Blockchain Security: A Survey of Techniques and Research Directions

Jiewu Leng, Man Zhou, J. Leon Zhao, Yongfeng Huang, and Yiyang Bian

Abstract—Blockchain, an emerging paradigm of secure and shareable computing, is a systematic integration of 1) chain structure for data verification and storage, 2) distributed consensus algorithms for generating and updating data, 3) cryptographic techniques for guaranteeing data transmission and access security, and 4) automated smart contracts for data programming and operations. However, the progress and promotion of Blockchain have been seriously impeded by various security issues in blockchain-based applications. Furthermore, previous research on blockchain security has been mostly technical, overlooking considerable business, organizational, and operational issues. To address this research gap from the perspective of information systems, we review blockchain security research in three levels, namely, the process level, the data level, and the infrastructure level, which we refer to as the PDI model of blockchain security. In this survey, we examine the state of blockchain security in the literature. Based on the insights obtained from this initial analysis, we then suggest future directions of research in blockchain security, shedding light on urgent business and industrial concerns in related computing disciplines.

Index Terms—Blockchain security, process security, data security, consensus algorithm, smart contract

1 Introduction

Blockchain is a chain structure that links data blocks sequentially according to the chronological order and thereby ensures that this distributed ledger cannot be tampered with or forged cryptographically. With the rapid and widespread adoption of Bitcoin [1], [2], blockchain is hailed as a disruptive innovation in the computing paradigm [3]. Blockchain has become a new secure and shareable computing paradigm for supporting business innovation [4].

As shown in Fig. 1, blockchain integrates multiple techniques, such as cryptography, P2P network protocol, and consensus algorithm, to achieve more security system functions. Blockchain can be integrated with smart contracts, ensuring that the program can execute the preset logic through self-limitation and security encryption credibly and automatically [5]. The P2P network protocol allows blockchain to handle unpredictable patterns so that the business logic will not be outdated [6], [7]. However, security issues in blockchain continue to impose a significant challenge [8]. Blockchain systems have suffered many outside attacks around the Internet [9]. Blockchain security is the protection of transactions in a block against internal, malevolent, peripheral, and unintentional threats. This protection depends on detection, prevention, and appropriate response to threats from different levels using security policies and tools [10]. However, a wide range of current blockchain security research is technical in nature, suffering from limited considerations of organizational and operational issues [11].

There have been several blockchain security-related surveys conducted from different perspectives, highlighting some research gaps and future exploratory directions for academics and practitioners. Lin and Liao [12] reviewed several blockchain security issues, such as majority attack, data scale, and cost problems. However, the analysis is not comprehensive enough for guiding future research. Li *et al.* [13] conducted a study on security threats to blockchain and surveyed the corresponding real attacks by examining popular blockchain systems such as Ethereum. This survey neglects security issues when utilizing these systems to build business applications. Joshi *et al.* [10] surveyed consensus protocols from the data security and privacy protection aspect. However, there exist security issues from other aspects, such as smart contracts. Hossain [14] overviewed blockchain research from the perspective of digital business transformation with its future evolutions. However, it lacks a discussion on the security issues of blockchain. Park *et al.* [15] adopted the blockchain security solution to cloud computing. However, other application scenarios were left out of the survey scope. Fran *et al.* [16] presented a systematic literature review of blockchain-based applications across multiple domains. However, the study lacks a discussion on the blockchain

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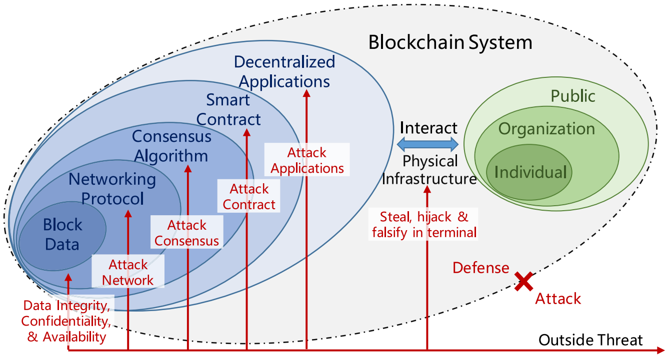

Fig. 1. Major elements and threats in blockchain security.

security issues. Moreover, many new blockchain security studies have been conducted in the last two years and therefore need to be included.

Blockchain security is a serious issue that must be considered as an element embedded in the whole lifecycle of system, from requirement analysis to coding and maintenance [17]. However, scholars from the information systems area seem to have limited awareness of the contributions achieved by the researchers of other disciplines. It is therefore necessary to study how and to what extent blockchain security issues have been addressed and then summarize relevant research methodologies in previous research. This study adopts the information systems perspective and presents a systematic survey of blockchain security from different layers shown in Fig. 1. The blockchain security is organized at the process level, the data level, and the infrastructure level, which we refer to as the PDI framework.

The rest of this survey is outlined as follows. Section II proposes a PDI framework for surveying blockchain security. The following three sections examine to what extent these security issues have been addressed. New directions for studying blockchain security are presented in section VI, followed by concluding remarks.

2 A Framework of Blockchain Security

There exist different architectures and models of system security, which can be used as a guideline to build a framework of blockchain security (see Table 1). Firstly, the first three architectures in Table 1 emphasize the implementation and organization security of a system. The Information Security Architecture (ISA) proposed by Tudor focuses on five essential components: 1) organization & infrastructure, 2) policies & procedures, 3) baselines & risk assessments, 4) awareness & training programs, and 5) compliance [18]. The Policy Framework for Interpreting Risk in E-Business Security (PFIRES) proposed by Rees *et al.* [19] addressed the policy rules to manage information among multiple organizations. Another security architecture proposed by Eloff *et al.* [20] identified the demands for an integrated architecture to achieve maximum security. Secondly, the next two architectures offered by two IT companies (i.e., IBM and Oracle) explain concepts in security. IBM [21] provided a view of security, including business, technology, service delivery, and fusion of domains tend to share common elements. Oracle [22] proposed a reference architecture for achieving security, namely, data security, fraud prevention, and compliance enablement.

TABLE 1
Typical Security Architectures, Frameworks, and Standards

Models	Author	Metrics
ISA	Tudor [18]	Guide the implementor to develop an effective security architecture.
PFIRES Life Cycle Model	Rees et al. [19]	Guidance to facilitate coordination between managers and engineers.
Security architecture	Eloff et al. [20]	An integrated architecture to achieving the maximum-security.
Security Reference Architecture	IBM [21]	A broad view of security, including business, technology, and service.
Security Conceptual View	Oracle [22]	Illustrate how security could be realized.
ISO/IEC 27000	ISO/IEC [23]	Summarize the best-practice of security management.
Critical Security Controls	CIS [24]	Help organizations focus their security resources and expertise.
Security Reference Architecture	Tripwire [25]	Automate security and IT operations.
Cybersecurity Framework	NIST [26]	A framework for enabling organization improving ability.

The last three references in Table 1 concentrate on the uniform information security standards summarized from practice. The ISO/IEC 27000 family of standards summarize a globally acknowledged best-practice of security management [23]. The Center for Internet Security (CIS) helps organizations focus their security resources and expertise on defending against cyber-attacks [24]. The Security Reference Architecture proposed by Tripwire integrates high-fidelity asset visibility and deep endpoint intelligence with business context, automate security, and IT operations [25]. The Cybersecurity Framework proposed by the National Institute of Standards & Technology (NIST) presents a security framework for enabling enterprises, improving their ability to defending against cyber-attacks [26]. In terms of the blockchain-based applications, the primary security problems include the generation and protection of private keys, vulnerabilities of the signature algorithm, the centralization of the consensus process, vulnerabilities of smart contracts, and vulnerabilities of decentralized application.

To integrate existing security architectures with blockchain-based applications regarding technological and organizational issues in a balanced way [27], this paper builds a Process-Data-Infrastructure model (PDI model) by mapping the security architectures proposed by IBM and Oracle to the five-level blockchain architecture. The PDI framework (shown in Fig. 2) includes three aspects: process level, data level, and infrastructure level. Data-level security is flanked by process and infrastructure. The blockchain security in the data level is composed of authentication, encryption, consensus algorithms, access control, and key management. The process level includes smart contracts, implementation security, operation standards, and fraud detection. The infrastructure level includes the terminal devices, network, and super-node server (if any). Security contributions can be mapped according to these three levels. The next three sections examine to what extent these issues have been studied.

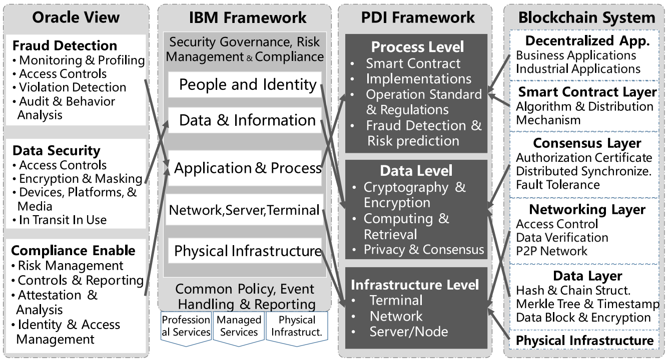

Fig. 2. A framework of blockchain security issues.

