



On the Operational Resilience of CBDC: Threats and Prospects of Formal Validation for Offline Payments

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On the Operational Resilience of CBDC: Threats and Prospects of Formal Validation for Offline Payments

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Abstract

Information and communication technologies are by now employed in most activities, including economics and finance. Despite the extraordinary power of modern computers in terms of information processing, storage, retrieval, and transmission, several results of theoretical computer science imply the impossibility of certifying software quality in general.

With the exception of safety-critical systems, this has primarily concerned the information processed by confined systems, with limited socio-economic consequences. In the emerging era of technologies for exchanging digital money and tokenized assets over the Internet, such as in particular central bank digital currencies (CBDCs), even a minor bug could trigger a financial collapse.

Although the aforementioned impossibility results cannot be overcome in an absolute sense, there exist formal methods that can provide correctness assertions for computing systems. We advocate their use to validate the operational resilience of software infrastructures enabling CBDCs, with special emphasis on offline payments as they constitute a very critical issue.

1 Objectives of the Study

1.1 CBDC and Digital Euro: A Digital Form of Cash

Central bank digital currencies (CBDCs) are set to become the latest technological step in the long history of money. After barter, cowrie shells, metal coins, and banknotes, the 20th century saw the introduction of digital money through the immateriality of bits stored on computers operated by banks, with account balances managed via bank transfers and debit or credit card transactions. In our modern developed societies, where most of our activities are digitally mapped, the way people pay has a digital dimension too, with more and more consumers around the world increasingly preferring to pay by using digital electronic devices rather than traditional physical cash, such as banknotes or coins. Therefore, in a context where the use of physical cash is declining, the idea of a CBDC directly controlled by the central bank has gained growing attention; it would represent the next step forward for legal tender issued by the central bank.

A CBDC would be a digital form of cash that complements banknotes and coins, giving people an additional choice of payment modalities. It would be issued by the central bank and freely available to all citizens. If managed under a federalist model, commercial banks would play a key role as the front-end interface with customers. Under this paradigm, commercial banks would remain responsible for managing the relationship with end customers, activating the necessary know-your-customer/anti-money-laundering (KYC/AML) procedures, distributing approved CBDC wallets to customers, and resolving any issue that might arise. However, citizens would be free to receive their salaries, pensions, and other types of small incoming payments directly into their own wallets. At the same time, they would be able to spend their money by using an online or offline service provided by the central bank, which would be secure and guarantee the appropriate level of privacy.

It is well known that today 137 countries and currency unions, representing 98% of the global GDP, are exploring CBDC solutions through ongoing investigations, studies, models, and pilot projects on the topic [5].

In particular, the European Central Bank (ECB) plans to introduce a digital euro [30] as a retail and wholesale CBDC. It will be freely available and free of charge for any digital payment to all citizens in the euro area. After an Investigation Phase that took place from October 2021 to October 2023, aimed at assessing feasibility, benefits, design options, possible risks, and issues, a two-year Preparation Phase was launched in November 2023.

The objective is to test the potential issuance, define the necessary rules, identify the infrastructure required for smooth and secure usage, and establish the legal frameworks and operational rulebook under which to pursue the issuance. Another key element is conducting user research to ensure that the digital euro project under development is able to address the vast majority of the needs of European citizens and is inclusive from the very beginning in all its forms.

The ECB has also made further progress on the design of the digital euro, with special attention and technical analysis dedicated to the offline payment solution to guarantee the financial inclusion of unbanked individuals. The offline payment solution is additionally intended to keep the digital euro operational during emergencies such as power or network outages caused by infrastructure faults, wars, natural disasters, or other similar events. In any case, the ECB remains committed to ensuring that cash continues to be accepted everywhere in the euro area. It is worth noting that, as of today, there is no single European digital payment solution capable of covering the entire euro area. In fact, 13 out of 20 countries rely on non-EU credit card issuers for card payments. In contrast, the digital euro will be a fully European digital form of payment, freely accessible and universally accepted across all euro area countries.

From the legal point of view, in 2023 the European Commission has approved a proposal for its regulation [30].

1.2 The Challenge of Operational Resilience in CBDC

Information and communication technology has become increasingly pervasive due to its everyday life application to basically any human activity, including economics and finance. After the invention of printing in 1400, which fostered a higher diffusion of knowledge, and the industrial revolution in 1700, which widened human physical capabilities through the introduction of mechanical machines able to carry out automated processes, the digital transformation, which started in mid 1900 with the advent of electronics, is continuously extending human cognitive capabilities through programmable devices like computers and smartphones and the rapid worldwide propagation of digital data through the Internet.

Computing systems, along with software methodologies and programming languages needed to design and implement them, have faced a growing complexity. From sequential systems, in which a single operation at a time can be executed, the first evolution has been toward concurrent and distributed systems [24], in which multiple computing devices run simultaneously and respectively exchange information through a shared memory or

via message passing. The second evolution, started with the financial crisis of 2008 and the consequent decreasing trust in institutional intermediaries, has led to decentralized systems [60], where parties not knowing each other perform transactions by relying on a distributed ledger and a consensus mechanism that ensure trust in an algorithmic way.

