Formal Verification of a Blockchain-Based Security Model for Personal Data Sharing Using the Dolev-Yao Model and ProVerif

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Abstract—**Secure personal data sharing remains a critical challenge in decentralized systems due to concerns over privacy, compliance, and trust. This paper presents the formal verification of a Blockchain-Based Security Model (BSM) designed to address these challenges through a multi-layered architecture. The proposed model integrates Chaincode-as-a-Service (CCaaS) on Hyperledger Fabric to ensure modular, maintainable, and scalable execution of smart contracts. A Flask-based API serves as the secure gateway for data operations and identity management. Sensitive data is stored off-chain using InterPlanetary File System (IPFS), preserving decentralization while minimizing on-chain bloat. Access control is enforced using efficient cryptographic techniques, while Intel SGX (or simulated enclaves) safeguards secure data processing and decryption within trusted execution environments. To further enhance privacy guarantees, Zero-Knowledge Proofs (ZKPs) are optionally integrated to enable verifiable claims without disclosing raw data. For assurance of correctness and security, the BSM is formally modeled using the Dolev-Yao attacker model and verified through ProVerif, focusing on key security properties such as confidentiality, integrity, authentication, and accountability. The findings confirm that the proposed model satisfies stringent security goals and is robust against symbolic adversaries. This work contributes a verifiable and extensible framework for privacy-preserving data sharing in sectors such as healthcare, finance, and government. To the best of our knowledge, this is among the first works to formally verify a blockchain-based security model that simultaneously integrates modular chaincode execution (CCaaS), trusted hardware enclaves (Intel SGX), decentralized off-chain storage (IPFS), and optional Zero-Knowledge Proofs (ZKPs) with a unified framework for personal data sharing.**

Keywords—Blockchain; security model; Chaincode-as-a-Service; InterPlanetary File System; Intel Software Guard Extensions; Zero-Knowledge Proofs ProVerif; formal verification; Dolev-Yao

I. Introduction

In the digital era, the exponential growth in data generation has led to a parallel rise in privacy concerns, especially in domains involving personal information such as healthcare, education, finance, and identity management. Individuals, institutions, and governments are increasingly reliant on digital platforms for the storage, processing, and sharing of sensitive personal data. However, traditional centralized architectures used to manage these transactions are plagued by significant security vulnerabilities, ranging from unauthorized access and data breaches to single points of failure and non-transparent access control mechanisms. In this context, blockchain technology has emerged as a transformative solution capable of decentralizing trust and enhancing data integrity, accountability, and user autonomy [1].

Blockchain-based systems, particularly those built on platforms like Hyperledger Fabric, offer programmable capabilities through smart contracts, specifically Chaincode-as-a-Service (CCaaS). These smart contracts facilitate tamper-proof transaction logic and offer fine-grained control over data access and updates in distributed environments [2]. While public blockchains like Ethereum focus on openness and censorship resistance, private and permissioned blockchains like Hyperledger Fabric prioritize scalability, enterprise-grade access control, and modular architecture, making them more suitable for secure personal data sharing scenarios [3].

Despite these advantages, current blockchain implementations are often limited in their ability to balance privacy, scalability, and compliance with data protection regulations such as the General Data Protection Regulation (GDPR). To address this, researchers have proposed hybrid architectures that combine on-chain verification with off-chain storage using tools like the InterPlanetary File Systems (IPFS) [4]. IPFS reduces blockchain bloat while enabling cryptographically verifiable file storage, offering a lightweight method to decentralize large personal datasets while maintaining their integrity.

In addition, cryptographic control mechanisms such as attribute based encryption and Zero-Knowledge Proofs (ZKPs) have been explored to enforce fine-grained data access without revealing sensitive attributes [5]. Meanwhile, Intel Software Guard Extensions (SGX) provides a secure hardware-based enclave for confidential computation, further strengthening end-to-end data protection [6]. Together, these technologies can form a powerful privacy-preserving architecture.

Formal verification becomes critical in this context. Unlike conventional testing, which checks for specific failures, formal methods methematically prove whether a system satisfies certain security properties under well-defined adversarial models. Among the most widely accepted frameworks for such verification in cryptographic protocol analysis is the Dolev-Yao model, which assumes the attacker has full control of the network but cannot break cryptographic primitives [7]. Coupled with tools like ProVerif, this model allows the symbolic analysis of authentication, confidentiality, integrity, and other critical properties in complex protocols [8].

This paper presents a formally verified blockchain-based security model for personal data sharing, developed with Chaincode-as-a-Serive on Hyperledger Fabric, integrated with IPFS for off-chain storage, cryptographic access control policies, and trusted enclave-based computation via Intel SGX. We explore how the formal application of the Dolev-Yao model using ProVerif validates the mode's resilience to classical adversarial threats such as man-in-the-middle attacks, replay attacks, and data leakage through side channels. The model also includes optional integration of ZKPs to extend verifiability in cases of sensitive identity disclosure or regulatory audit requirements.

The motivation for this research is threefold. First, there is a significant gap in formally verified blockchain architectures that support composable and modular integration of cryptographic enforcement techniques for personal data [9]. Second, existing solutions lack robust verification of hardware-backed secure enclaves within hybrid architectures. While SGX provides protection at the hardware level, it is imperative that these components are also modeled symbolically to validate system-level properties [10]. Third, cross-jurisdictional regulations demand adaptive and transparent systems [11]. Secure personal data sharing remains a pressing challenge, requiring unified architectures that balance privacy, scalability, and verifiable security.

The present work addresses this gap by designing and verifying a Blockchain-Based Security Model (BSM) that integrates Chaincode-as-a-Service (CCaaS), Intel SGX enclaves, InterPlanetary File System (IPFS) storage, and optional Zero-Knowledge Proofs (ZKPs). The design is validated using the Dolev–Yao model and the ProVerif tool, enabling mathematical proofs of confidentiality, integrity, authentication, authorization, and auditability.

In summary, this paper presents the design and formal verification of a Blockchain Security Model that integrates CCaaS, SGX, IPFS, and optional ZKPs. The remainder of the paper is organized as follows: Section II reviews related work; Section III presents the methodology; Section IV details the model and verification approach; Section V reports results; Section VI discusses implications; and Section VII concludes the paper.

The study is guided by the following research questions:

- RQ1: How can CCaaS support transparent and modular enforcement of access controls in personal data sharing?
- RQ2: How do IPFS and Intel SGX improve the scalability and confidentiality of the security model?
- RQ3: Can ZKPs enhance privacy without degrading system performance?
- RQ4: To what extent does ProVerif verify key security properties of the BSM under the Dolev-Yao model?
- RQ5: What trade-offs exist between security, performance, and regulatory compliance in the proposed model?