3 Process Security in Blockchain

A business process requires the practitioner to decide on and adhere to policies that participants can enact to keep their systems secure. Blockchain security on the process level is complicated due to multiple tasks and governance [28]. Four aspects of process security in blockchain are reviewed in this section (Fig. 3).

3.1 Security of Smart Contract

Smart contracts refer to scripts automatically executed on a distributed network consisting of mutually distrusting nodes without an external trusted third-party [29]. To complete the data transactions between the participants, smart contracts expose the transaction data to the risk of compromising sensitive information. Otherwise, difficulties of supervision arise [30]. Since smart contracts transfer value, both their correct execution and secure implementation against attacks/tampering are crucial [31]. Criminals can leverage Criminal Smart Contracts (CSC), a new critical cyber-weaponry, to produce 0-day vulnerability data transactions [32]. The smart contract is one of the most significant sources of security issues on the process level of blockchain. Besides, a smart contract (e.g., blockchain wallet, crowdfunding fund) can hardly be revised once having been issued. A recorded fault or malicious data transaction cannot be deleted from the blockchain application [33]. The method to roll back a recorded data transaction is to make a hard fork on the blockchain, and it calls for new consensus among the participated members and thereby damages the trustworthiness of the system [34]. Therefore, the security of the smart contract often determines the security of

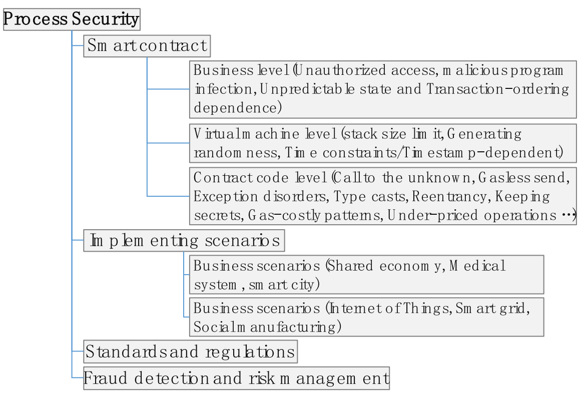

Fig. 3. Major aspects of the process security in the blockchain.

Fig. 4. High-level flow illustrating how securify finds a security issue [39].

blockchain [35]. Many smart contracts are vulnerable to attacking [36].

The security issues of smart contracts occur in three levels, namely, business level, virtual machine level, and contract code level. Specifically, *business level* security issues include unauthorized access, malicious program infection, unpredictable state, and transaction-ordering dependence. The *virtual machine level* security issues include stack size limit, generating randomness, and time constraints. The *code level* security of smart contracts is a critical issue to blockchain applications [31]. The volume of transactions involved in smart contracts in the blockchain is enormous, and more practical scenarios are needed to test the system stability to find potential code vulnerabilities. Smart contracts could be applied in more complex situations, and the complexity and technical difficulty of the contract code may also increase accordingly. Typical code level security issues of contracts include *call to the unknown*, *gasless send*, and *deadlocked state* [33]. Reentrancy and unpredictable states are also common code vulnerabilities [37]. Failure to encode a correct state machine (e.g., neglecting to check the current state and omitting specific transitions) is the most frequently observed issue.

To verify the security of contracts, it is of considerable significance to capture their semantics and the security properties from the bytecode being executed [38]. Tsankov *et al.* [39] proposed a security analyzer named Securify, which automatically extracts precise semantic information of the security of smart contracts from the code. Fig. 4 illustrates how Securify finds a security problem. The input factors, namely, Environment Virtual Machine (EVM) bytecode and security patterns, are marked with the green color, the output (a violated instruction) is marked with the red color, and the gray color refers to intermediate analysis results. Securify works via 1) decompiling the bytecode into a single static assignment, 2) inferring semantics of the smart contract, and 3) matching the violated patterns of the restricted write property. Securify can check whether contract behaviors are safe or not concerning a given property via compliance and violation patterns. To inspect the logic security of smart contract code, some scholars have proposed the automated security process method [40] and the symbolic execution system [41] to identify security bugs.

In the stage of contract design, a semantic framework is needed for aiding the design of contracts and generating smart contracts via a set of design patterns automatically [33]. New security-related design patterns (e.g., Rate Limit and Balance Limit) could be designed to code smart contracts [35]. Also, more security properties (e.g., call integrity and atomicity) for smart contracts could be defined to model the semantics of bytecode for obtaining executable code [38]. However, complex semantics still impose

TABLE 2
An Overview of the Implementation Security of Typical Blockchain

Scenarios	Goals	Issues	Countermeasures	References
Internet of Things	Full autonomy capability on processing and exchanging data without human intervention	TPS, privacy violation, denial-of-service, network disruption	Robust identification and authentication of devices	[45], [46], [47], [48], [49], [50]
Shared economy	Enforce the agreement between demanders and suppliers of services without any trusted party	Leak privacy of involved parties	Zero-knowledge proof	[51], [52]
Electronic medical system	Deal with the security and privacy issue in the electronic medical system	Interconnect multi-organization	Sidechain	[53]
Smart city	Provide better services to its citizens while ensuring optimal utilization of resources	Digital disruption	Fraud detection & robust consensus	[54], [55]
Smart grid	Solve the trustworthiness issue of decentralized energy exchanges	Privacy protection of trading data	Zero-knowledge proof	[56], [68]
Social manufacturing	Endow intelligence to every entity on the manufacturing network	Bonding the physical and cyber world	Digital twin technology	[58], [67]

significant challenges to automate the coding of smart contracts in a blockchain securely.

3.2 Implementation Security of Blockchain

Apart from the well-known cryptocurrency and blockchain-based Fintech applications, there are broad sectors of blockchain implementations in the contexts of Internet of Things (IoT), shared economy, healthcare systems, smart city, smart grid, social manufacturing, and supply chain management [42] in social services [43]. Consequently, much risk exists when implementing blockchain. The integration of blockchain with existing systems may impose substantial challenges in real businesses. Implementation of high security requires rigorous testing of critical code. Original business models may not fit in blockchain-enabled business logic [44] as the realization of security is strongly correlated with deployment environments. Table 2 provides an overview of the implementation security of typical blockchain-based systems.

Internet of Things (IoT) is a critical enabling technology for the interactions of devices to exchange data for smart decision-making [45]. However, lacking security countermeasures makes the IoT network vulnerable to cyber threats and attacks [46], which thereby has an impact on the privacy protection of the involved stakeholders [47]. It is cumbersome to create a centralized authentication system because of the massive data scale and high costs of server maintenance costs for IoT [48]. The capabilities of blockchain, including tamper-resisting, transparency, auditability, and network resilience, can amend the architectural shortcomings of centralized IoT and industrial networks [49]. With heterogeneous devices ranging from sensors to servers, a dynamically adaptable multi-layer security architecture could be designed with intelligent standardization of the networked IoT devices [50]. The deployed protocols, together with conversion mechanisms, need to interoperate at different layers of the IoT network.

With the increase of the shared economy scenarios such as digital copyright management and asset heritage, few users are eager to adopt blockchain to enable decentralized applications due to security issues arising from unsuitable business models. In a conventional centralized operation architecture, security risk of the trusted center itself becomes the core problem in system security [51]. Trust-free systems are usually developed to support the shared economy by enabling complex interactions among participants who require high trust [52]. While blockchain-based applications have many desirable metrics, they may leak private information of involved participants due to its openness to the public network. Nevertheless, challenges remain in engineering trust-free systems in the shared economy because the intricacies of trust vary with the context of blockchain. Meanwhile, it requires different interfaces to build blockchain ecosystems.

Electronic medical systems are playing a critical role in improving the healthcare of people. Patient health conditions can now be monitored continuously, processed remotely, and transferred to a cloud medical data center. The growing volume of data managed by the medical system implies higher exposing of sensitive and private data. The privacy protection requirements in the transmission and storage process are of significant concern [53], which needs to satisfy specific demands on data availability and system resilience. The primary difficulty of adopting blockchain in the electronic medical system is how to build secure interconnections across multiple organizations and hospitals. Sidechain technologies may resolve this challenge.

Smart city is a vision of using new generations of information technology to manage cyber, physical, and social infrastructures to provide better services to its citizens while maintaining the optimal utilization of resources. Biswas *et al.* [54] presented a blockchain-enabled security model integrally engaging with resources to provide a secure environment for the smart city. Dorri *et al.* [55] showed a blockchain-enabled security system for privacy protection of the vehicular ecosystem. However, digital disruption imposes great challenges related to implementing security and information privacy. Challenges such as fraud detection and robust consensus mechanism may surface in the blockchain-based smart city system.

Smart grid is envisaged to offer sophisticated consumption monitoring and energy trading via bi-directional communication flow. Blockchain can help to resolve the trustworthiness issue of decentralized energy exchanges, enabling automated and auditable multi-party transactions based on contracts between decentralized energy providers and consumers. Smart contracts could be utilized to facilitate the monetization of energy transaction flows and financial transactions without the support of a trusted third-party, and thereby to reduce the operation costs and to increase the resilience of the energy integration system [56]. Internet of Energy is a potential practical networking approach for the smart grid. Huang *et al.* [57] proposed the lightning network and smart contract (LNSC) model to improve the security capability of trading in the authentication and scheduling among electric vehicles and distributed charging piles. However, the privacy protection of consumption trading data remains a critical issue.