Several advanced paradigms are by now in place. They range from mobile computing, where devices are no longer tied to physical locations (IoT – Internet of Things [57]), global computing, which implements the abstraction of a single computer accessible anywhere anytime (cloud, edge, fog infrastructures [25, 17]), and autonomic computing, typical of systems capable of adapting to unpredictable changes (via sensors, actuators, policies [51]), to machine learning, deep learning, and large language models (AI – Artificial Intelligence [68, 80, 48]). Moreover, ongoing research is focusing on future paradigms such as quantum computing [61], which should make computation faster, and reversible computing [52], which should reduce energy consumption.

The increasingly complex computer and network infrastructures developed nowadays have profoundly transformed the backbone of all information processes required to sustain the full functionality of the intricate web of interactions among individuals, institutions, and digital systems. Some of these interactions are very critical; think, e.g., of the software used to regulate the flight traffic of an international airport or the computer procedures necessary to control the core of a nuclear fission in a nuclear power plant. Digital financial transactions should be considered critical as well because of the socio-economic impact of possible errors in their enabling infrastructures.

This high complexity exacerbate the problem of software quality; the interested reader is referred to [81] for a list of major software disasters and their consequences in terms of costs, human lives, and environmental impact. Software quality is not only about code functional correctness, because it is equally important to avoid poor performance, security breaches, and bad interfaces. Moreover, the usually adopted approach of testing software is not enough as it does not guarantee the absence of errors. Therefore, it is of paramount importance to adopt software verification techniques, which are mostly based on the early development of software models and hence need to be accompanied by model-driven software engineering methodologies.

While the presence of errors in a non-safety-critical software designed to handle information may be merely annoying or pose some unpleasant consequences, an infinite loop, a logical flaw, or a structural weakness in a system designed to manage digital money or tokenized assets can lead to devastating outcomes from a socio-economic viewpoint. Consider the scenario in which a hacker is able to create CBDC tokens out of thin air,

steal monetary reserves from a bank, or generate, steal, or forge smart contracts associated with tokenized assets. In such cases, the capitalization of an entire financial asset could collapse within hours or even minutes, as investors trust – the foundational requirement for a healthy financial system – would be irreparably damaged. Furthermore, if we are dealing with a CBDC, the consequences could trigger instability across the entire financial system and potentially take on a geopolitical dimension.

The trend of cybercrimes involving hackers stealing money is closely monitored by specialized institutions. For example, the International Monetary Fund (IMF) reports more than 20,000 cyber incidents in the traditional financial sector between 2004 and 2023, with total losses of 10 billion USD (see Figure 3.2 of [47]). In cryptocurrencies and the decentralized finance (DeFi) sector, both supported by public blockchains, Chainalysis reports nearly 14 billion USD in losses from 1,329 hacking events between 2015 and 2024 [18]. Even if not all the breaches described above are necessarily linked to structural flaws in the software, the phenomenon remains deeply concerning.

The reader should note a fundamental difference between the infrastructure of the traditional financial sector and that of public cryptocurrencies and the DeFi sector. In the former, the networks connecting financial institutions are private and not directly accessible via the Internet. One example is the SWIFT interbanking system, which has nevertheless been the target of significant attacks such as Banco del Austro (Ecuador) in January 2015, Bangladesh Bank in February 2016, and Banco de Chile in May 2018. In contrast, the entire crypto-asset sector – whose market capitalization now exceeds 3 trillion USD – is directly accessible via the Internet and therefore more exposed. The CBDCs that are being introduced – and those already in operation, such as the Chinese e-CNY – are being deployed with Internet connectivity to support peer-to-peer transactions between users or between users and institutions, interoperability with wallets, commercial banks, and payment systems, real-time updates, centralized control, and, last but not least, financial inclusion. This implies that exposure to hacking threats will significantly affect CBDCs.

1.3 Formal Methods for Ensuring Software Quality of CBDC

Theoretical computer science provides several impossibility results, which arise from the undecidability of many computational problems. In the specific case of software quality, suppose that we create a program P to compute a function f_P . If P is not properly designed, its execution may be subject to two different kinds of errors. The first one

corresponds to a situation in which the program enters an infinite loop; when this happens, the only possible action is to interrupt the computation, that is, to shut down the system. The second one, if possible, is even worse: the system appears to be working correctly, but the function it is computing is actually a wrong one, $f_W \neq f_P$.

To overcome these two highly undesirable situations, one might consider building two test programs. The first one, T_l , is designed so that, when supplied with the code lines of P , it can answer “Yes” or “No” in finite time to the question: “Does P enter an infinite loop in some situations?”. The second one, T_f , is able to answer “Yes” or “No” in finite time to the question: “Does P compute the function f_P ?”. Unfortunately, two fundamental results of computability theory – due to Turing [77] and Rice [67] – establish the impossibility of constructing such tests for all programs. The practical consequence of these two results is that upon every software release there remains a residual risk of malfunction.