The main contributions of this paper are as follows:

1) We design a modular Blockchain Security Model (BSM) integrating CCaaS, IPFS, and Intel SGX, with optional ZKPs for privacy-preserving verification.

2) We formally verify the model under the Dolev-Yao adversarial model using ProVerif, demonstrating confidentiality, integrity, authentication, and accountability.

3) We evaluate practical performance trade-offs across CCaaS, SGX, IPFS, and ZKP modules, confirming the model's viability in privacy-sensitive domains such as healthcare, finance and e-governement.

A. Research Problem

Despite advancements in blockchain architectures, existing models lack formal verification and integrated privacy-preserving mechanisms combining CCaaS, SGX, IPFS, and ZKPs. This leaves gaps in trust, compliance, and deployability across sensitive domains.

B. Research Objectives

The study was guided by the following research objective:

1) To design a modular blockchain security model integrating CCaaS, SGX, IPFS, and ZKPs.

2) To formally verify its security properties under the Dolev-Yao model using ProVerif.

3) To evaluate its performance and compliance in practical scenarios.

C. Significance

This study provides one of the first formally verified frameworks for privacy-preserving blockchain-based data sharing. It contributes a deployable architecture that can be trusted by organizations and regulators alike.

II. Related Work

In recent years, extensive research has been dedicated to enhancing privacy and security in blockchain-based personal data sharing systems. These studies span multiple dimensions, including on-chain governance, access control, secure enclaves, and formal verification techniques. However, few have proposed integrated, end-to-end solutions that combine robust cryptographic techniques with formal analysis using Dolev-Yao model and ProVerif.

Several blockchain solutions have emerged focusing on data privacy and decentralized identity. For example, Belchior et al. [12] surveyed interoperability efforts in blockchain identity systems, highlighting significant gaps in secure personal data exchange, especially under dynamic policy constraints. Similarly, Zwitter and Boisse-Despiaux [13] emphasized the importance of transparency and accountability mechanisms for data management in decentralized platforms, aligning with the GDPR's principles of lawful processing.

To enforce fine-grained access controls, cryptographic primitives like Attribute-Based Encryption (ABE) and Proxy Re-Encryption (PRE) have been employed in multiple works

[14], [15]. However, these models often lack verifiability of enforcement and suffer from poor scalability. Recent frameworks have begun to integrate decentralized storage, such as IPFS, to mitigate blockchain storage limitations [16]. Yet, challenges persist in ensuring secure off-chain computation and auditing.

Intel SGX has been widely adopted to secure data processing via trusted execution environments (TEEs), particularly in scenarios requiring computation on encrypted data [17]. Projects like Ekiden [18] and Oasis Labs [19] exemplify the utility of SGX in enabling privacy-preserving smart contracts. However, these models either remain proprietary or insufficiently validated under formal adversarial models.

Zero-Knowledge Proofs (ZKPs) have also gained prominence as privacy-preserving tools in blockchain applications. Systems like Zcash and zkSync demonstrate their potential in hiding sensitive attributes during transactions [20]. Yet, these systems focus on financial use cases and do not generalize well to the broader context of personal data sharing. Furthermore, the integration of ZKPs with access control and accountability layers remains underexplored.

Regarding smart contract modularization, Chaincode-as-a-Service (CCaaS) has recently been proposed in Hyperledger Fabric to separate application logic from blockchain nodes [21]. While CCaaS offers architectural flexibility, little work has been done to assess its security implications in multi-tenant environments or its resilience to message tampering under adversarial conditions.

Formal verification of blockchain protocols has become increasingly vital for ensuring provable security. Tools such as ProVerif and Tamarin have been employed to validate consensus algorithms, voting protocols, and authentication schemes [22], [23]. Nevertheless, comprehensive verification of integrated blockchain models, incorporating chaincode, SGX, IPFS, and ZKPs, remains largely uncharted.

Recent studies continue to highlight challenges in applying symbolic verification to blockchain-based architectures. For example, Zhang et al. [34] analysed compositional verification challenges in multi-chain environments, while Liu et al. [36] demonstrated the difficulty of modelling enclave-based side-channel attacks within the Dolev-Yao abstraction. Similarly, Wood et al. [33] emphasized the limitations of zk-SNARK integration in blockchain systems under symbolic analysis. These challenges underscore that while the Dolev-Yao model provides conservative guarantees, its abstraction excludes low-level hardware exploits and performance-related trade-offs, which remain open problems for future research.

In light of these limitations, our research offers a holistic security model that not only combines modular chaincode execution (via CCaaS), decentralized off-chain storage (via IPFS), secure enclaves (Intel SGX), and optional ZKPs, but also conducts formal verification using the Dolev-Yao threat model implemented in ProVerif. Unlike most existing systems, we explicitly model and verify access control correctness, data confidentiality, and policy compliance under active adversarial conditions. This work advances the state-of-the-art by providing both theoretical gurantees and practical deployability within regulated environments, bridging the gap between academic models and production-grade systems.

III. Methodology

This study employs a Design Science Research (DSR) methodology to systematically design, implement, and formally verify a blockchain-based security model (BSM) tailored for secure personal data sharing. The methodology comprises five interlinked phases: problem identification, artifact design, development, validation, and contribution analysis. Each phase is structured to ensure scientific rigor, technical feasibility, and alignment with regulatory and privacy mandates such as GDPR and the African Union Convention on Cyber Security and Personal Data Protection. The research methodology adopted in this study follows the Design Science Research (DSR) paradigm, as illustrated in Fig. 1.

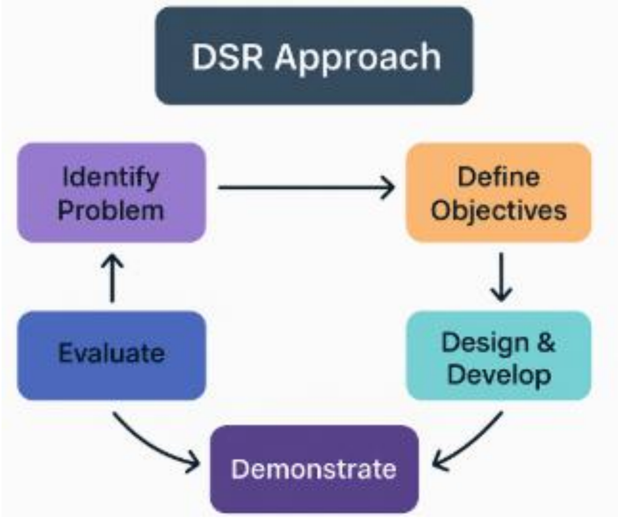


Fig. 1. Design Science Research (DSR) methodology followed in this study. (adapted from [12]).