The sustainability goal of the government calls for investigation on how blockchain can make manufacturing more sustainable. Social manufacturing is a vision of open-sourced product manufacturing processes. An increased requirement for prosumers leads to verifying the quality and authenticity of individualized products. Leng *et al.* [58] proposed an anti-counterfeiting system by integrating chemical signature with blockchain. Specific chemical signature data is physically bonded with the parts and then linked to a securitized blockchain, making transactions in the manufacturing network trustworthy. Smart contracts can be introduced for crowdsourcing of machining tasks in the collaborative manufacturing paradigm [59], [60], [61] and supporting the decentralized scheduling in the workshop level [62], [63]. Digital twin [64], [65], [66] is a key enabling technology of authenticating the subjects and ensuring security in synchronizing blockchain with the physical system.

Although blockchain promises to facilitate the sharing of information across industrial partners, it is of great importance for decision-makers to ascertain their specific situations for their particular business contexts [13]. The scalability of blockchain-based system is another practical issue in its implementation process [67]. Blockchain could be implemented only if it is applicable and offers better securities for achieving more business benefits.

3.3 Operation Standards and Regulations

Blockchain is immature in the areas of scalability, performance, and interoperability with other systems. In addition to technical challenges, enterprises face management challenges since blockchain must be assimilated within complex institutional, regulatory, social, economic, and physical systems [69]. The open-source blockchain platforms create anomalies in attaining a boarder sense of unified approaches with its own standards and code [15]. Standardization of terminology and technologies is critical for optimizing the interoperability of different models [70]. Governance is crucial for successfully implementing blockchain while protecting participants and enhancing the system resilience against cybersecurity attacks. Despite the self-governing nature of blockchain, the regulation of a decentralized system remains to be resolved in the actual implementation [71]. The lack of common standards and clear regulations severely limit the ability of blockchain to scale. The lack of standardization and regulation means that it is hard for practitioners to benefit from others' exploration and mistakes. Besides, when users incorporate blockchain into the business context, they need to identify which blockchain models fit their specific requirements. The standardization for evaluating the performance of security needs to be conducted previously (Table 3). For instance, Standards Australia is exploring global standards for blockchain technology with ISO. Meanwhile, the R3 Blockchain Consortium has started to develop industry standards for interbank applications. The General Data Protection Regulation (GDPR) from the European Union identifies privacy protection demands on the processors and controllers [72]. Standardization in blockchain includes basic data models, consensus algorithms, and smart contracts [70]. Standards play critical roles in certifying the interoperability among multiple blockchain implementations. The regulatory works promote future innovations of blockchain [73].

TABLE 3
Typical Standardization Work Related to Blockchain

Type	Group/Content
World Wide Web Consortium (W3C)	Credentials Community Group, Digital Verification Community Group, Blockchain Community Group, Verifiable Claims Working Group, Interledger Community Group, Web Ledger Protocol
ISO TC 307	Joint ISO/TC 307 - ISO/IEC JTC 1/SC 27
Standards Australia	Roadmap for Blockchain Standards
International Telecommunications Union	Focus Group on DLT (FG DLT)
IEEE	Blockchain and DLT
SWIFT	Blockchain and DLT
European Union	General Data Protection Regulation (GDPR)
China Electronics Standardization Institute	Reference architecture of blockchain

However, rules and regulations will affect more new security risk complexity rather than a technical issue. Guo and Liang [74] proposed a regulatory sandbox of industry implementation to give a more flexible space for innovations while imposing simplified access standards and procedures. A maturity model helps guide organizations to make decisions more systematically in the blockchain-implementation process [75]. A benchmarking system is also practical for evaluating the data processing performance of blockchains [76]. Particularly, operation standards and regulations are necessary for the redactable blockchain and controllable blockchain [77], or editable blockchain [78] to remove and rewrite inappropriate data. To create trust, it is necessary to establish standards to address concerns of security, resilience, privacy protection, and governance in blockchain implementations [79]. Enforcing restrictions on the automatic execution of transactions of blockchain directly could reduce the regulatory compliance and auditing costs [80]. However, any regulation of the technology might hamper its development until it has been adequately tested.

3.4 Fraud Detection and Risk Prediction

Fraud detection is a critical security aspect in the running process of information systems, such as the tax administration system [81]. Fraud detection usually relies on rules and schemes to recognize usual from suspicious and disruptive behavior. The rules and schemes may be summarized or learned from the data mining and analysis of behavior patterns. Scholars have utilized the blockchain to solve some fraud detection issues in information systems [82]. Meng *et al.* [83] reviewed the intersection of intrusion detection and blockchains. Blockchain not only improves the capability of fraud detection but also cut down illegitimate manipulation [84].

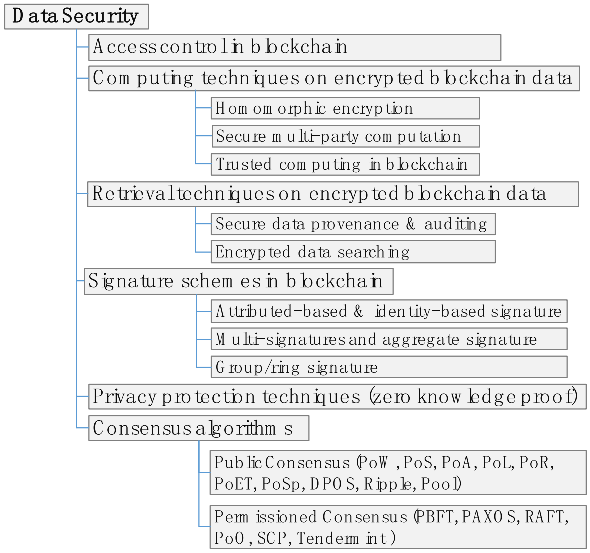

Fig. 5. Major aspects of data security in the blockchain.

However, the blockchain-based application suffers from objective fraud, subjective fraud, and rating fraud [85]. Thus, fraud detection is needed to enhance its robustness. Feng *et al.* [86] presented cyber-insurance and cyber-risk management approaches to neutralize cyber-attacks on the blockchain service network. Fraud detection in blockchain could be deployed via two aspects, namely, preventative control and detective control. Preventative control can monitor the activity of users proactively, predict the potential risk/fraud, and exert countermeasures. Detective control can perform audits and what-if analysis via dedicated criteria in blockchain [87]. There is a pressing need to predict and prevent potential threats from detecting existing attacks. The key is how to identify potential risks automatically and effectively with minimal human intervention.

4 Data Security in Blockchain

Data security in the blockchain can be characterized into integrity, confidentiality, and availability. This section surveys data security issues in blockchain from the aspects of cryptography, signature schemes, encryption techniques (including computing and retrieval), privacy protections, and consensus algorithms (Fig. 5).

4.1 Access Control in Blockchain

Access control has become more complicated in evolving information systems from integrated systems to distributed, cloud-based, and blockchain-based applications [22]. In blockchain research [88], [89], [90], [92], fine-grained access control of decentralized data is usually maintained by combining smart contract and Attribute-based Encryption (ABE) schemes. A smart contract can store the updated ciphertext of ABE, express the logic semantics of authorization, and flexibly define access control policies for removing and editing the data. Recently, scholars tried to combine a smart contract with machine learning models to provide automated, dynamic, optimized, and self-adjusted access control (authorization) [93].

Although smart contract-based access control has many advantages, scholars need to deal with security issues for improving the availability of blockchain. Access control strategies in blockchain are Public Key Infrastructures rather than a trusted Certificate Authority and can lead to significant security improvements [94]. The Stealth Address (SA) technique has been adopted in blockchain to make it unlikable among multiple payments made to the same payee [95]. However, some variants of SA techniques lack enough security assurance [96]. A robust SA method is needed for preventing data leakage and attacks.

In the ABE schema, private key is associated with the ciphertext data after encryption to a specific set of properties. Only when the property of the private key matches the property of the ciphertext can the user decrypt it [97]. Lewko and Waters [98] proposed a distributed ABE algorithm to allow participants to publish properties and distribute keys as administrators. The algorithm supports combinations of features to set the access control policy when encrypting data in the blockchain. However, the immutability of blockchain prevents the updating of attributes of ABE. Thus, its adoption has been severely hindered by the incompatibility between the immutability of blockchain and the essential need for revocations attribute of ABE. How to enable secure attribute updating in ABE-based access control for blockchain is challenging.

A redactable blockchain to secure and control access to the data is a potential solution to allow access policies. Adams proposed a hybrid fine-grained access control model in blockchain to store participant data postings in long-term–isolated environments [99]. Fig. 6 shows the process of one encrypts his postings in a block and gives the keys to another for the specific shared postings. In detail, Alice's biometric is input to the fuzzy extractor component to generates a uniformly random key K, from which the derivation function derives n symmetric encryption keys, along with a private signing key S. These symmetric keys are used to encrypt Alice's n postings, which are assembled into a block. The key S is used to digitally sign the block appended to the blockchain. Alice can share key k_2 with Bob if she wishes to share posting #2 with him. Bob can thereby get the ciphertext c_2 from the blockchain, decrypt it with k_2, and obtain the plaintext posting m_2. It is a hybrid use of the randomness of fuzzy extractor-generated binary strings, the illegibility of AES encryption, the unforgeability of ECDSA digital signature operations, and the collision-resistance of SHA hashing.