In the last 50 years, several approaches have been developed to assess the quality of software under conditions that make such a problem decidable. These are collectively called formal methods in computer science. They are mathematically rigorous techniques for specifying and verifying computing systems, based on the idea that appropriate mathematical analysis can contribute to a dependable software design like in other engineering disciplines. In the following, we recall some of the prominent formal methods.

On the specification side, formal models of software can be provided at different levels of abstraction and revolve around automata, algebras, and logics. An automaton [45] consists of a set of states and a set of transitions between states. Every state of an automaton represents a state of the computation, like for instance the current statement to be executed in a program along with the value contained in every program variable, while a transition describes a state change, which can be accompanied by possible inputs and outputs. There is a hierarchy of automata classes, ranging from finite-state automata to Turing machines, which correspond to the hierarchy of formal languages established by Chomsky [19]. Moreover, in addition to traditional automata in which states are global, there are variants called Petri nets [65, 66] in which the underlying graph is bipartite so that states can be represented in a distributed way across loci of computations, which is well suited for concurrent and distributed software.

Process algebras [58, 43, 39, 6, 15] are more abstract than automata because they provide a number of operators whereby to obtain complex system models by combining simpler ones. Among these operators we mention sequential, alternative, and parallel compositions, which allow one to express the fact that two processes – intended as the

behaviors of two systems – are executed one after the other, alternative to each other, or run in parallel, respectively. An important notion in this setting is that of behavioral equivalence, with bisimilarity – intended as the capability of mimicking each other’s behavior stepwise – being one of the most important approaches, which identifies syntactically different processes that feature the same observable behavior. Compositional modeling is accompanied by compositional reasoning when the considered equivalence is a congruence – i.e., it allows to replace equals with equals like in arithmetic – with respect to the process algebraic operators.

Logics are even more abstract in that they express the behavioral properties that a computing system should possess. The simplest example is given by Hoare logic [42, 22] and its variants, including separation logic [63], which are used to enrich programs with annotations containing logical formulas that state properties that should be valid in those points of programs execution. Other examples are modal and temporal logics [46, 33]. They respectively are extensions of classical logic with modal or temporal operators. The former denote the possibility or the necessity of performing certain activities in a given order. The latter express a property to be valid in the next step or the fact that a certain property has to hold until another one becomes satisfied, along at least one computation or all computations.

On the verification side, we mention in particular model checking [56, 21, 7] and equivalence checking [15]. A model checker takes as inputs a program model, described as an automaton or a process term, and a property it should possess, formalized as a modal or temporal logic formula, then communicates whether the program model meets that property or not. In case of failure, it provides diagnostic information in the form of a program model execution that does not fulfill the property. An equivalence checker considers instead a model of the specification of the program and a model of the implementation of the program, then checks whether the two models are behaviorally equivalent to each other or not. In case of failure, it exhibits a distinguishing modal or temporal logic formula, i.e., a formula that is satisfied by only one of the two models.

The aforementioned modeling and verification techniques, originally developed for functional features of programs, have been subsequently extended to deal with software architectures and quantitative aspects too [3, 38, 71, 2, 41, 40, 1, 23, 36]. In this way, it is possible to address also systems including probabilistic behaviors – think, e.g., of cryptocurrencies based on proof-of-stake consensus – or real-time constraints – think, e.g., of the deadline by which a bank transfer can be canceled. Moreover, they have been adapted to address security properties as well, like for instance the use of equivalence checking

to assess noninterference of information flows among different security levels [35, 32, 26]. Many software tools have been developed – and employed in large-scale case studies – to implement formal modeling and verification, like for instance CADP [34], mCRL2 [36], GreatSPN [2], PEPA Workbench [41], TwoTowers [3], Spin [44], NuSMV [20], Uppaal [54], PRISM [50], Modest Toolset [37].

In this paper we advocate the use of formal methods to validate the operational resilience of extremely critical software infrastructures such as those underlying CBDCs, with special emphasis on offline payments as they constitute a troublesome matter.

2 Issues and Risks of Offline Payments in a CBDC

One of the main innovations in the proposal for a CBDC is the possibility of enabling digital offline payments. This means that it would be possible to transfer value – the digital money of a CBDC – between the wallets of two physical devices without requiring an Internet connection to any ledger system. This could be due to the total absence of Internet coverage or temporary or local difficulties in telecommunications connectivity as a consequence of a system outage. However, the offline solution could also be chosen as a way to preserve the highest level of privacy during the transaction, as this kind of money transfer would replicate some key features of a cash exchange.