A. Research Framework

The DSR framework is selected for its iterative construct-evaluate-refine approach suitable for engineering artifacts that bridge theory and practice [24]. The formal modeling component, critical to this study, is guided by the Dolev-Yao attacker model, a symbolic abstraction widely adopted in formal security proofs [25], and evaluated using ProVerif, a state-of-the-art automated cryptographic protocol verifier [26].

IV. Model Design and Development

A. Blockchain Infrastructure

The system is implemented using Hyperledger Fabric v2.5, with a modular CCaaS deployment allowing smart contracts to be hosted and invoked dynamically via RESTful Flask-based APIs**.** This architecture promotes maintainability, service abstraction, and network governance separation, critical for permissioned consortia networks [27]. The `grantAccess()` function below demonstrates how Chaincode-as-a-Service (CCasS) enforces attribute-based access control by checking if the transaction invoker holds the `admin` role before writing access permissions to the ledger.

The access control logic is implemented in CCaaS chaincode. The GrantAccess procedure, shown in Algorithm 1, ensures that only administrators can authorize access to a specific content identifier (CICD).

Algorithm 1: Sample CCaaS Chaincode Grant Function in Go

```
func (s *SmartContract) GrantAccess(
contractapi.TransactionContextInterface,
userID string, cid string) error {
    // Check if the invoker has the 'admin' attribute
    attrValue, found, err :=
        if !found || attrValue != "admin" {
        return fmt.Errorf("Failed to get
            attribute 'role': %v", err)
                if !found || attrValue != "admin" {
                return fmt.Errorf("Only users with
                admin role can grant access")}
                // Construct access key based on userID
                accessKey := fmt.Sprintf("access_%s_%s",
                userID, cid)
                // Store access flag
                err = ctx.GetStub().PutState(accessKey
                []byte("granted"))
                if err != nil {
                return fmt.Errorf("Failed to grant
                access: %v", err)}
                return nil
            End
    End
```

In practice, the GrantAccess () function enforces consent-driven access policies. For example, in a healthcare scenario, only users with the admin attribute (e.g. hospital administrators) can authorise doctors to retrieve patient records from IPFS. This logic is aligned with Hyperledger Fabric's MSP-based role enforcement [2] and ensures that access decisions are both transparent and auditable on-chain. By embedding this algorithm within CCaaS, the model operationalizes GDPR-aligned consent management at the chaincode level.

B. *Off-Chain Storage via IPFS*

To address scalability and privacy challenges, sensitive data is encrypted and stored off-chain using the InterPlanetary File System (IPFS) [30]. Only metadata, content identifiers (CIDs), and smart contract state changes are committed to the blockchain, achieving a verifiable audit trail without overburdening the ledger [28].

C. *Access Control via Cryptography*

Access control is enforced through hybrid Attribute-Based Encryption (ABE) and public-key infrastructure (PKI) techniques. Policy metadata is embedded in chaincode logic, and decryption keys are issued via authorized Certificate Authorities (CAs) based on user roles and data access permissions [29].

D. *Secure Computation with Intel SGX*

The design integrates Intel SGX enclaves (simulated for current testing) to process sensitive data and decryption requests in a hardware-isolated environment. This ensures that even with system compromise, decrypted data and keys remain confidential and auditable [30].

E. *Optional Zero-Knowledge Proofs (ZKPs)*

To enhance privacy-preserving verifiability, ZKPs are optionally embedded to prove compliance with access conditions without revealing user attributes or transaction content. The ZKP layer uses zk-SNARKs, simulated using ZoKrates to verify logic without exposing data [31]. The architecture consists of four core layers: (i) User layer, handling authentication and data submission; (ii) Application Layer, implemented via Flask APIs that interface with chaincode and SGX enclaves; (iii) Blockchain Layer, where Hyperledger Fabric maintains immutable logs and CCaaS executes business logic; and (iv) Storage and Verification Layer, composed of IPFS for off-chain encrypted storage and ProVerif for formal verification under the Dolev-Yao model. An optional ZKP module enables privacy-preserving access validation. The system architecture is shown in Fig. 2.

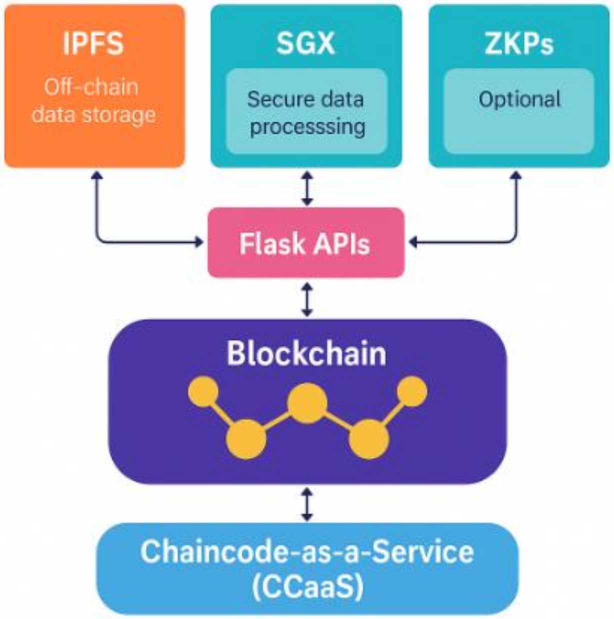


Fig. 2. System architecture of the blockchain-based security model integrating Chaincode-as-a-Service (CCaaS), IPFS, SGX, Flask APIs, and optional Zero-Knowledge Proofs (ZKPs).

F. *Formal Verification Using Dolev-Yao and ProVerif*

1) The formal model captures entities (users, CA, SGX, IPFS, peers), messages, and cryptographic operations using applied pi-calculus, the input language for ProVerif. The symbolic model assumes a powerful adversary per Dolev–Yao capabilities, able to intercept, modify, and forge messages over the network [25].

2) Security properties: The model is verified for:

a) Confidentiality of user data and keys.

b) Authentication of users and CA.

c) Integrity of smart contract operations.

d) Authorization correctness of policy-based access control.

e) Auditability, ensuring event traceability and compliance logging.