Many access control schemes in blockchain [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99] are complex to implement or use. Designing an efficient and easy-to-use model that enables both privacy and fine-grained access control in a blockchain is in practical need. How to efficiently and securely achieve revocation in access control schemes (i.e., to remove access to previously-shared posts) is challenging.

4.2 Computing Techniques on Encrypted Blockchain Data

4.2.1 *Homomorphic Encryption in Blockchain*

The attacks, such as collision attack, primage attack, and attacks on user wallets, motivated homomorphic encryption [100]. Homomorphic encryption supports algebraic calculations executed directly on the ciphertext instead of plaintext [101], [102], resulting in the confidentiality of data [103].

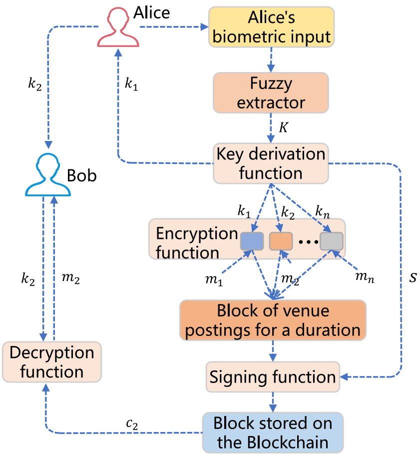

Fig. 6. A hybrid fine-grained access control model in blockchain [99].

Enabling the homomorphic encryption in blockchain could support users' data without any information about themselves [104]. Hsiao *et al.* [105] combined the blockchain with homomorphic encryption to perform the e-voting without any trusted third-party. The full-homomorphic encryption mechanism is usually inefficient, and thus partial homomorphic encryption attracts more attention from researchers [106] (e.g., the Pedersen commitment [107] in Enigma).

The homomorphic signature is proposed as an essential primitive to perform data authentication and to assure the information correctness [108]. There exist different kinds of homomorphic signatures, including the linear homomorphic signature scheme, polynomial homomorphic scheme, and leveled-fully homomorphic scheme. For instance, Lin *et al.* [109] designed a linear homomorphic signature scheme in identity-based cryptography. The proposed identity-enabled linearly homomorphic signature avoids the shortcomings of using public-key certificates. Li *et al.* [110] proposed a homomorphic signature scheme for networking and inter-operation of multiple devices in IoT. When integrating the homomorphic signature into the blockchain model, the computation and analysis could be executed while realizing the data authentication. However, in practical blockchain applications such as the federated learning model, other secure computing techniques such as pseudo-random noise generation and differential privacy are utilized as an alternative solution, due to the inefficiency and immaturity of full-homomorphic encryption in practice. Multiplicative depth of circuits is the primary practical limitation in the performance of the majority of homomorphic encryption algorithms. In terms of malleability, homomorphic encryption schemes have weaker security properties than non-homomorphic schemes. Still, they lack practical and efficient full-homomorphic signature schemes for blockchain in addition to the Gentry algorithm, especially for enabling the security and deep learning of decentralized blockchain data efficiently.

4.2.2 Secure Multi-Party Computation in Blockchain

Extending blockchain to support private data opens the door to many exciting new applications in healthcare, insurance, finance, etc. [111]. It is critical for multiple parties to compute a specific task while maintaining their input privacy and fairness collaboratively [112]. Secure multi-party computation (SMPC) [113] is cryptography for enabling multi-parties to cooperatively compute on their joint inputs while making those inputs private [114]. Unlike the conventional cryptographic methods that the adversaries are outside of the network to ensure data security and communication integrity, the adversaries in SMPC are also participants [115]. The decentralization characteristic of blockchain makes SMPC an ideal model in applications that needs privacy. To analyze a massive amount of data on the public blockchain, Enigma [115] used SMPC to offload intensive computations to off-chain. PlatON [116] delegated all control and incentive mechanisms to the smart contract, in which computation tasks and data can be kept confidential.

Many issues exist in integrating SMPC within blockchains, such as computation cost [117], poor scalability, and computation latency for the large-scale networks [118]. To obtain fairness against malicious behavior, full nodes providing computation/storage resources are required to submit a security deposit to a smart contract. Most SMPC methods are not verified practically in terms of communication bandwidth and computation costs. Some ongoing works try to make scalable solutions via hardware design or multi-processor architecture that supports the efficient simultaneously-computing on the joint data.

4.2.3 Trusted Computing in Blockchain

Some blockchain applications, such as sealed-bid auction, need verifiable computations [119]. Trusted computing (also termed as verifiable computation) improves data security by introducing an incentive mechanism [120] and usually offloads the computation of some functions to other untrusted clients while maintaining verifiable results [121], [122]. In a blockchain, the smart contract can only be verified by the miner's repeated computation to get consensus, which is not verifiable and results in the inefficient computation [120]. A malicious node may return forged computations to other parties in Enigma [115] and PlatON [116]. Therefore, verifiable computation (e.g., xjSnark framework [123]) is introduced to guarantee the integrity of the computation and the correctness of the computation result [118]. Incorporating blockchain into trusted execution environments (TEEs) helps the privacy protection in the executing implementations [124].

Combining the hardware design (e.g., the Intel SGX technology) with an execute-order-validate smart contract execution system could prevent rollback attacks on the enterprise-level TEE implementations [125]. Fu and Fang [126] employed an encryption algorithm for enhancing data privacy and then utilized the Proof-of-Credibility to build trusted computing in the social network. The integrity of computing can be ensured only via verifiable results (Fig. 7). Malicious nodes cannot obtain permission to the data computing in the TEE. Other trusted computing techniques include 1) building off-chain channels to resolve exchanges bilaterally without incurring a blockchain transaction, which boosts the overall throughput of the system; 2) addressing state continuity for memoryless secure processors that have access to a blockchain; 3) leveraging trusted execution to enhance the resilience of consensus protocols.

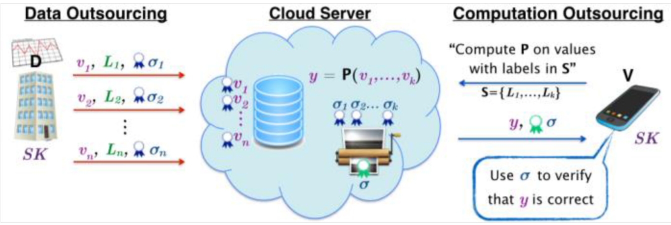

Fig. 7. Rational of trusted computing on outsourced data [127].

Distinguishing failed nodes from compromised nodes may send incorrect information to other nodes. Thus it is critical to achieving trusted computing by identifying the information transmissions [128]. Although the amount of verifiable computation is negligible compared with mining in consensus algorithms such as Proof-of-Work, trusted computing demands that device suppliers obey the technical specifications and community consensus for enabling interoperability among various computing stacks. Also, their technical specifications are still changing due to the evolution of blockchain. How to avoid the constraint that the blockchain must run the verifiable computation in an EVM is of great significance.

4.3 Retrieval Techniques on Encrypted Blockchain Data

4.3.1 *Secure Data Provenance and Auditing in Blockchain*

Holding complete transparency and control over digital identity will become far more common. Data provenance is based on metadata that captures the creation, change, and operation event that happened on the data. Provenance monitors observe nodes externally and record the evolution of data securely. Secure data provenance is critical to achieving data privacy and accountability. Assembling an accurate provenance record across the distributed environment can be realized by incorporating blockchain into the system. The blockchain transactions could anchor the provenance records to track data operations while preserves data privacy as well [129]. Incorporating smart contracts into blockchain could prevent malicious alteration data [130]. For instance, Liang *et al.* [131] proposed a decentralized data provenance architecture named ProvChain to enabling tamper-proof provenance, privacy protection, and low-cost cloud storage reliability. Tosh *et al.* [132] provided an assured data provenance method and modeled the block withholding attack while considering the incentive reward factor. However, new emerging regulations impose more data provenance protection demands on the processors and controllers.

Secure data auditing maintains an accurate audit history tracking of data operations/interactions, which is the precondition to distribute encrypted user-sensitive data securely. Blockchain could enable data usage to audit with high availability and privacy [133]. Deploying publicly auditable smart contracts on the blockchain could provide data accountability and provenance tracking ability, which increases data transparency [72]. Amir [134] customized a data authentication protocol for integrating blockchain with local storage to decentralized sensitive data. The protocol abstracts encrypted interactions to form a dashboard for secure auditing, testing, and evaluation data. Xia *et al.*

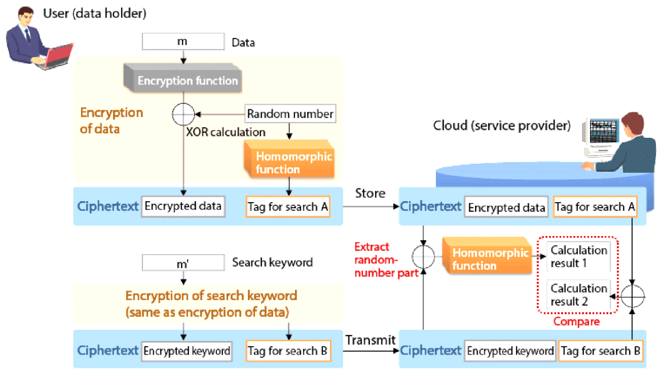

Fig. 8. Mechanism of searching on encrypted data [146].