Another important advantage of the offline payments solution is that it would enable the financial inclusion of unbanked people, who could use offline payments as a substitute for cash. This could also address the consequences of the declining use of cash [12], with the CBDC acting as a medium for pseudonymous or anonymous payments [27]. Furthermore, in a scenario in which cash is gradually abandoned as a medium for transferring value, commercial banks might find it economically disadvantageous to offer services to unbanked people, who are de facto financially excluded groups. Therefore, the introduction of offline payments as an instrument of financial inclusion is becoming a necessity to support the most vulnerable parts of our societies, which would otherwise be excluded from the economy. To achieve this, only a minimal technological infrastructure would be required – essentially, a smartphone, a basic computer, or a laptop.

In a report by the World Bank Group, it is estimated that globally 1.4 billion adults are unbanked [82]. As for the EU, a 2024 Economic Bulletin of the ECB [29] states that “*nearly one out of five adults (19.4%) in the euro area reports not having either debit or credit cards or payment accounts*”. As a consequence, the offline payments solution with cash-like features is strongly recommended as an instrument for financial inclusion also

in the context of the future digital euro. Indeed, it constitutes the second requirement in the “Report on a digital euro” by the ECB [28]:

Requirement 2 (R2): cash-like features. To match the key distinctive features of cash, a digital euro aiming to tackle a decline in the acceptance of cash should permit offline payments. Moreover, a digital euro should be easy for vulnerable groups to use, free of charge for basic use by payers and should protect privacy. It should have a strong European branding.

A further element supporting the offline payments solution derives from a survey conducted by the Innovation Hub of the Bank for International Settlements (BIS). It shows that “49% of central banks surveyed consider offline payments with retail CBDC to be vital, while another 49% deemed it to be advantageous” [8].

Unfortunately, even if highly recommended, the offline payments solution presents some challenges and issues from operational and technical points of view. In an expository study by the Bank of Finland, a case study named “Project Pluto” is discussed, aimed at studying the risks of offline CBDCs [62]. In contrast to the Riksbank’s e-krona pilot in Sweden [73, 74, 75], the Pluto application focuses on the token-based model and relies on reusable tokens.

In a note of the Bank of Canada [59] it is explicitly written that:

From a financial risk perspective, concerns exist that an extended offline solution may become a target for fraud and financial crime. These concerns, in addition to security concerns, mean that extended offline functionality implies some risk.

The Bank of England also aimed to assess whether it is technically feasible to implement a secure offline payment functionality for a digital pound. The conclusions highlight some critical issues [12]:

This project demonstrated that while it might be technically feasible to implement an offline payment functionality for a digital pound, there are trade-offs, particularly around user experience and preventing double spending and counterfeiting, that make implementing it challenging.

But the most detailed study on the secure feasibility of the offline payments solution is the one conducted by BIS, which has recently produced a series of analytical documents to illustrate “Project Polaris”. The first report, entitled “A Handbook for Offline Payments with CBDC” [8], outlines the current technical solutions for offline payments with a CBDC, the possible risks, threats, and vulnerabilities associated with them, and the

countermeasures to mitigate these issues. The second report, “A Security and Resilience Framework for CBDC Systems” [9], is devoted to a study of the objectives and design criteria required to achieve security and resilience in a CBDC framework. The third report, “Closing the CBDC Cyber Threat Modeling Gaps” [10], addresses the problem of analyzing the adequacy of current cybersecurity standards and frameworks through real-world observations of security flaws; the goal is to develop cyber threat models that need to be addressed to achieve full control over the security necessary in a CBDC framework. The fourth and final report, entitled “A High-Level Design Guide for Offline Payments with CBDC” [11], outlines the suggested design choices for offline payment solutions, also analyzing the security, risk, and impact on resilience of the offline system.

From all these studies, we can deduce each of the main issues and vulnerabilities of the offline payments solution that need to be addressed.

Generally speaking, as noted in [14], we must state that basing part of the security of offline solutions on the assumption of inviolability of secure elements¹ is simply naive. Furthermore, in general even a single compromised device could print and spend counterfeit money without restrictions. For example, a hacker able to break a single secure element could send counterfeit money to a colluding device. Moreover, without adequate countermeasures, offline payment recipients cannot distinguish legitimate payments from counterfeit ones, so central banks would be forced to bear these risks of fraud.

We briefly illustrate here a tentative and non-exhaustive list of threats based in part on the first report of “Project Polaris” [8] by the BIS and on the expository study of the Bank of Finland [62]:

Counterfeiting by taking control of a device. If a payment device is allowed to generate and redeem tokens, a bad actor could take over the device and generate additional tokens.

Counterfeiting by a physical breach. Using an offline CBDC payment feature means that there must be some digital representation – a binary string – of the CBDC tokens stored inside a physical device, be it a smart card, a smartphone, a hardware wallet, or other. A bad actor could try to clone or manipulate this string through a physical attack on the device, in order to (double-)spend the balance with another device or alter the original balance. Note that the attacker could be in possession of the device, with unlimited time to mount such attacks without being detected.

¹A secure element is a microprocessor chip with enhanced security protections that should prevent unauthorized access. It can be embedded in smart cards and smartphones or in removable subscriber identity module (SIM) cards.