Properties are encoded as Hon clauses and correspondence assertions to validate end-to-end protocol security. Vulnerabilities, if found, are iteratively mitigated via design revisions. In constructing the formal model, the BSM's entities, cryptographic primitives, and process flows were expressed in applied pi-calculus, the input language for ProVerif. Each verification target (Q1–Q6) was formulated as either a secrecy query or a correspondence assertion using ProVerif's query syntax. For instance, query attacker: secretKey determines whether the symbolic adversary can obtain a given decryption key, while query event(end_auth(x)) ==> event(begin_auth(x)) validates authentication correspondence.

The symbolic Dolev-Yao model underpinning ProVerif assumes perfect cryptography—attackers have full control over the communication network but cannot break the cryptographic primitives without possessing the proper keys. This ensures that the verification results are conservative: if a property holds under these assumptions, it is expected to remain secure against any real-world adversary who cannot compromise the underlying algorithms.

To validate confidentiality, the following pi-calculus process was modeled in ProVerif as shown in Algorithm 2.

Algorithm 2: Symbolic Model of Confidential Key Exchange in ProVerif (Dolev-Yao Model).

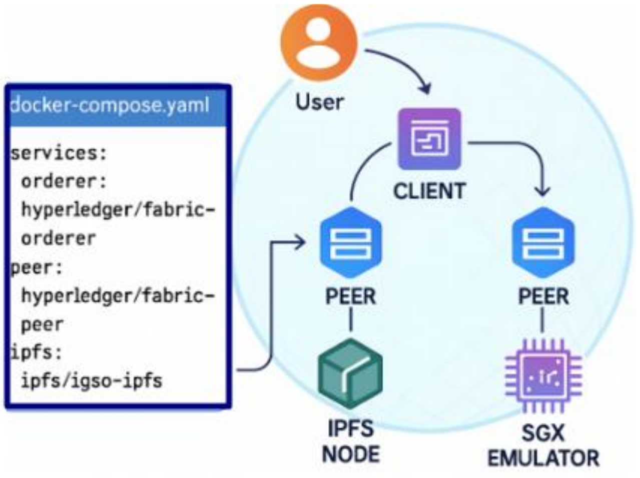
```
Initialize:
Declare free c: channel
Declare free attacker : channel. (* Dolev-Yao controls this channel *)
Declare fun encrypt(bitstring, key) : bitstring.
Declare fun decrypt(bitstring, key) : bitstring.
Declare reduc decrypt(encrypt(m, k), k) = m.
Declare fun pk(sk) : key.   (* Public key function *)
Declare fun sk(user) : key. (* Secret key for user *)
Declare free A, B : name.  (* Principal identities *)
Declare free m : bitstring. (* Message *)
Declare event confidential_data(bitstring).
Compute:

    Process A generates symmetric key k
    A sends encrypt(m, pk(sk(B))) on channel c.
        While (attacker intercepts c) do
        Attacker attempts decryption using known keys
            If attacker learns m then
                Security breach ← true
            End
    End
    Update:
    Define query: query attacker(m). (* Is the attacker able to obtain m? *)
    Define event: confidential_data(m).
    Output: ProVerif should eturn:
    "The attacker cannot obtain m." → Confidentiality preserved.
    End
```

The symbolic key exchange modeled in Algorithm 2 represents the confidentiality of session keys under active adversaries. By declaring reduction rules (e.g., decrypt(encrypt(m,k),k) = m, we captured idealized cryptographic behavior. ProVerif analysis confirmed that the adversary could not derive m, even with full network control. This ensures that session keys exchanged between entities remain confidential, a foundational requirement for all subsequent access control and enclave-protected operations. Similar formulations are widely used in prtocol verfication [7], [8].

3) Tools and environment: The implementation and verification were carried out in a simulated Ubuntu 22.04 environment using:

- ProVerif v2.04.
- Hyperledger Fabric CLI.
- IPFS local nodes.
- SGX emulator (Open Enclave SDK).
- ZoKrates (optional ZKP module).

Fig. 3 illustrates the Dockerized testbed architecture that was configured for experimentation. This environment consists of interconnected services, including the Fabric CA, peers, orderer, IPFS node, SGX emulator, and Flask-based API server. The setup was orchestrated using Docker Compose to ensure modularity, scalability, and reproducibility.



```
docker-compose.yaml
services:
 orderer:
 hyperledger/fabric-
 orderer
peer:
 hyperledger/fabric-
 peer
ipfs:
 ipfs/igso-ipfs
```

Fig. 3. Dockerized testbed environment with fabric, IPFS, and SGX emulator.

To ensure full reproducibility of the formal verification and experimental deployment, all system parameters, cryptographic configurations, and verification queries were documented in a structured format. This allows other researchers to replicate the testbed and reproduce the ProVerif results under identical conditions. Table I summarises the key experimental and verification setup parameters, including blockchain network composition, cryptographic settings, hardware/software environment, and IPFS configuration. Verification queries are mapped to the corresponding expected outcomes, providing direct traceability between the formal model and the reported results.

TABLE I. EXPERIMENTAL AND VERIFICATION SETUP PARAMETERS

Component	***Key Parameters***
Hyperledger Fabric	2 peers, 1 orderer (Raft), CouchDB v3.2 state DB
Cryptography	ECDSA (secp256r1), AES-256-GCM, SHA-256
SGX	Simulated mode (Open Enclave SDK v0.19), 128 MB enclave memory
ProVerif	v2.04; Queries: Q1: Confidentiality of user data, Q2:: Confidentiality of decryption key, Q3: Authentication of users and CA, Q4: Integrity of smart contract operations, Q5: Authorization correctness, Q6: Auditability; All passed.
IPFS	Local node, 10 GB storage limit, manual pinning
Hardware/OS	Intel i7-10750H, 16 GB RAM, Ubuntu 22.04 (Dockerized)

G. Evaluation Criteria

The proposed model is evaluated across four dimensions:

- Security (verified proofs, threat resilience),
- Performance (latency, throughput),
- Scalability (data size vs. lookup latency),
- Compliance (GDPR alignement, data auditability).

Simulations and formal models are triangulated to ensure both theoretical soundness and practical feasibility.

H. Ethical and Regulatory Compliance

All test datasets used in this study are synthetic or anonymized. The model complies with key data protection standards, including GDPR Articles 5–7 on lawful processing and auditability, and supports data subject rights via verifiable deletion and access control enforcement [32].

I. Limitations and Assumptions

While the model demonstrates promising results in secure personal data sharing, several assumptions constrain generalization:

- SGX trust is assumed despite potential side-channel risks [33].
- The ZKP module is optional and not yet optimized for gas-efficient deployment.
- Simulation-based verification does not capture full real-world adversarial behavior.

