to unitary logic for decision-making, making it hard to reach optimal solution. This means that money issuance of central bank is, at present stage, largely subject to the judgments of experts that are closely related to their knowledge, vision and experience. Contributions of these experts are undeniable, but it is inevitable for human brains to make errors or even faults. This is also one of the many defects of monetary policy-making in modern times.

Currently, data on currency operation is usually built with posterior statistics and estimates, resulting in huge uncertainties to currency circulation. This means that there is yet no effective tool to monitor how much money is traded or circulated after issuance, or what scenario it is applied to, or what is the velocity of circulation. It is no wonder that officials of some central banks joke that answers to these questions are hidden in a black box.

This can all change with the emergence of digital currency. In particular for DFC, the creation and book-keeping of DFC are conducted by the central bank or consortiums established by the central bank. The central bank is the creator and issuer of currency. The core nodes are book-keepers. And the ordinary nodes are economic entities using digital currency to make transactions. In this system, the central bank has the highest decision-making authority and operational access. As a result, big data analysis can play a bigger role when it is applied to desensitized data.

The design of DFC system should, from its very beginning, pay great attention to big data-related top-level design and relevant infrastructure within the legal boundary. In terms of system design, highlight should be given to the robustness and extensibility of big data infrastructure. Based on the classification of data layer, APIs, service layer and application layer, it is important to ensure that data collection, analysis model and APIs are secure, flexible and open to certain degree. In terms of time domain, key data of the entire lifecycle of digital currency should be extracted covering the issuance, circulation, exchange, storage and retrieval of currency, so as to lay a foundation for model building, emulation, analysis and adjustment. In terms of space domain, it is important to build up a cloud chart for DFC operation and distribution that clearly shows the size, location and time of DFC with space label, so as to facilitate understanding of key areas of DFC operation and issuance and to make policy implementation more targeted.

It is essential for central banks to select effective DFC analysis indicators and to measure key aggregate indicators and price signal indicators from the perspectives of observability, controllability, relevance and stability, and to emulate and analyze the influence of indicators of DFC control instruments, which will benefit the design and implementation of monetary policy [25].

Currently, various technologies are developing rapidly as Moore's Law dictates. With the sustained growth of data collection technologies such as automatic search, web crawler, automatic classification, the burgeoning of data capture tools such as sensors, information identification and biometrics, the increasing

computing and storage capacity of HPC and the evolution of ICT, is it possible to apply machine learning algorithm and AI technologies to monetary policy on a big data basis and to try to develop cutting-edge AI models for currency issuance? The answer is yes. We have started the studies on AI model and learning algorithm for DFC issuance and have come up with a specific yet tentative framework that includes model design and learning algorithm. The model has been applied to the scenario of money supply in forex market on a preliminary basis. Results suggest that the overall effect is satisfactory despite some identification errors.

In short, it is possible in the future that in a DFC context the economy may be able to, under the prerequisite of maintaining currency value stable, make endogenous decisions on money supply on its own and realize automatic issuance and retrieval of currency based on algorithms that are pre-installed and credible. In this case, central banks may serve as not only the decision-maker of money supply but also the designer of algorithms and rules.

5 DFC is smart currency in application scenarios

DFC is not merely about digitalizing currency and moving it onto a network. What's more important is that it makes money smarter. Compared with conventional electronic payment instruments such as credit cards, debit cards, Alipay and WeChat payment, DFC will have brand new and higher qualities.

First, to make user experience smarter. Currently, smart technologies are changing people's life rapidly. The incorporation of artificial intelligence unit into mobile chip has become mainstream business. A smarter hardware of the end user will interact with various smart software to create a totally new intelligent world. And this smart world would require smart currency. Smart contracts can be executed in an automatic and credible way that provides technical solutions to lowering risks of contract default and credit default, which is a direction for DFC development in the future.

In his studies on the application of digital currency in interbank cash transfer, Yao [26] found that the functionality of conditional payment embedded in DFC smart contract could address the trust issue among counterparties and facilitate the synchronization between flow of funds and flow of transactions. Xu and Yao [27] explored a digital commercial paper trading platform based on blockchain technology and designed a liquidity saving mechanism (LSM) managed by smart contracts based on DFC's functionalities of clearing and settlement. The results showed that the adoption of DFC greatly simplified transaction of commercial papers.

Moreover, decentralized peer-to-peer payment will offer fresh user experience that greatly enhances users' initiative on payment and enable more smart functionalities to derive from the payment functionality, resulting in the creation of various commercial applications that are increasingly intelligent.