Counterfeiting by a cryptanalysis breach. This is a non-intrusive breach such that the security of a transaction – which is based on cryptographic protocols – is compromised by the knowledge of the private key, which is stolen from the owner or derived through a successful cryptanalytic attack.

Side-channel attack. The physical devices used in the framework of offline payments are digital electronic devices that can leak electromagnetic fields while operating. It is therefore possible, for a bad actor, to analyze the variations of these fields and perform signal analysis on the electromagnetic radiation. This could allow them to deduce some information about the electrical quantities that physically represent the bit strings associated with the digital representation of the CBDC tokens or the private key involved in a transaction.

Third-party device compromise. The physical devices used to perform offline payments are third-party devices not under the direct control of the central bank. They might be affected by structural hardware or software weaknesses or flaws, which could be exploited by a bad actor to obtain control of the cryptographic keys or directly of the digital representation of the CBDC tokens.

Third-party device complexity. Offline CBDC payment systems may be forced to use technologies that are not well understood by the internal staff of a central bank. This could increase reliance on third-party expertise and constitute an operational risk.

Device obsolescence. As in our common experience, software and hardware devices need to be updated when necessary to ensure vendor support. Deprecated software versions or unsupported hardware can offer a trapdoor to bad actors, who can exploit bugs or other vulnerabilities no longer fixed by vendors to breach the system.

Double spending. The double-spending issue can be associated with several previously described situations or contexts. Moreover, note that the double-spending issue for offline CBDC payments is different from the more famous problem of double-spending cryptocurrencies on a public and disintermediated blockchain. In the latter case, the problem of consensus on an asynchronous network must be solved, but it is well known that the extended version of the Byzantine generals problem does not admit theoretical solutions [31]. Nevertheless, practical solutions based on proof-of-work [60] and proof-of-stake [49] protocols offer some level of security.

In contrast, in the case of offline payments for a CBDC, trust needs to be ensured by the tamper-resistant nature of the user device and the shared cryptographic protocols of the wallet. It is therefore necessary to ensure that double-spending attempts will be rejected by the payee’s wallet.

Fraud. Since bad actors may attempt to persuade users to pay them by impersonating payees known to the user, it is necessary to design an offline system with the capacity of uniquely identifying payees to prevent this kind of fraud. Clearly, this conflicts with requirements that support privacy by design.

Lost value. The digital representation of the CBDC tokens stored inside a physical device poses another kind of risk, because the value associated with it can be lost under several scenarios. Examples are the device being lost or broken, the user becoming unable to use the device or losing the credentials to use it, or the transaction being torn, in the sense that the tokens have left the payer’s wallet but have not been received by the payee’s wallet due to an interrupted transaction.

Insider threat. Internal staff of the central bank with roles requiring privileged access to technological infrastructures, such as IT administrators or system operators, could accidentally or deliberately affect the regular system operativity, acquiring knowledge aimed at tampering with the system, stealing funds, changing balances, or other malicious actions.

Scalability of risk in counterfeiting. If we compare the effects of counterfeiting between the old technology of physical cash based on banknotes and the new technology of an offline payment system based on a CBDC, a striking difference in the capacity of a bad actor to scale counterfeiting becomes evident. Counterfeiting banknotes is a production-heavy process because, apart from the technical expertise and special skills required, the bad actor also needs special inks, holograms, special printing machinery, and raw materials. In other words, there exist several production-related factors that limit the ability to scale up the counterfeiting of banknotes. On the contrary, counterfeiting digital tokens scales very efficiently. Once the offline CBDC system has been compromised, due to the immaterial nature of the digital representation of the CBDC tokens it is virtually possible to generate an unlimited number of tokens at a cost that is essentially zero, as the only physical resources necessary to perform the counterfeiting are a computer and/or a smartphone. This implies that the consequences in the loss of trust in an offline CBDC

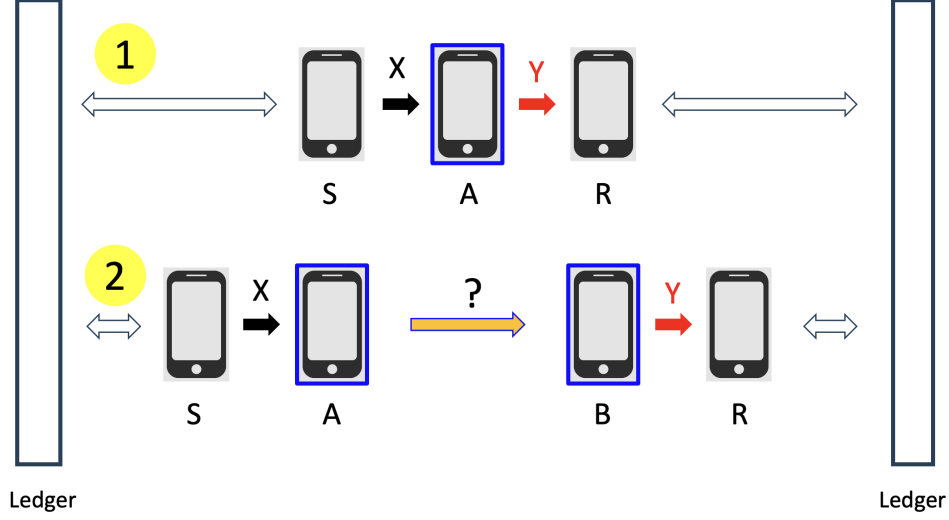


Figure 1: The risk of devices staying offline: the bordered ones always remain offline [62].