[135] proposed a blockchain-based data auditing system named MeDShare to secure control for shared cloud medical datasets. However, an empirical analysis of metadata utilization suggests that users need to improve the auditability of blockchain transactions and smart-contract protocols [136]. Meanwhile, there are still some other crucial challenges, such as data assurance and resilience issues.

4.3.2 *Encrypted Data Searching in Blockchain*

A secured searchable data service is essential in a blockchain-type storage system for the data owner to upload their data in an encrypted form and enable others to search it [137]. However, encryption in blockchain limits the computability of the data block. It is complex to search the keywords in encrypted transaction data. On the other hand, keeping confidentiality in searching encrypted data on an untrusted server is tough [138]. Conventionally, the cloud storage adopted in a searchable symmetric encryption (SSE) model is usually implemented privately. In a public blockchain system, there exist two concerns in an SSE. The first concern is the security of encrypted data searching, which is critical for privacy protection and trustless computation [139]. The second concern is how to increase search efficiency [140]. Zhang *et al.* [141] introduced TKSE (i.e., Trustworthy Keyword Search Encryption) to realize server-side verifiability in cloud computing. It preserves servers and data from being attacked by malicious users in a storage step (Fig. 8). However, keyword-based search methods suffer from the limited capability of reflecting all search intentions of the user.

Moreover, preventing the service provider from forging the search result is difficult in a trustless context [142], [143]. It is necessary to put the data on a public blockchain to resist malicious adversary. Utilizing smart contracts could provide an encrypted data searching service [144]. The smart contract-based SSE mechanisms could ensure that the participants get the expected results [145]. Nevertheless, with the growth of data amount, the search issue is more intractable. Various efficient searchable encryption models should be developed according to implementation scenarios.

4.4 Signature Schemes in Blockchain

Conventional signature algorithms in blockchain include lattice-based signature [147], blind signature [148], ring signature [149], aggregation signature [150], multi-signature

[151], and threshold signature [152], [153]. This paper reviews the signature schemes in blockchain from the following three aspects.

4.4.1 Attribute-Based and Identity-Based Signature for the Blockchain

There are two kinds of cryptosystems, namely, attribute-based signature (ABS) and identity-based signature. The first kind refers to that the public key could be reasoned from the user's identifiers. The second kind can simplify certificate-based public key models to realize authentication in the blockchain. The attribute-based scheme is a useful tool to form cryptographic primitives [154]. ABS enables the signer to obtain a fine-grained control ability to identify information when endorsing a message. The signature provides a reliable guarantee for signers on privacy protection and a security guarantee for verifiers on the unforgeability. Many derived models have been proposed [155]. Sun *et al.* [156] proposed a decentralized ABS model for preserving data privacy in healthcare blockchain. Guo *et al.* [157] presented an ABS model with multi-authorities that do not need a third party to generate the public and private key. It prevents the escrow issue from happening in blockchain. Nevertheless, both two kinds of cryptosystems are still insufficient to satisfy the distributed demands.

4.4.2 Multi-Signatures and Aggregate Signature in Blockchain

The most widely used method of creating the contract is a multiple-signature technique called multisig [15]. Multi-signature enables multiple users to sign the same document. For instance, Boneh *et al.* [158] proposed the accountable-subgroup multi-signature model for compressing signature and aggregating the public key. The multi-signature-based authorization model could improve the security, extensibility, and programmability of Internet resources [159]. Hybrid use of blockchain, multi-signature, and anonymous encrypted data streams enable peers to negotiate and secure transactions [151].

An aggregate signature scheme supports shorten the size of the signatures on multiple messages. Yuan *et al.* [150] proposed an aggregate signature model for blockchain-based on the elliptic curve discrete logarithm and bilinear maps, where the size of the signature on the blockchain remains unchanged under a different number of inputs. Li *et al.* [160] used an anonymous vehicular announcement aggregation model for privacy-preserving incentive announcement. However, enabling non-deterministic users to generate and send signatures anonymously is still insufficient in the untrusted context.

4.4.3 Group/Ring Signature in Blockchain

Blockchain has obvious limitations for its uncertainty on the transactions to be confirmed. Dash uses a technique known as CoinJoin, which provides different variants of anonymity for multiple transactions [161]. However, Dash still suffers from the disclosure privacy of the users when malicious users abuse the server. Further, Monero [149] was proposed as a hybrid cryptographic model independent from the central nodes. There exist two kinds of models in Monroe: stealth address [96] and ring signature. Stealth addresses enhance the privacy of participants [162]. Ring signatures enable any participant to generate a signature representing the group without exposing its identity [163]. A linkable ring signature [164] provides linkable anonymity in a public blockchain. Scholars have improved the linkable ring signature from the following aspects: 1) storage space-saving capability [149], 2) multi-layered structure to enable verifiable hidden key details of transactions [165], 3) interactive incontestable scheme by which transactions can be written into blockchain in a non-repudiation manner [166], and 4) Lattice-based one-time Linkable Ring Signature (L2RS) scheme for absolute anonymity and privacy-preserving in the post-quantum stage [167].

The ring signature could be integrated with other techniques to enhance anonymity. Heilman *et al.* [148] combined blind signatures with Bitcoin transaction contracts to solve the anonymity and fairness problem for both transactions on and off the blockchain. Wang *et al.* [168] proposed a self-management anonymous electronic voting scheme while integrating homomorphic encryption and ring signature. A CryptoNote is designed to provide complete anonymity associated with key re-usage, and tracing [169] is (Fig. 9). In detail, a user (e.g., B in Fig. 9) could hide the link to his output among the foreign keys. To prevent double-spending, the user can derive the Key image from his One-time private key. Then, the user can sign the transaction and appends the resulting Ring Signature to the end of the transaction. In general, the incontestability of dealers and the unforgeability of owners are two ultimate goals of securing a signature scheme.

4.5 Privacy Protection Techniques in Blockchain

Although the blockchain relies on asymmetric encryption technology, it lacks identifying both the sensitivity and security level of data provided. The privacy protection is the primary goal in the data security level of blockchain systems [170]. Sensitive information is still easy to be obtained by cluster analysis and correlation analysis on an open distributed ledger. Zero-knowledge proof (ZKP) is a model with which the user can prove to another user that the statement is correct with high probability without revealing any information except the statement [171]. A zero-knowledge proof satisfies properties of completeness, soundness, and zero-knowledge. Combined with robust encryption methods and techniques [172], zero-knowledge proofs establish a much more secure way of storing and accessing data, enhancing the ability of data managers to protect critical information [173]. Zero-knowledge proofs can guarantee that transactions are correct even though the details remain hidden (e.g., Zerocoin [174], Zerocash [175], zkLedger [176], and Solidus [177]). Thomas *et al.* [178] proposed the ChainAchor framework for protecting privacy in a permissioned blockchain. Kosba *et al.* [179] proposed a ZKP-based privacy blockchain system named Hawk to generate a cryptographic protocol for enabling contractual parties to interact with the blockchain. The advantage of ZKP lies in that auditors can efficiently audit transactions [180]. However, ZKP suffers from many security issues on scalability [181], computation cost [182], as well as implementing complexity

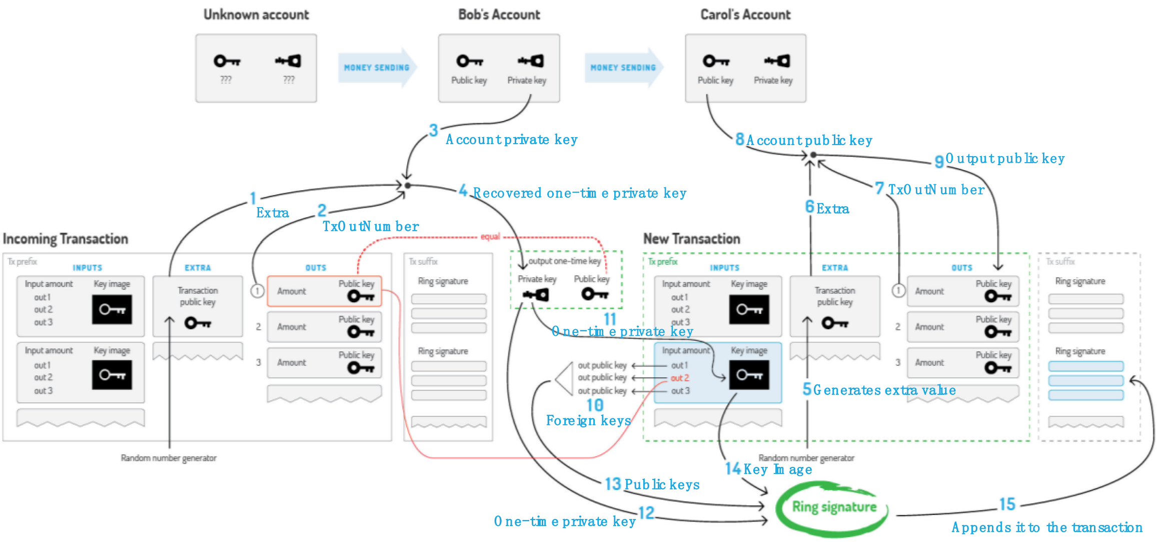

Fig. 9. A standard CryptoNote transaction [169].