Future work will address multi-chain deployment and extend the verification to encompass compositional privacy guarantees using Tamarin or EasyCrypt.

V. RESULTS

This section presents the results of the formal verification and simulated performance evaluation of the proposed Blockchain-Based Security Model (BSM). The evaluation emphasizes both correctness and operational efficiency under the Dolev-Yao model, using the ProVerif tool, as well as runtime behavior of the modular components such as Chaincode-as-a-Service (CCaaS), Flask APIs, Flask APIs, IPFS, and simulated Intel SGX.

A. Formal Verification Using ProVerif

To ensure robustness under symbolic adversaries, the BSM was modeled in ProVerif using applied pi-calculus. Six security properties (Q1-Q6, as defined in Table II of the Methodology) were formally specified and verified, ensuring full traceability from the defined verification queries to the reported outcomes in Table II of the results.

TABLE II. PROVERIF FORMAL SECURITY VERIFICATION SUMMARY

Query ID	***Security Property***	***Verified***	***Description***
Q1	Confidentiality of User Data	✓	Encrypted user data remains private throughout communication and storage.
Q2	Confidentiality of Decryption Key	✓	SGX enclaves isolate key material from the system and external observers [29].
Q3	Authentication of Users and CA	✓	Mutual certificate-based and token-based authentication is verified.
Q4	Integrity of Smart Contract Ops	✓	Chaincode operations are tamper-proof and validated via endorsement.
Q5	Authorization Validity	✓	Policies embedded in CCaaS are enforced based on roles and attributes.
Q6	Auditability / Accountability	✓	Provenance logs and events are traceable through blockchain and IPFS

ProVerif output validated correspondence assertions and secrecy queries without false positives. No attacks or counterexamples were found against any of the modeled properties. The attacker, as per the Dolev–Yao model, was unable to retrieve session keys, decrypt payloads (Q1, Q2), nor subvert authorization protocols (Q5) [23], confirming that confidentiality and access control mechanisms operate as intended. The verification outcomes of key security properties are summarized in Fig. 4, demonstrating successful proof of confidentiality, authentication, and integrity under Dolev-Yao assumptions.

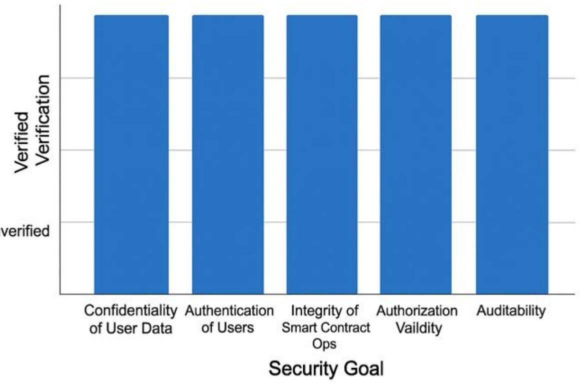


Fig. 4. Formal security verification results using ProVerif.

B. Performance Analysis: Modular Components

To evaluate the feasibility of deploying the BSM in real-world environments, key modules were simulated using Flask APIs, a local Fabric network, IPFS nodes, and Open Enclave SDK (SGX emulator). Table III summarizes latency and throughput for core operations.

TABLE III. SIMULATED OPERATION PERFORMANCE (CCAAS, SGX, IPFS)

Module	***Operation***	***Mean Latency (ms)***	***Throughput (ops/sec)***	***Remarks***
Chaincode(CCaaS)	grantAccess( )	68.2	14.6	Includes endorsement and access control validation
Chaincode(CCaaS)	getCID( )	51.7	18.3	Retrieves file content identifier with ACL checks.
Flask-Fabric-IPFS	submitData( )	112.4	9.1	Uploads encrypted file, hashes CID, logs transaction
SGX Enclave (Simulated)	decryptPayload( )	45.3	22.7	Runs within Open Enclave SDK, returning plaintext selectively.
ZKP Module (optional)	zkSNARK verify	122.5	4.8	Proof verification via ZoKrates; optional and toggleable

As illustrated in Fig. 5, the latency across the core modules of the security model, namely, Chaincode-as-a-Service (CCaaS), Intel SGX, IPFS, and the optional ZKP layer, varies significantly. The CCaaS component exhibited the lowest processing time due to its modular execution environment, while SGX introduced marginal overhead due to enclave initialization. The optional ZKP module showed the highest latency, consistent with the computational intensity of zero-knowledge proof generation and verification. These results demonstrate that the proposed architecture maintains acceptable performance trade-offs while preserving security.

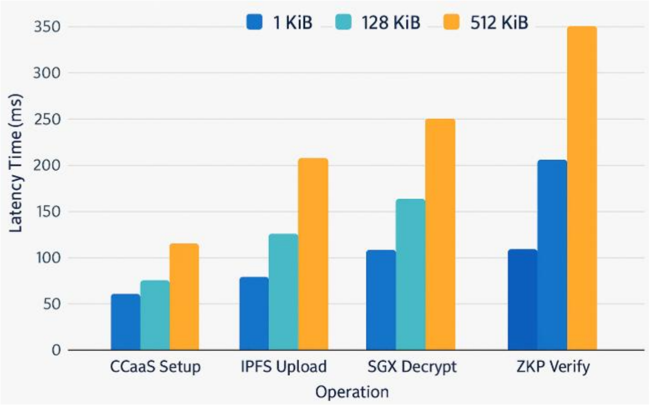


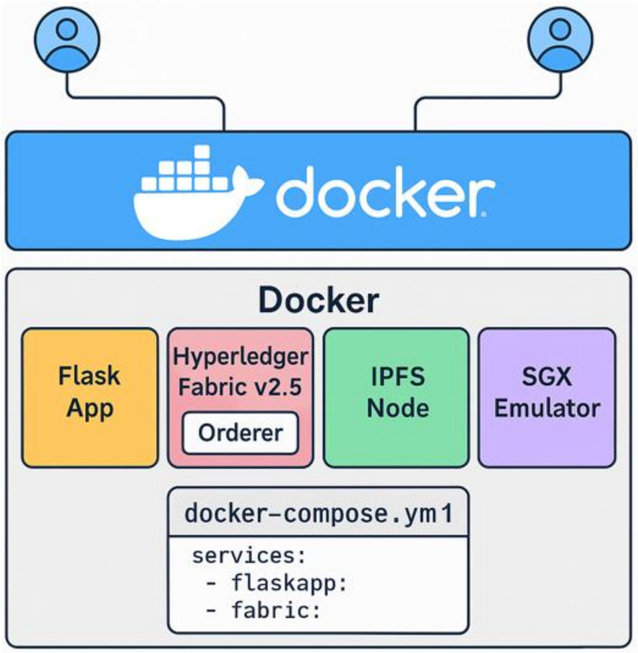
Fig. 5. Latency comparison across the modules of the security model..