system would be far more severe than in the case of banknotes. Moreover, since in general it is the payee who bears the risk of economic loss in case of receiving a counterfeited payment, the attractiveness of offline payments based on the CBDC could decline considerably. While for a banknote a payee has some capacity to check and verify its authenticity – e.g., by using technological devices dedicated to this task – in the case of an offline payment the payee has no real instrument for checking the authenticity of the transaction.

The risk of devices staying offline. This is probably the most insidious problem that, to the best of our knowledge, has not been solved yet. Suppose that there are two chains of offline transactions, #1 and #2, as in Figure 1. In both transaction chains, a certain amount X of tokens is moved, while the bordered smartphones always remain offline [62].

In transaction chain #1 the sender S is in offline mode and transfers X tokens to A . Then A transfers a counterfeited token Y to the final receiver R . When both smartphones S and R switch to online and connect to the ledger, we assume that it is possible to realize that Y is counterfeited. At this point, using the transaction history of the devices, the system can plausibly presume that A was the fraudster even if A stays offline. This is because it is possible, in principle, to mirror the transaction chain through information received from wallets S and R when they enter online mode again.

The situation is completely different in transaction chain #2. When S and R come back online after the offline transactions, the system can certify that S has sent X tokens to A and R has received Y counterfeited tokens from B. But it is impossible to detect whether A or B has produced the counterfeiting. Likewise, it is also impossible to deduce whether there have been more devices in between A and B.

All the risks, issues, and vulnerabilities described above need to be tackled under a global approach able to formally validate, from the security and anti-counterfeiting point of view, all the concurrent processes in action when the offline payment system associated with a CBDC is activated. It is well evident to anyone that a loss of trust in the financial institutions behind a CBDC, represented by central banks, could result in a deadly blow to the entire financial system.

3 A Methodology Based on Formal Methods

The formal methods and related tools mentioned in Section 1.3 have been successfully used in a number of case studies, some of which conducted in collaboration with industries. They cover distributed algorithms and systems, communication and coordination protocols, telephony systems, mobile agents, operating systems, database management, robotics, hardware/software codesign, embedded software, security and cryptography, software architectural styles, bioinformatics, healthcare, power management, flood control, railways, avionics, space mission control, autonomous vehicles, multimedia, games, Internet of things, cloud computing, web services, human-computer interaction, e-government, manufacturing systems, and business systems.

As far as economics and finance are concerned, the application of formal methods is rather limited. In the case of traditional centralized systems, we are aware of very few case studies; among them we mention [4, 53, 69, 64, 55, 70, 72]. In the case of modern decentralized systems, apart from some works about blockchain consensus like [78, 79, 16], the formal methods literature is focusing on smart contracts [76]; see, e.g., [13].

As for CBDC and offline payments, to the best of our knowledge there are no applications of formal methods. We thus complete this section by discussing how they could be used in this critical setting.

3.1 Model Setup

The first phase of our methodology is to develop a formal model of the CBDC of interest, like the digital euro, together with the related online and offline services. The model should take into account the most important functional, performance, and security aspects of the entire system. Among the various formalisms presented in Section 1.3, we expect that process algebras may play a key role due to their compositional nature. This inherently supports the interplay of a multitude of submodels for the various system components such as the central bank, commercial banks, digital ledgers, user wallets, and online and offline transactions.

A prerequisite for this phase is the establishment of a fruitful collaboration between all stakeholders, in particular the central bank, and formal methods researchers. Without knowing the specification defining a system of interest, it is not possible to build any model for that system.

3.2 Proposed Analysis

The second phase focuses on the verification of the model that has been built in the first phase. We expect to employ both model and equivalence checkings. In the case of the former, the idea is to formalize the properties of interest via suitable modal or temporal logic formulas, which should account for all major correctness, efficiency, and privacy criteria to satisfy. As for the latter, the appropriate functional, performance, and secure behaviors have to be described through specific models that are viewed as formal specifications, then the overall model – intended to be an implementation that should conform to a specification – is checked for equivalence with each of the specific models after possibly hiding some irrelevant details in the overall model.

Once the verification phase is passed, the prototyping of the CBDC system with its online and offline services can start. This should be carried out in a model-driven manner, in such a way that the resulting software preserves by construction the properties formally proven on its model.