TABLE 4
Signature Schemes and Privacy Protection Techniques in the Blockchain

Techniques	Advantages	Security issues	References
Homomorphic Encryption	Allowing arbitrary computing calculations on the encrypted dataset without the decryption key	Lack of efficient homomorphic encryption implementation	[102], [104], [105], [106], [107], [109]
Secure Multi-party Computing	Enabling distrusted nodes to compute over mutual inputs while ensuring confidentiality jointly	Computationally intensive impractical, inefficiency and not scalable	[111], [112], [115], [116], [117], [118]
Trusted computing	Allowing servers to provide improved security on that which is currently available	How to enable more ubiquitous computing tasks verifiable efficiently	[119], [120], [121], [122], [123]
Secure data provenance	Recording the history of the creation, change, and operations performed on the dataset	The privacy and availability of the provenance data	[129], [130], [131], [132]
Secure data auditing	Keeping a trust-less audit tracking for data operations and controlling access to the dataset	Data assurance and resilience issues are challenges	[39], [72], [133], [134], [135], [136]
Encrypted data searching	Enabling the encrypted data on an untrusted server searchable without leaking information	The fairness of searching service providers and users	[139], [140], [141], [142], [143], [144], [145]
Multi-signatures	Requiring multiple keys to finish a transaction	Original signer forgery attack	[15], [150], [151], [158], [159], [160]
Group/Ring Signature	Providing a characteristic of linkable anonymity	Privacy-preserving in any post-quantum secure applications	[148], [149], [157], [167], [168]
Zero-Knowledge Proof	User can prove to another that the statement is correct via revealing the veracity of the statement	Poor scalability, expensive proof generation, and engineering complexity	[122], [173], [174], [175], [176], [177], [178], [179], [180], [181], [182]

[177]. For instance, the security of zkSNARKs (provides zero-knowledge proof using elliptic curves [181]) used in Zerocash has not yet been proved in theory.

Table 4 provides an overview of data security techniques. The integration of blockchain with these cryptographic techniques can perform more secured functions that are difficult to be realized by the blockchain itself or other technologies. Still, security issues in the integration process need to be further addressed.

4.6 Consensus Algorithms for Distributed Data Synchronization

Ethereum blockchain was launched in July 2015 [31], followed by Hyperledger [111], Eris [117], Stellar [118], Ripple [119], and Tendermint. Blockchain needs to motivate participants via sophisticated consensus algorithms in the absence of trust under the Internet environment. It is necessary to propose robust consensus algorithms with higher fault tolerance and anti-fraud ability. The consensus algorithm enables nodes in the distributed system to reach an agreement given faulty processes or deceptive behaviors [183]. It is the indicator from which we can judge the blockchain, whether public or permissioned is. The consensus is the data synchronization used in decentralized blockchain. Any user in the public blockchain can participate in verifications of data. Permissioned consensus-based blockchain has strict access control for the dataset while enabling the privacy protection of data transactions.

4.6.1 *Consensus for Public Blockchain*

Well-known consensus algorithms for public blockchain includes Proof of Work (PoW), Proof of Stake (PoS), Proof of

TABLE 5
Comparative Analysis of Public Blockchain Consensus Algorithms

Algorithms	Ref.	Advantages	Issues
POW	[185]	Complete decentralization, ad free entry, and exit of nodes	51% Vulnerability, selfish mining attack, and double-spending
POS	[188]	Shorten the time to reach consensus	Requires mining
DPOS	[189]	Second-level consensus validation	Relies on tokens, while many applications do not require tokens
PoA	[190]	Integrates POW with POS while producing less delay	Demands a large number of computations for mining
PoL	[191]	Low-latency transaction validation and equitably distributed mining	It is expensive to violate the security requirements of the TEE for all participants
PoR	[192]	Provide quality-of-service guarantees	An efficient set of parameters, choices, protocol variants, and tradeoffs in the implementation of POR remains a problem
PoET	[194]	Use trusted computing to regulate random waiting times for the generation of data block	Lack of theoretical security analysis
PoSp	[195]	Replace the computation in PoW as a disk space.	An efficient implementation remains a problem.
Ripple	[196]	Circumvent the network synchronization demand by using collectively-trusted subnetworks in the super network	Lack of clearly-defined incentive verification mechanisms

Activity (PoA), Proof of Luck (PoL), Proof of Retrievability (PoR), Proof of Elapsed Time (PoET), Proof of Space (PoSp), Delegated Proof of Stake (DPOS), Ripple, and Pool [184]. As information is visible across the entire public blockchain network, transactions based on the exposed data could be tracked by users, and thereby, individuals may not be able to obtain privacy protection under this mechanism.

Although the Bitcoin has been thoroughly analyzed, the security provisions of variant PoW-powered blockchains have not obtained enough attention [185]. The 51 percent vulnerability [186], selfish mining attack [187], and double-spending are still significant security issues in PoW-powered blockchains. PoS-powered blockchains stake with rigorous security guarantees. It shortens the time to reach consensus. Gervais *et al.* [188] presented a reward mechanism for incentivizing PoS for preventing selfish mining. However, it still requires mining, which has not solved the pain points of commercial application.

DPOS-powered blockchain is a candidate for the inefficient PoW. Andreina *et al.* [189] proposed two DPOS consensus protocols to solve the issue of nothing-at-stake and stop malicious users from launching long-range attacks. However, it relies on tokens, while many commercial applications do not require tokens. PoA is designed to ensure that the data transactions are genuine. It is a mixed model that integrates POW with POS while producing less networking delay [190]. PoA still needs massive computations for mining. PoL-powered blockchains use a trusted execution environment (TEE) system's random number generator to select a consensus leader with the advantages of highly-efficient validation and deterministic confirmation [191]. However, it is expensive to violate the PoL assumption that all participants should satisfy the security demands of the TEE. PoR allows an archive to reliably produce and transmit a concise proof that a verifier can check and recover without downloading all the files [192]. PoR is a type of cryptographic proof of knowledge (POK) [193] to manipulate large-scale data. Searching an efficient set of modeling parameters, protocol variants, and points of equilibrium in the practical implementation of POR remains a problem under rigorous quality-of-service guarantees. PoET uses trusted computing to regulate random waiting times for the generation of the data block. However, the PoET system lacks a thorough theoretical security analysis for evaluating its strength in front of failures and malicious attacks [194]. PoSp is a method that a service demander needs to spend a large amount of storage space instead of the computing complexity in PoW [195]. However, searching for an efficient set of modeling parameters, protocol variants, and tradeoffs in the implementation is costly. Ripple circumvents the demand that all participants in the system communicate synchronously by utilizing collectively-trusted subnetworks within the more extensive network. It is a low-latency consensus model with high robustness for Byzantine failures [196]. However, the decentralization character is doubtful in Ripple since it lacks a clearly-defined incentive mechanism

The consensus mechanism of public blockchain may suffer from a coordinated attack since it is assumed that most of the participants are honest to run the blockchain application [30]. The existing consensus mechanisms have the characteristics of decentralization and trust-free, leading to the difficulty in balancing equality, efficiency, and energy consumption [197]. The POW has proved to be the most mature consensus mechanism at present, which is entirely decentralized, but requires many resources to "mine" and takes a long time to reach consensus. POS takes less time to reach consensus than the POW mechanism, but mining is still needed. DPOS can achieve second level consensus verification. However, it also depends on the token mechanism. Pool verification is developed based on the integration of traditional distributed consistency and data verification mechanism. It has been widely used in the industry blockchain. Table 5 summarized the advantages and disadvantages of consensus mechanisms. One challenge faced by blockchain is that consensus on the attack had to be reached in a disseminated environment because it is decentralized with no central authority or node.

The energy consumption of the public blockchain is prohibitive to enterprise scenarios. New attempts (e.g., Fabric) were made to deal with these issues. However, the above solutions are dedicated solely to satisfy the individualized requirements of the specific business context. The existing

TABLE 6
Comparative Analysis of Permissioned Blockchain Consensus Algorithms

Algorithms	Ref.	Advantages	Issues
PBFT	[201]	Reach a consensus despite malicious nodes propagating incorrect information	The additional cost from protocol complexity
PAXOS	[206]	Guarantee safety (consistency) that can prevent it from making progress	Hard to understand and challenging to implement
RAFT	[207]	Easy to understand and implement	Searching an efficient set of parameters, modeling choices, protocol variants, and tradeoffs in the implementation of these algorithms remains a problem
PoO	[208]	Enable offline ownership proofs	
SCP	[209]	Make no assumptions about the rational behavior of attackers	
Tendermint	[210]	Do not need costly mining	

enterprise security systems compromise on performance when adopting complex protocols. Therefore, one potential research agenda in public blockchain platforms is to study the optimization of the consensus algorithm. Some platforms (e.g., Coco [198]) are designed to cut down energy consumption.

4.6.2 *Consensus for Permissioned Blockchain*

The popular consensus algorithm for permissioned blockchain includes Practical Byzantine Fault Tolerance (PBFT), PAXOS, RAFT, Proof of Ownership (PoO), Stellar Consensus Protocol (SCP), and Tendermint [184] (shown in Table 6). Permissioned blockchain is composed of prespecified nodes with the data access authority in the distributed network. Its participants do not fully trust each other, and thus should select their consensus nodes. Meanwhile, private blockchain allows a central authority to be present with higher efficiency in verification and validation of transactions. For instance, a Fabric project hosted by the Linux Foundation enables the blockchain network to be configured to particular scenarios and trust models for running distributed applications.