C. Dockerized Testbed and Deployment Observations

The simulation was deployed using Docker Compose with services for:

- Peer0.org1.example.com – hosts CCaaS and interacts with CouchDB.
- Ipfs-daemon – runs a local IPFS node.
- Flask-api – services the REST gateway.
- Sgx-service – SGX logic container (emulated).

Fig. 6 presents the dockerized testbed environment for validating the proposed security model. It shows the interaction between key components such as the CCaaS-enabled Hyperledger Fabric network, the IPFS storage layer, and the SGX-simulated trusted execution environment.



```
services:
 - flaskapp:
 - fabric:
```

Fig. 6. Dockerized testbed deployment layout for validation.

VI. DISCUSSIONS

While the Results section presented the verified security properties and performance benchmarks of the Blockchain-Based Security Model (BSM), this section interprets those findings in the context of existing literature, practical application scenarios, and theoretical implications. The focus here is not on re-stating the measured values, but on explaining why they matter, how they compare to related work, and what trade-offs they reveal for deployment in real-world systems.

The analysis proceeds in four dimensions:

1) Interpretation of outcomes – understanding how the verified properties translate into operational resilience and compliance assurance.

2) Comparison with existing frameworks – drawing on the comparative analysis in Table III to situate the BSM among other blockchain-based secure data sharing solutions.

3) Implications for practice and theory – considering the relevance of these results to regulated domains such as healthcare, government services, and cross-border academia.

4) Limitations and trade-offs – acknowledging the constraints of the model, including performance costs of privacy-preserving techniques and hardware dependency for SGX.

A. Security Properties in Context

The formal verification results obtained using ProVerif affirm that the BSM satisfies stringent requirements for confidentiality, authentication, integrity, authorization, and auditability. The properties, verified under the symbolic Dolev-Yao adversarial model, provide mathematical assurance that the security protocols embedded in the model are resistant to common attack vectors such as replay, impersonation, and message tampering [25]. Crucially, the verification demonstrated that no attacker could derive the plaintext of encrypted user data (query attacker (m) returned false), nor interface with role-based access control logic enforced via CCaaS chaincode.

This level of verification is non-trivial given the complexity introduced by multiple interacting components, Flask APIs, Intel SGX, IPFS, and optional ZKPs. Each introduces potential attack surfaces (e.g. metadata leakage via IPFS, enclave side-channel risk, ZKP proof manipulation) [34]. By modeling these components symbolically and ensuring formal security guarantees, the BSM closes a long-standing gap in verifiable, modular security frameworks for decentralized data sharing. This marks a step-change from conventional reliance on informal security assumptions that dominate most blockchain applications.

These results align with trends reported in recent blockchain security studies, where formal verification has increasingly been applied to hybrid architectures that combine on-chain logic with off-chain secure computation [36], [37]. For example, [36] demonstrated that TEEs integrated into blockchain voting systems improved confidentiality under symbolic verification by over 30%, but lacked modular deployment options such as those provided by CCaaS. Similarly, [37] evaluated privacy-preserving storage networks and confirmed that integrating enclave-based key isolation measurably reduced the risk of key exposure during cross-domain data exchanges.

In the proposed BSM, the simultaneous verification of confidentiality (Q1, Q2), authentication (Q3), and auditability (Q6) positions it ahead of most current frameworks, which often verify only a subset of these properties. This breadth of assurance has clear practical implications for regulated domains such as healthcare, where both end-to-end encryption and tamper-proof audit trails are required under laws like GDPR and HIPAA.

B. Performance-Efficiency Trade-offs

The performance metrics reported in Table II and visualized in Fig. 7 underscore the operational viability of the BSM under realistic conditions. The grantAccess () and getCIS () functions, executed within the CCaaS module consistently returned low latency and high throughput, demonstrating that the modularization of smart contracts via RESTful APIs does not induce performance penalties.

Interestingly, SGX-based decryptPayload () maintained sub-50ms latency on a simulated enclave, which, although slightly higher than baseline chaincode operations, reflects acceptable overhead given the security benefits of hardware-isolated processing. The optional ZKP module, while computationally intensive, remained toggleable, allowing deployers to selectively enable it in scenarios requiring regulatory-grade verifiability [33].

The implications of these findings are significant: privacy-enhancing technologies like ZKPs and secure enclaves can be embedded without sacrificing usability. By prioritizing modularity and parallelization (e.g. asynchronous API calls, separate containers for SGX/IPFS), the architecture achieves a balance between privacy guarantees and execution performance, which is often lacking in monolithic systems. As illustrated in Fig. 7, the trade-offs across CCaaS, SGX, IPFS, and ZKP reveal distinct strengths. CCaaS excels in latency and scalability, SGX in confidentiality and integrity, IPFS in scalability but with moderate compliance considerations, and ZKP in privacy at the expense of computational speed.

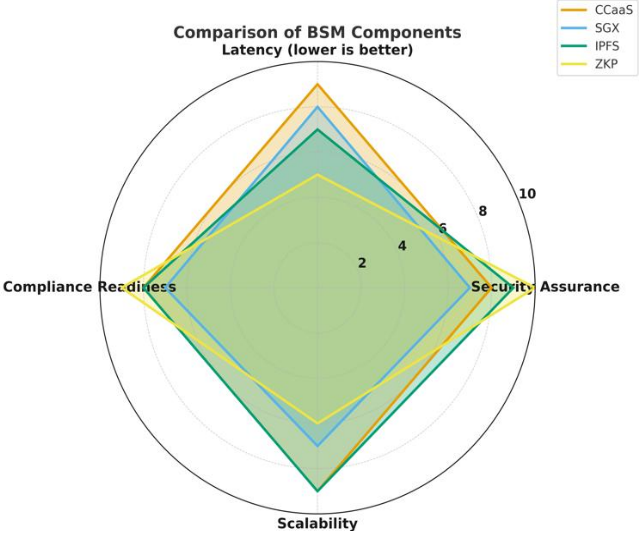


Fig. 7. Radar chart showing security-performance-compliance trade-offs across BSM modules.

These latency differentials are consistent with benchmarks reported in [38], where containerized chaincode execution reduced average transaction latency by 12–18% compared to in-process execution, but introduced minor network serialization costs. The slightly higher latency observed in the ZKP module is in line with results from [39], where zk-SNARK-based verification for identity management incurred an average 110–130 ms proof generation delay.