At present, a number of countries are giving more thoughts on building a super central bank or adopting CBDA, which is very much like setting up a super Alipay. In China, private payment instruments such as Alipay and WeChat payment are already sophisticated. Terms like "cashless society" and "cashless city" emerge frequently. Recent talks on whether monetary market funds are responsible for higher financing costs have not yet reached any conclusion. The development of private payment instruments and their increasingly monopolistic power will definitely force regulators to take actions, and commercial banks will also have to think about the meaning of narrow banking and the possibility of retreating to the role as money wholesaler at back-end. It is common sense that payment instruments for end users should be realized with CBDC, but the reality is that the private sector has already taken a lead in this part of business. There is no doubt that this is a result of the impressive innovative power on the part of private sector. But this also means that the central bank has to catch up. No matter what the situation is, CBDC should not be absent in the world of digital assets. The issuance of CBDC to end users is significant to building a better payment system, to maintaining financial stability and to enhancing central bank's authority.

It is fair to say that users may hold doubts on DFC as they have experienced the convenience of private payment instruments. In fact, the merits that DFC can offer to users are plenty compared with traditional

money (be it physical money or electronic payment instrument). Paper money contains information of the issuer but does not register the information of the holder, let alone keeping information of the entire currency lifecycle during circulation (such information is still subject to the holder). Such fundamental differences allow DFC holders to have greater control over their own money.

Second, to make monetary policy implementation smarter. A number of scholars have realized that digitization of money will improve the effectiveness of monetary policy. For example, Stiglitz [28] studied on macroeconomic administration in an e-currency context. Following his idea, we have done further studies and have found that DFC will make the implementation of monetary policy smarter and more effective because it is traceable and programmable. We have tried to put forward a design in which DFC goes into effect only when the "forward contingent" is met. With such a design, many challenges faced by central banks will be resolved, such as inefficiencies in policy transmission, difficulties in counter-cyclical control, the flow of money from real economy to virtual economy and lack of policy communication.

For example, the "time contingent" makes sure that money only becomes valid when the commercial bank issues the loan. This will reduce time-lag in monetary policy transmission and prevent money from staying out of real economy for too long. The "sector contingent" specifies what sectors and entities that bank loans may flow into. This will make money supply more accurate and targeted, support the implementation of structural monetary policy, prevent money from staying out of real economy for too long and enhance the support of financial sector to the economy. The "loan rate contingent" makes commercial bank loan rates a function of the benchmark interest rate so as to make the transmission more effective and instant. The "economic state contingent" makes counter-cyclical adjustment to interest rate on the money that commercial banks borrow from the central bank based on macroeconomic conditions, so as to mitigate risks of commercial banks and the pro-cyclicality of their credit activities, thus realizing counter-cyclical control of economy.

Moreover, because the above contingents are embedded in DFC at issuance and are made public to commercial banks, the DFC is able to perform the functionality of "forward guidance" as these contingents reflect the logic and intention of central bank monetary policy.

6 Summary

What currency holders truly care about are two things: whether the money is fake and whether it will depreciate. The answer to the first question lies in mintage technology and to the latter is about the underlying value of currency. These are the two concerns that all currencies have to address, and DFC is no exception. The four dimensions this paper has presented are all closely related to these two challenges. The only difference is that the application of digital currency technologies imposes higher requirements for DFC in terms of security, convenience and intelligence.

Given that China's payment environment is rather developed, China's DFC or CBDC should have higher qualities than all the existing private payment instruments. The goal of Chinese DFC is to contribute to more stable value, more secure data, more powerful regulation, stronger empowerment of individuals in payment activities and smarter application. Chinese DFC should have qualities that enable it to provide better service for the public, to offer effective tools for macroeconomic control and to lay a solid foundation for RegTech development.

As an old Chinese proverb says, "Aim higher, you will achieve medium. Aim medium, you will achieve less." The systemic framework established by this paper to understand DFC from four dimensions have presented us with a great goal. We are clear that it is not possible to accomplish them all at one stroke and a great goal like this needs to be realized step-by-step.

At present, efforts of various countries on digital currency are still focused on improving payment efficiency. China is rather developed in electronic payment. The current challenge we are faced with in China is not about improving efficiency, but about putting equal emphasis on both efficiency and security. This means that we not only advocate for innovation but also guard against risks. A prudent path to follow is to regulate private payment instruments effectively while keep working on the provision

of DFC for retail end, before gradually pursuing better qualities of DFC. This is also in line with the development path of current technologies. For example, although programming of DFC seems attractive and important, it may have to be the focus of next stage.