The primary deficiency of private blockchain is that it does not ensure decentralized security provided by the public blockchain [10]. Conflicts happen among nodes may become malicious [199]. Secondly, unsynchronized and isolated nodes always exist in consensus schemes [200]. It is not conducive to efficient and robust-time synchronization in industrial applications, which is crucial for achieving high accuracy. Thirdly, compared with crash fault tolerance (CFT), the Byzantine fault-tolerant (BFT) system has not been implemented practically because of the substantial cost relative to crash fault-tolerance (CFT) in algorithm complexity [201]. Scholars have proposed many methods to avoid these deficiencies. For instance, Fan [202] proposed a short-lived signature-based PBFT variant utilizing blockchain-based distribution methods to update keys regularly. Liu *et al.* [203] introduced cross fault tolerance to provide the reliability guarantees of both CFT and BFT protocols asynchronously. Sankar *et al.* [204] proposed the concept of quorum slices and federated byzantine fault tolerance. Pîrlea and Sergey [205] presented the formalization of a consensus algorithm with a proof of its consistency mechanized in an interactive proof assistant.

PAXOS is usually adopted in a condition that the system durability and consistency is required, in which the amount of stable state could be considerable. Many variants such as Cheap PAXOS, Fast PAXOS, Multi-PAXOS, Generalized PAXOS, Fast Byzantine Multi-PAXOS have been proposed [206]. RAFT [207] provides a generic method to distribute a state machine over a cluster of nodes while assuring that each participant agrees upon the same series of state transitions, which is more understandable and reasonable than PAXOS due to its separation of logic. PoO [208] enables offline ownership proofs in which copyright holders can prove their ownership without any other third-party. SCP does not need any assumption about the rational behavior of malicious attackers. Compared to decentralized PoW, SCP [209] has lower computational requirements, making it easier to entry and consequently opening up an economic system to newly-join participants. Tendermint [210] does not need costly mining to the Byzantine Generals Problem.

In general, prior research mainly analyzed the security properties of the consensus algorithm by probabilistic reasoning based on a composition of distributions. Engineering blockchain consensus is similar to developing a cryptographic system, and designers should refer to the best-practice on cryptography and distributed security for developing trustworthy systems [211]. Searching an efficient set of parameters, modeling choices, protocol variants, and tradeoffs in the implementation of these algorithms remain problems. An executable semantic model can be developed to prove correctness conditions and the eventual consistency of the system.

5 Infrastructure Security in Blockchain

Blockchain infrastructure becomes more exposed to vulnerabilities than ever before [151]. This section reviews Infrastructure Security in Fig. 10. Generally, infrastructure security contains three aspects: private key management, terminal and networking vulnerability, and compliance enablement.

5.1 Private Key Management in the User Side

The blockchain generates a dual encryption system of the public key and private key employing encryption. However, there is still a lack of a mechanism for key security storage and recovery [212]. Private keys and digital wallets are at risk of being stolen. Once the private key is lost, nothing can

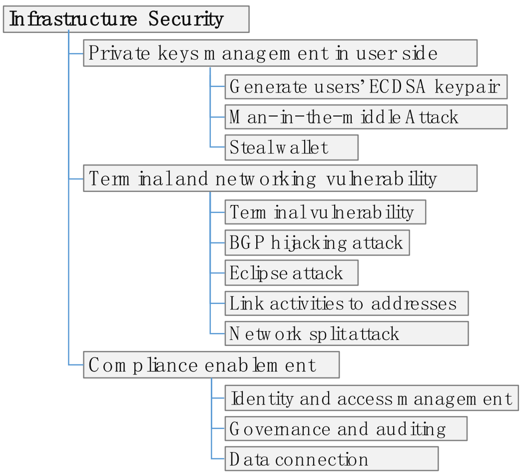

Fig. 10. Major aspects of the infrastructure security in the blockchain.

be done with the account [213]. Secure key management models are recognized as analytical technology for achieving infrastructure security.

Unlike traditional public-key cryptography, private keys in blockchain are managed by users themselves instead of a third-party. Since there is no mechanism for establishing an association between the key and the user's identity in the blockchain, a private key not only protects the privacy of user identity but also leads to high-cost in key recovering. Blockchain applications confirm a user's identity via private keys. The precondition of falsifying transaction information is to get the private key. For instance, Mayer [214] discovered a vulnerability in Elliptic Curve Digital Signature Algorithm (ECDSA): An implementation that does not guarantee enough randomness in the signature allows a malicious attacker generate/recover the private key pair of a user. Therefore, under a decentralized security framework, it is vital to figure out how to establish a more secure private key management mechanism in order to achieve overall security. It is, therefore, critical to design a practical scheme for directly obtaining user keys, even if the number of malicious hosting agents is greater than or equal to the threshold value (i.e., a Man-in-the-middle attack). Thus, a dynamic lifecycle management mechanism needs to be established to replace the current permanent key management methods.

5.2 Terminal and Networking Vulnerability

The terminal linked to the blockchain (including a computer, mobile phone, tablet, and other terminal devices) is a security vulnerability outside of the blockchain itself [215]. Watanabe and Fan [216] proposed a chip-level blockchain security system for the IoT network. Suankaewmanee *et al.* [217] introduced a new blockchain model named MobiChain to secure transactions in mobile commerce without the need for costly mining processes on mobile devices. In general, enabling terminal security needs intensive studies on designing the hardware and securing customized core operating-system-level modules.

The infrastructure security issues at the networking level mainly include the conventional DDoS attacks, Border Gateway Protocol (BGP) hijacking attack, Eclipse attack, link activities-to-address, and network split attack. To disrupt the networking traffic of the blockchain system, malicious users usually tamper the BGP routing, which is a gateway protocol for managing the reachability information across the autonomous system. The BGP guides routing decisions by analyzing the prespecified network paths, policies, and rules. BGP hijacking is the process of rerouting network traffic to a mining pool managed by the attackers and thus to steal digital assets from the users. Apostolaki *et al.* [218] analyzed the impacts of node-level and network-level routing attacks. Because the BGP security extensions have not been widely implemented, the operators of the blockchain network have to rely on a monitoring system. Moreover, solving a BGP hijacking is time-consuming since it is a complicated reconfiguration process [13]. Besides, attackers could launch the eclipse attack to isolate users from the other part of the blockchain network and block their incoming and outgoing interactions [219]. The eclipse attack may lead to other attacks such as selfish mining and splitting mining power.

There are many anti-malware filters to identify the suspected actions in terminal devices through attack pattern matching managed in a central server, vulnerable to malicious uses [10]. Noyes [220] proposed an anti-malware system to manage the learned attack patterns through the blockchain. To establish secure connections light client to each full node, as well as cut-down the client-side complexity and speed-up verification, Costa *et al.* [221] proposed a secure verification protocol for the blockchain named Distributed Lightweight Client Protocol, which requires clients to encrypt a request once, allowing a prespecified set of full nodes to manage it. Lee *et al.* [222] presented a blockchain-enabled firmware update model to check a firmware version securely and to validate the correctness of firmware. Using the private and public keys in conjunction with data encryption may provide the blockchain with a higher level of infrastructure security.

A distributed data storage mechanism creates a border attack range of blockchain. It allows an attacker to has more alternative nodes and terminal devices to access data [79]. Perpetrators could be either insider (authorized users) or outsiders who clandestinely access a system [223]. Wu and Monticelli [224] presented a survey of various network modeling models for security analysis. Protective security countermeasures [225] call for substantial managerial vigilance and an adequate level of awareness for defining the responsibilities of critical roles in the organizations.

5.3 Compliance Enablement

Organizations in blockchain applications are required to demonstrate compliance with various regulations. Compliance enablement is to demonstrate data security in access management and privileges [22]. A valid user awareness program could be developed and implemented to communicate the policies and procedures to all participants and make them aware of the consequences of abuse of information. Also, a periodic compliance evaluation model could be established to track the effectiveness of the security algorithm [18].

Besides, the data connection between blockchain and external data resources is vulnerable. Blockchain and smart contracts often need to interact with the off-chain dataset. Because the contract deployed on the network cannot access

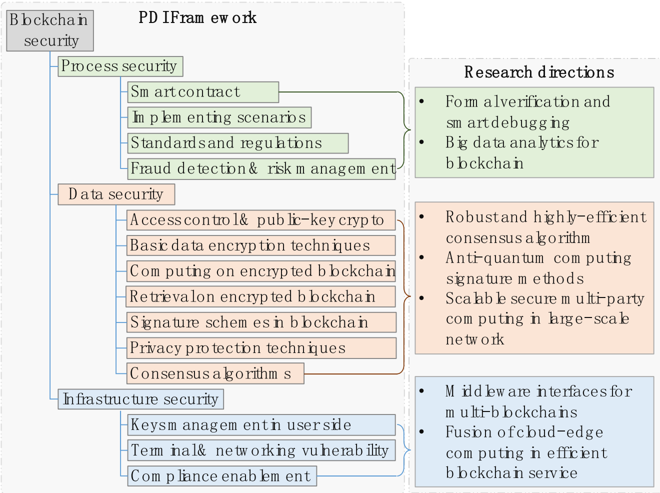

Fig. 11. Research directions from the PDI view of blockchain security.

external data directly through HTTPS, Zhang *et al.* [226] proposed an authenticated data feed system named Town Crier for aiding the robust and secure interaction between HTTPS data and smart contracts. Also, in the Web era, the compliance enablement of blockchain-based applications may be facilitated by integrating with service computing methods.