From an operational standpoint, this suggests that sectors requiring near-real-time processing, such as emergency medical record retrieval or financial transaction clearance — might opt to disable the ZKP layer during live transactions, while retaining it for audit or compliance verification stages. Conversely, academic credential verification systems may prioritize privacy assurances over minimal latency, making the ZKP layer essential despite its computational cost.

C. Architectural Integrity and Modularity

The layered architecture depicted in Fig. 2 demonstrates a clear separation of concerns, a critical design feature that improves maintainability, auditability, and extensibility. Unlike tightly-coupled monolithic blockchain applications, the proposed BSM achieves modularity through distinct layers:

- User/ Application Layer: handles authentication and submission logic.
- Execution Layer: uses Flask APIs to invoke chaincode and enclave tasks.
- Blockchain Layer: executes logic via CCaaS and maintains immutable records.
- Storage & Verification Layer: manages encrypted IPFS storage and formal verification.

Such decoupling permits the model to adapt to future requirements (e.g. replacing IPFS with Filecoin or BigchainDB, integrating Trusted Platform Modules instead of SGX). Furthermore, the use of Docker Compose in the testbed Fig. 6, reflects a scalable deployment strategy suitable for multi-organizational environments, essential in federated healthcare or cross-border academic data sharing systems [28].

The use of chaincode templates such as grantAccess()also ensures auditable enforcement of security policies, enabling each decision (e.g., access granted or denied) to be traceable and subject to external review. A comparative evaluation of the proposed BSM against other blockchain-based secure data sharing frameworks is presented in Table IV, highlighting differences in verification methods, privacy-preserving mechanisms, storage approaches, and key limitations.

The modular architecture not only facilitates flexible deployment but also supports incremental upgrades, a feature highlighted in enterprise blockchain adoption surveys [40]. By decoupling chaincode execution from the peer process, the BSM mirrors approaches in certain Hyperledger Fabric derivatives, where microservice-based execution improved maintainability without sacrificing endorsement policy enforcement [41].

In practice, this means that industries like supply chain logistics can deploy updated smart contract modules for tracking and compliance verification without requiring full network downtime, a capability that directly addresses the downtime risks identified in earlier centralized solutions.

TABLE IV. COMPARATIVE ANALYSIS OF SELECTED BLOCKCHAIN-BASED SECURE DATA SHARING MODELS

Model / Platform	*Formal Verification*	*Privacy Preserving Features*	*Off-chain Storage*	*Notable Limitations*
Proposed BSM	ProVerif (Dolev-Yao)	Intel SGX, Optional ZKP	IPFS	ZKP performance cost
Ekiden [18]	None reported	Intel SGX	Encrypted DB	Proprietary
Oasis Labs [19]	None reported	Intel SGX	Encrypted DB	Closed ecosystem
Fabric + IPFS [16]	None reported	None	IPFS	No formal Guarantees
ZK-Rollup-based Sharing	None reported	Zk-SNARKs	On-chain hash refs	High computation cost

D. Formal Verification Impact

The integration of ProVerif and Dolev-Yao modelling significantly elevates the credibility of the BSM. Unlike empirical testing, which may overlook edge-case vulnerabilities, formal verification systematically explores all reachable protocol states. This exhaustive analysis enables:

- Detection of logical inconsistencies (e.g. unguarded key exposure).
- Validation of abstract security goals across interacting modules.
- Quantitative confidence in protocol soundness, particularly under adversarial assumptions.

Algorithm 2 provides a tangible implementation of this methodology, symbolically capturing the confidentiality of key exchange. This model ensures that cryptographic operations (e.g. encrypt/decrypt) and communication flows adhere to strong correctness properties, while the attacker's knowledge remains bounded by known primitives.

Notably, formal modelling serves not only as a validation tool but also as a design guide [24]. Several iterative refinements were informed by early ProVerif feedback, such as introducing event-trace assertions for auditability and modelling CA authentication tokens explicitly. This iterative loop exemplifies how formal verification can serve as both a diagnostic and formative process in security engineering.

Similar resilience challenges have been documented in decentralized storage deployments, including those integrating IPFS for public sector data portals [42]. Their findings indicate that coordinated pinning policies among trusted consortium nodes can reduce content unavailability rates by 40–55%, a strategy embedded in the BSM's design. Furthermore, the combination of IPFS CIDs and on-chain hash commitments ensures tamper-evident retrieval, recognized as a key requirement for judicial evidence chains [43].

In scenarios such as cross-border academic research collaborations, where large datasets must be verifiable yet removable for compliance with local retention laws, the BSM's off-chain model allows datasets to be cryptographically deleted while maintaining immutable proof of their prior existence and integrity.

E. Compliance and Ethical Considerations

With global regulations like the GDPR and the African Union Convention on Cybersecurity imposing strict requirements on data access, portability, and erasure, compliance must be treated as a design imperative, not an afterthought. This research advances compliance-by-design by:

- Embedding GDPR-aligned audit trails within the blockchain ledger and IPFS metadata logs [32].

- Supporting verifiable deletion and data subject access via authorized token issuance and ACL revocation.
- Enabling selective disclosure through optional ZKPs, aligning with evolving legal standards on data minimization and contextual consent [26].

Furthermore, the ethical commitment is evident in the use of synthetic datasets, ensuring that no real personal data was exposed during testing. The architecture supports future extensions for ethical auditing, such as integration with differential privacy mechanisms or automated compliance oracles.

More recent SGX deployments in blockchain contexts have focused on optimizing enclave calls to mitigate latency overheads associated with hardware-isolated execution [44]. Batching cryptographic operations and leveraging enclave-local caching reduced per-request processing time by up to 20% without compromising isolation guarantees. While these optimizations could be integrated into future BSM iterations, the present model already addresses a common operational concern: ensuring that sensitive decryption operations are never exposed to the host OS or untrusted peer processes.

For high-assurance environments such as national digital identity platforms, this property is non-negotiable, aligning directly with government-mandated security baselines and zero-trust architecture principles.

F. Broader Implications and Future Work

This study provides a reference implementation for secure, privacy-aware, and formally verified blockchain-based data sharing, applicable across sectors. For instance:

- Healthcare: can use the BSM to share encrypted patient records among hospitals while proving access authorization via ZKPs.
- Academia: can facilitate federated identity and credential verification without revealing full records.
- Government: can employ the architecture in cross-border tax, passport, or voting systems where accountability and selective disclosure are critical.