3.3 An Illustrative Example

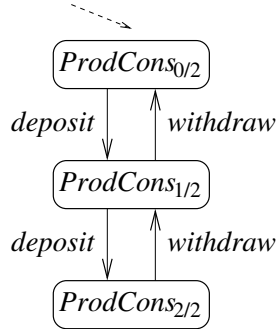
To illustrate our methodology in the case that process algebras and equivalence checking are employed, let us consider the design of a producer-consumer system. In general, this system is composed of a number of producers, a finite-capacity buffer, and a number of

consumers. Each producer deposits items into the buffer as long as the buffer capacity is not exceeded. Stored items can then be withdrawn by each consumer according to some predefined discipline, like first-come-first-served or last-come-first-served. For simplicity, we consider a scenario in which there are a single producer and a single consumer and the buffer has only two positions. We also assume that the items are all identical, so that the specific discipline that has been adopted for withdrawals is not important.

Since the only observable activities are deposits and withdrawals, the specification of the producer-consumer system – with which every correct implementation should comply – can be formalized through the following process algebraic equations:

$$\begin{aligned} ProdCons_{0/2} &\triangleq deposit . ProdCons_{1/2} \\ ProdCons_{1/2} &\triangleq deposit . ProdCons_{2/2} + withdraw . ProdCons_{0/2} \\ ProdCons_{2/2} &\triangleq withdraw . ProdCons_{1/2} \end{aligned}$$

where $ProdCons_{0/2}$ represents the initial state of the system (in which the buffer is empty), $ProdCons_{1/2}$ represents the state in which only one position of the buffer is occupied, and $ProdCons_{2/2}$ represents the state in which the buffer is full. Operator $a . P$ is called action prefix and describes the possibility of executing action a and then behaving as process P . Operator $P_1 + P_2$ describes a nondeterministic choice between processes P_1 and P_2 , which is based on the actions they initially enable. The underlying automaton is the following, where the dashed arrow indicates the initial state:



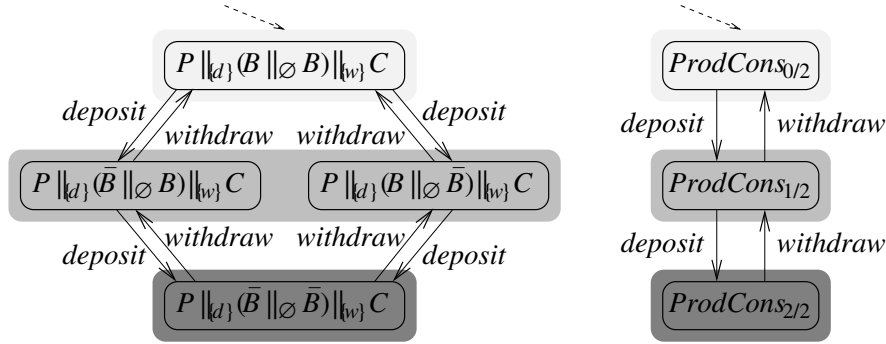
There are at least two possible implementations of the producer-consumer system. The first option is a concurrent implementation, in the sense that the two-position buffer is made out of two independent one-position buffers:

$$\begin{aligned} PC_{\text{conc},2} &\triangleq Prod \parallel_{\{deposit\}} (Buff \parallel_{\emptyset} Buff) \parallel_{\{withdraw\}} Cons \\ Prod &\triangleq deposit . Prod \\ Buff &\triangleq deposit . withdraw . Buff \\ Cons &\triangleq withdraw . Cons \end{aligned}$$

Operator $P_1 \parallel_S P_2$ describes the fact that processes P_1 and P_2 run in parallel and have

to synchronize when executing actions in S ; this set is empty in the first equation above in the case of the two positions of the buffer. Note that $Prod$ (resp. $Cons$) repeatedly tries to deposit items into (resp. withdraw items from) the buffer.

To show that this is a correct implementation of the producer-consumer specification, we have to investigate the existence of some relation between $PC_{conc,2}$ and $ProdCons_{0/2}$. The first step consists of comparing the automata underlying $PC_{conc,2}$ and $ProdCons_{0/2}$, which are shown below:



In the states of the automaton on the left-hand side, every process name and every action has been shortened with its initial. Moreover, $\bar{B}$ stands for $withdraw . Buff$.