6 Research Directions

Blockchain needs an integrated technological, organizational [227], policy-based intelligence, and security informatics solution [228]. Based on the above analysis, future directions are gathered (Fig. 11).

6.1 Directions for Enhancing Process Security of Blockchain

6.1.1 Formal Verification and Smart Debugging Mechanism

Extensive adoption of cryptographic algorithms in blockchain may introduce unpredictable vulnerabilities in the implementation processes [30]. The issues of carrying out transactions in a secure manner consistently are vital challenges to blockchain [79]. Current research usually analyzes the security properties of the consensus algorithm by probabilistic reasoning as a composition of distributions. An executable semantics model can be developed to prove correctness conditions and the eventual consistency of the system. From the contract security aspect, the problems in modeling semantics of the contract are troublesome. It is of considerable significance to identify their semantics and the security properties in the bytecode being executed [38]. An automated analyzer to mine semantic information of the security of contracts helps check behaviors as safe or unsafe concerning a prespecified property via compliance and violation patterns. From the implementation security aspect, a regulatory sandbox of implementation could give a more flexible space for innovations while imposing simplified standards and procedures. A verification protocol is a requisite to harness the infrastructure security.

This dimension includes three future sub-directions. In terms of the contract security, new vulnerability scanning methods that could discover unknown vulnerabilities (infer whether there are vulnerabilities that have identical or similar principles to the known vulnerabilities) and optimize vulnerability detection capability is of great significance. Secondly, in terms of the correctness of smart contracts, formulating/designing the standards for the programming and development processes of smart contracts is also critical. Also, visualizing the contract execution process using formal modeling tools such as Petri Nets is a promising direction. Finally, the mathematical model is more rigorous and reliable for formal verification. Combining formal verification algorithms with vulnerability analysis algorithms to complement each other is also helpful.

6.1.2 Big Data Analytics for Blockchain

Since participant behavior in the blockchain network is traceable, many blockchains take countermeasures such as one-time accounts and private keys for protecting the transaction privacy of users, which are not robust enough as required [13]. To pursue a more secure way to share data, blockchain needs to provide significant high-quantity data [79]. Although data in the blockchain is tamper-resisting, attackers can conduct data analysis to extract valuable information [30]. Various statistical characteristics regarding transactions (e.g., sum, skew, variance, and outlier) can be audited correctly without missing any transactions. Techniques such as context discovery, classifiers [229], link prediction [230], graph summarization [231], and flow analysis [232] could be utilized. The public transaction graph could be annotated and analyzed to find and summarize the activities of all participants statistically [233], [234]. Threats to data integrity and tampering with data may affect crucial decisions [235].

When the credibility of data can be assured in blockchain, more trustworthy outcomes would be achieved with artificial intelligence. Three aspects of implementing big data analytics in blockchain could be further studied. Firstly, in the process level, deep learning [236], [237] methods can be introduced to analyze the interaction contexts in the blockchain network for risk and attack prediction. Secondly, most public blockchains adopted incentive mechanisms whose security performance is untested. Deep reinforcement learning could be introduced to analyze attacks on incentive mechanisms [238]. Thirdly, decentralized management of data has substantial impacts on big data processing [239], [240]. Due to throughput, latency, and stability issues [241], there is a severe problem with leveraging big data analytics to process high-quality blockchain data. Federated learning algorithm is a promising direction to unfolding the high-quality data in the blockchain system to achieve group decision intelligence while preserving data privacy.

6.2 Directions for Enhancing Data Security in Blockchain

6.2.1 Anti-Quantum Computing Signature Methods

An indispensable part of the transaction data is the signature of transaction. With the rapid development of quantum computing research, the traditional public-key algorithms, such as RSA (Rivest, Shamir, Adleman), ECDSA (Elliptic Curve Digital Signature Algorithm)], ECDH (Elliptic Curve Diffie-Hellman), and DSA (Digital Signature Algorithm)

[242], face enormous challenges, since the quantum computing makes the attacks possible based on Grover's and Shor's algorithms [243]. Quantum computing can crack 1024-bit keys in seconds theoretically. If an anti-quantum digital signature algorithm with a short signature can be constructed, the signature security of blockchain can be much guaranteed. For instance, a quantum-safe transaction authentication scheme based on lattice-based cryptography is presented to provide a standard transaction model to prevent quantum attacks [244]. Some scholars have suggested the hardware design of quantum-safe blockchains. For instance, the IOTA (www.iota.org) program used ternary hardware (instead of traditional binary hardware), which supports a new hash function called CURL-P, to resist quantum attacks. Other scholars suggested using quantum cryptography to implement smart contracts. More research is necessary for the physics-based methods that are known as Quantum-Key Distribution. The transition from pre-quantum to post-quantum blockchains requires recognizing relevant security demands to ensure an accurate grasp of risks and countermeasures before implementing quantum-secured blockchain [245].

6.2.2 Robust and Highly-Efficient Consensus Algorithm

Consensus algorithms are critical to achieving data consistency among all distributed participants in a system. In general, prior research mainly analyzed the security properties of consensus algorithms by probabilistic reasoning based on a composition of distributed components. Searching an efficient set of parameters, modeling choices, protocol variants, and tradeoffs in the implementation of these algorithms remain to be open problems. An executable semantic model can be developed to prove correctness conditions and the eventual consistency of the system. Moreover, a light-weight and highly-efficient consensus on the public blockchain is desired. One potential research agenda in public blockchain platforms is to study the optimization of the consensus algorithm to cut down energy consumption.

On the other hand, the hybrid consensus protocol is a promising approach to cherry-pick individual protocol components to fulfill specific application needs. The flexibility and fast switchover of plugging among different consensus algorithms could achieve better performance under dynamic and asynchronous network conditions.

6.2.3 Scalable Secure Multi-Party Computing in Large-Scale Network

Dealer incontestability and owner unforgeability are the ultimate goals of a secure signature scheme. It is favorable for non-deterministic users to generate and send signatures anonymously in the untrusted context. There are many issues in integrating SMPC with blockchains, such as computation cost, poor scalability, and computation latency for large-scale networks. Improving the scalable hardware design or multi-processor architecture to support efficient simultaneous computing on the joint data is one promising research direction. More practical leveled fully homomorphic encryption schemes can be developed for enabling the secure and efficient transfer learning of decentralized blockchain data.

6.3 Directions for Enhancing Infrastructure Security of Blockchain

6.3.1 Middleware Interfaces for Multi-Blockchains

The lack of middleware interfaces makes it hard for practitioners to benefit from known exploration and mistakes. Middleware interfaces play a critical role in ensuring interoperability among multiple blockchains. Establishing middleware interfaces to address the security, resilience, privacy protection, and governance concerns in blockchain could create trust [79]. Interfaces should be deployed to support open standards among security components [22]. Cross-chain middleware [246] plays a similar role in limiting the scope of security crisis in cross-chain cooperations. Heterogeneous information fusion could be helpful for credibility assessments in border security [247]. A unified middleware interface for upper applications is convenient for security monitoring. Also, sidechain technologies could be investigated to build secure interconnections across blockchains.

6.3.2 A Fusion of Cloud-Edge Computing for Efficient Blockchain Service

Blockchain applications face various scalability issues as adoption increases [15]. Besides effort on optimizing the consensus algorithm and infrastructure (such as SBFT [248], SMChain [249], RapidChain [250], and LinBFT [251]), one trend in blockchain research is the shift of data services to centralized clouds, because of convenience and cost-saving reasons [252]. With the integration of blockchain into cloud computing, blockchain could be improved into an efficient service with more robust security [253]. A distributed secure cloud architecture based on blockchain could provide on-demand services under computing infrastructures [254]. Granular computing [255], [256] can be introduced for searching the optimal granularity of node selection in the blockchain application. However, using conventional cryptographic models to address privacy issues in a blockchain-based cloud context is questionable [257]. Identifying the cause of security violations in the cloud context would result in heavyweight collection tasks of logs from a massive number of sources. The dynamic networking topology between the cloud server and the edge devices is a bottleneck for latency-sensitive disaster recovery [258]. Fog computing is a potential architecture to resolve these issues [259], allowing provisioning services between the cloud and the end machines, and closer to edge devices. Incorporating fog computing into blockchain is not a replacement for cloud computing but an excellent complement.

7 Concluding Remarks

This paper surveys the landscape of blockchain security issues and outline research opportunities in information systems and services. The security of the blockchain is categorized into three levels, namely, the process level, the data level, and the infrastructure level, which we refer to as the PDI model of blockchain security. Our study also examines to what extent these security aspects have been addressed. Based on insights obtained from the analysis of research issues, promising research directions for blockchain security are outlined. We believe that our study reflects significant conceptual and technical advances in this junction of dramatic development, and we hope that our effort lays a strong foundation for making blockchain security a new venue of service research and engineering.

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