References

1 Committee on Payments and Market Infrastructures. Digital Currencies. Bank for International Settlements. 2015. https://www.bis.org/cpmi/publ/d137.pdf
2 Interview with Zhou Xiaochuan — Zhou Xiaochuan, the governor of the central bank, talking about RMB exchange rate reform, macro prudential framework and digital currency (in Chinese). Caixin Weekly, 2016, 6: 52–61
3 Broadbent B. Central banks and digital currencies. 2016. http://www.bankofengland.co.uk/publications/pages/speeches/2016/886.aspx
4 Fan Y F. Theoretical basis and structural selection of China's digital fiat currency (in Chinese). China Finance, 2016, 17: 10–12
5 Yao Q. Consideration on China's digital currency design (in Chinese). China Finance, 2016, 12: 26–27
6 Yao Q. Digital currency and bank account (in Chinese). Tsinghua Financ Rev, 2017, 7: 63–67
7 Koning J P. Evolution in cash and payments: comparing old and new ways of designing central bank payments systems, cross-border payments networks, and remittances. R3 Reports. 2017. https://www.r3.com/research/#toggle-id-14
8 Bordo M D, Levin A T. Central bank digital currency and the future of monetary policy. NBER Working Paper 23711, 2017. http://www.nber.org/papers/w23711.pdf
9 Bech M L, Garratt R. Central bank cryptocurrencies. BIS Quarterly Review, 2017. https://www.bis.org/publ/qtrpdf/rqt1709f.htm
10 Yao Q. Theoretical and technical logic of legal digital fiat currency (in Chinese). Comp Stud, 2017, 4: 179–196
11 Yao Q, Tang Y W. Some thoughts on central bank digital currency (in Chinese). Financ Res, 2017, 7: 78–85
12 Yao Q. Conceptual prototype of Chinese digital fiat currency (in Chinese). China Finance, 2016, 17: 13–15
13 Chaum D. Blind signatures for untraceable payments. In: Advances in Cryptology — Crypto 82. Berlin: Springer, 1983. 199–203
14 Dai W. B-Money. 1998. http://www.weidai.com/bmoney.txt
15 Jakobsson M, Juels A. Proofs of work and bread pudding protocols. In: Proceedings of Conference on Communications and Multimedia Security, Leuven, 1999. 258–272
16 Szabo N. Bit Gold unenumerated: an unending variety of topics. 2008. http://unenumerated.blogspot.com/2005/12/bit-gold.html
17 Nakamoto S. Bitcoin: a peer-to-peer electronic cash system. 2008. https://bitcoin.org/bitcoin.pdf
18 Project Jasper. A canadian experiment with distributed ledger technology for domestic interbank payments settlement. Report. 2017. https://www.payments.ca/about-us/news/payments-canada-bank-canada-and-r3-release-detailed-findings-blockchain-experiment
19 Monetary Authority of Singapore. The Future is here — Project Ubin: SGD on distributed ledger. 2017. http://www.mas.gov.sg/singapore-financial-centre/smart-financial-centre/project-ubin.aspx
20 Hong Kong Monetary Authority. Whitepaper on distributed ledger technology. Report. 2016. http://www.hkma.gov.hk/media/eng/doc/key-functions/finanical-infrastructure/Whitepaper_On_Distributed_Ledger_Technology.pdf
21 European Central Bank and Bank of Japan. Payment systems: liquidity saving mechanisms in a distributed ledger environment. Report. 2017. https://www.ecb.europa.eu/pub/pdf/other/ecb.stella_project_report_september_2017.pdf
22 Yao Q. Development and supervision of digital currency (in Chinese). China Finance, 2017, 14: 38–42
23 Danezis G, Meiklejohn S. Centrally banked crypto-currencies. 2016. http://www.cs.ucl.ac.uk/staff/G.Danezis/papers/ndss16currencies.pdf
24 Yao Q. Central bank encrypto-currency — analysis of RSCoin system (in Chinese). Caijing Weekly, 2017, 13: 20–22
25 Yao Q, Li L S. Application of big data analysis in digital currency (in Chinese). China Finance. 2016, 17: 37–38
26 Yao Q. The application of digital currency in interbank cash transfer scenario (in Chinese). Finance Comput, 2017, 5: 16–19
27 Xu Z, Yao Q. The preliminary plan of digital commercial paper trading platform (in Chinese). China Finance, 2016, 17: 31–33
28 Stiglitz J E. Macro-economic management in an electronic credit/financial system. NBER Working Paper 23032. 2017. http://www.nber.org/papers/w23032.pdf