It turns out that $PC_{conc,2}$ is strongly bisimilar [58] to $ProdCons_{0/2}$, i.e., they are able to mimic each other's behavior stepwise. The bisimulation proving this fact has been represented graphically by giving the same color to states in the same equivalence class and different colors to different equivalence classes. The depicted relation is a strong bisimulation because in both automata:

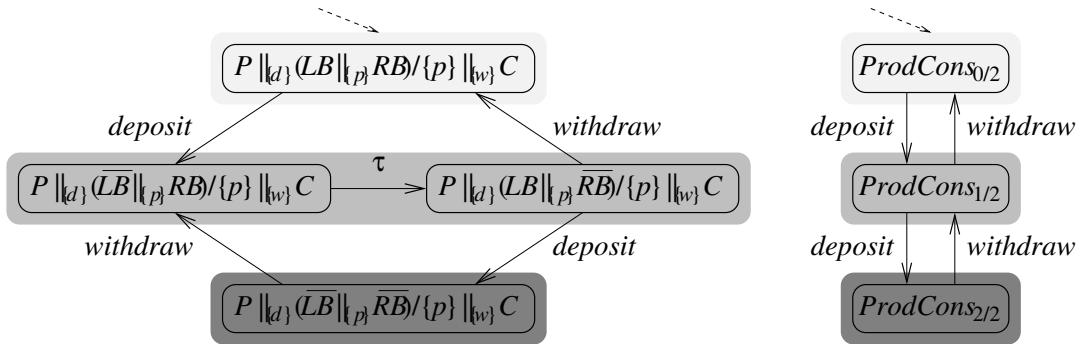
- A light gray state can only reach a gray state by executing *deposit*.
- A gray state can only reach a dark gray state by executing *deposit* or a light gray state by executing *withdraw*.
- A dark gray state can only reach a gray state by executing *withdraw*.

The second option is a pipeline implementation, in which the two-position buffer is obtained as the parallel composition of two communicating one-position buffers:

$$\begin{aligned}
PC_{pipe,2} &\triangleq Prod \parallel_{\{deposit\}} (LBuff \parallel_{\{pass\}} RBuff) / \{pass\} \parallel_{\{withdraw\}} Cons \\
Prod &\triangleq deposit . Prod \\
LBuff &\triangleq deposit . pass . LBuff \\
RBuff &\triangleq pass . withdraw . RBuff \\
Cons &\triangleq withdraw . Cons
\end{aligned}$$

Action *pass* models the passage of one item from the left buffer to the right buffer and occurs both in the synchronization set of $LBuff \parallel_{\{pass\}} RBuff$ and in the hiding set of $/\{pass\}$ applied to the previous subprocess. We have decided to hide the execution of *pass*, which thus becomes the unobservable action τ within transition labels, as it represents an implementation detail that should not be perceived by an external observer.

To prove that this is a correct implementation of the producer-consumer specification, similar to the concurrent implementation we have to investigate the existence of some relation between $PC_{pipe,2}$ and $ProdCons_{0/2}$. Thus the first step consists of comparing the automata underlying $PC_{pipe,2}$ and $ProdCons_{0/2}$, which are shown below:



In addition to the same shorthands as before for process names and actions on the left-hand side, we have $\overline{LB}$ for $pass . LBuff$ and $\overline{RB}$ for $withdraw . RBuff$.

It turns out that $PC_{pipe,2}$ is weakly bisimilar [58] to $ProdCons_{0/2}$, in the sense that τ -actions are ignored in the bisimulation game. The weak bisimulation proving this fact has been represented graphically by means of colors. The depicted relation is a weak bisimulation because in both automata:

- A light gray state can only reach a gray state by executing *deposit*.
- A gray state can only reach a dark gray state by executing *deposit* (possibly preceded by τ), a light gray state by executing *withdraw* (possibly preceded by τ), or a gray state by executing τ or staying idle.
- A dark gray state can only reach a gray state by executing *withdraw*.

We conclude by pointing out that, in the considered simplified scenario, it is easy to establish the equivalence of both implementations to the specification. However, it would become very hard, if not impossible, to address realistic scenarios featuring multiple producers and consumers that work in parallel on a huge buffer without the use of automated tools rooted in formal methods.

4 Conclusions

Contrary to what happens with SWIFT and other commercial bank circuits, CBDCs and the digital euro will be deployed directly on the Internet. This poses the highest level of risk in terms of hacking and the possibility of generating counterfeit money. The need to provide an offline solution for digital euro tokens – to offer cash-like features and promote financial inclusion – constitutes, in itself, a problem in search of a solution, especially in cases where some devices remain offline for a long time.

On the other hand, the impossibility results mentioned in Section 1.3, concerning the inability in general to theoretically guarantee the quality and correctness of the protocols and the software required to implement them, mean that we cannot absolutely ensure the perfect and secure functioning of the CBDC infrastructure. This leaves the risk of possible trapdoors, open to exploitation by bad actors, which could be used to create counterfeit transactions and money.

The formal instruments briefly described in Section 1.3 – automata and Petri nets, process algebras, modal and temporal logics, model checking, and equivalence checking – together with the many software tools that have been developed and successfully employed in large-scale case studies for formal modeling and verification – CADP, mCRL2, GreatSPN, PEPA Workbench, TwoTowers, Spin, NuSMV, Uppaal, PRISM, Modest Toolset – could help mitigate the aforementioned risks by enabling the automated validation of all processes and protocols involved in a highly safety-critical financial system such as the implementation of the digital euro. To the best of our knowledge, they have never been used for this purpose before; therefore, we strongly recommend their adoption. The trust and reputation of the ECB are at stake, with no room for errors.

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