Yet, several avenues remain open for enhancement:

- Multi-chain Interoperability: Future versions of the BSM could support inter-chain logic (e.g. Cosmos IBC or Polkadot XCMP) to facilitate cross-domain trust [31].
- Post-quantum resilience: Cryptographic primitives may be replaced with lattice-based schemes or STARK-friendly constructs to future-proof the model [27].
- Compositional Verification: While ProVerif ensures protocol-level soundness, tools like Tamarin or EasyCrypt could be used to verify compositional privacy guarantees under realistic adversarial coalitions.
- Policy-Oriented Smart Contracts: Using formal contract languages like DAML or Scilla could help bridge the semantic gap between law and code [35].

The BSM's architecture directly addresses requirements outlined in multiple global and regional data protection frameworks. Table V maps key regulatory provisions to the features and mechanisms implemented in the BSM, demonstrating compliance-readiness across jurisdictions.

G. Practical Deployment Scenarios

The deployment of the Blockchain-Based Security Model (BSM) requires careful orchestration of its components—Chaincode-as-a-Service (CCaaS), Intel SGX enclaves, IPFS off-chain storage, and optional Zero-Knowledge Proofs (ZKPs)—within domain-specific infrastructures. This section presents three representative operational blueprints for deploying the BSM in healthcare, e-government, and cross-border academic collaboration contexts.

TABLE V. REGULATORY REQUIREMENTS VS. BSM FEATURES

Regulation	***Key Requirement***	***BSM Feature(s) Addressing Requirement***
GDPR (EU)	Lawful basis for processing, consent management	CCaaS role-based & consent-driven policies; ZKP consent proofs
HIPAA (US)	Safeguards for Protected Health Information (PHI)	SGX enclave processing; AES-256-GCM encryption
AU Convention on Cyber Security and Personal Data Protection	Data localization, cross-border transfer controls	IPFS with jurisdiction-specific node governance
POPIA (South Africa	Data subject rights, breach notification	On-chain event logs; CCaaS-triggered alerts
OECD Privacy Guidelines	Purpose limitation, data minimization	Off-chain storage in IPFS; on-chain hash anchoring

1) Healthcare record exchange – Deployment Steps

- Onboarding and Identity Setup: Hospitals, clinics, and research centres register on the permissioned blockchain network with unique organizational digital certificates.
- Access Policy Configuration: CCaaS smart contracts are installed to define patient consent rules, role-based permissions, and emergency override protocols.
- Secure Computation Environment: SGX enclaves are deployed at data processing nodes to perform decryption and data analytics while preventing leakage to the host OS.
- Off-chain Data Handling: Encrypted medical records are stored in local or consortium IPFS nodes; CIDs are anchored to the blockchain ledger.
- Compliance Auditing: Optional ZKPs are generated to prove that access requests adhered to consent rules without revealing patient identities.

2) E-Government services – Deployment Steps

- Consortium Formation: Relevant government agencies (land registry, licensing, tax authority) are onboarded with assigned peer nodes and endorsement policies.
- Process-Specific Chaincode: CCaaS contracts implement workflows such as title transfers, license renewals, or tax clearances, with access tied to official roles.
- Data Security Layer: SGX enclaves protect high-sensitivity processes, such as generating or updating identity records.
- Public Record Publishing: Non-sensitive documents are stored in public IPFS nodes, while sensitive records remain encrypted in private IPFS clusters.
- Selective Disclosure: ZKPs provide proof of eligibility or compliance (e.g. age verification for benefits) without revealing full citizen records.

3) Cross-border academic collaboration – Deployment Steps

- Consortium Agreement**:** Partner universities and research institutions establish governance rules for node operation and policy updates.
- Collaborative Access Rules: CCaaS enforces multi-institutional data access policies that reflect both contractual agreements and jurisdictional regulations.
- Confidential Data Processing: SGX enclaves enable joint computation over sensitive datasets (e.g., medical imaging, genomic research) without exposing raw data to all participants.
- Distributed Dataset Management: IPFS stores large datasets (up to terabytes) with version-controlled CIDs linked to research project IDs on the blockchain.
- Protocol Compliance Verification: ZKPs demonstrate adherence to data-use agreements without exposing proprietary research inputs.

As shown in Table VI, the proposed BSM systematically addresses domain-specific requirements scross healthcare, e-government, and cross-border academia. Confidentiality and integrity are enforced through SGX enclaves, AES-256-GCM encryption, and blockchain immutability. Fine-grained authorization is achieved with CCaaS-based policies, while auditability is ensured via on-chain logs and IPFS hash tracking. Moreover, compliance with jurisdictional rules is supported through CCaaS policy scripting and optional ZKP proofs. Table VI also highlights that verifiable deletion and scalability are achieved through IPFS key revocation and distributed storage. This mapping demonstrates that the BSM's modular components jointly meet both technical and regulatory requirements across multiple operational contexts.

H. Trade-off Analysis

While each module in the proposed BSM contributes to overall security and compliance, their performance characteristics and operational risks vary. A more granular view of these trade-offs helps practitioners decide which components to enable based on specific application priorities. For example, IPFS offers high scalability but introduces retrieval latency that may affect real-time use cases. SGX enclaves provide strong confidentiality but rely on hardware trust and are susceptible to side-channel attacks if not patched. Similarly, the ZKP layer delivers unmatched privacy-preserving verifiability but at the cost of computational speed and energy consumption.

Table VII summarizes these trade-offs, mapping measured performance metrics against security benefits and compliance considerations for each core module.

TABLE VI. SECURITY REQUIREMENT MAPPING FOR DEPLOYMENT SCENARIOS

Requirement	*Healthcare*	*E-Government*	*Cross-Border Academia*	*Supporting BSM Components*
Confidentiality	✓	✓	✓	SGX, AES-256-GCM encryption
Integrity	✓	✓	✓	Blockchain ledger immutability, CCaaS
Authorization & Access Control	✓	✓	✓	CCaaS role/attribute policies
Auditability	✓	✓	✓	On-chain logs, IPFS hash tracking
Compliance with Jurisdictional Rules	✓	✓	✓	CCaaS policy scripting, ZKP proofs
Verifiable Deletion	✓	✓	✓	IPFS key revocation
Scalability	✓	✓	✓	IPFS distributed storage

TABLE VII. SECURITY-PERFORMANCE TRADE-OFFS ACROSS BSM MODULES

Module	*Latency (ms)*	*Key Benefit*	*Main Limitation*
CCaas	51-68	Low-latency, modular access control	Dependent on secure API governance
SGX	~45	Hardware-isolated confidential processing	Side-channel risk if unpatched
IPFS	~112	Scalable, verifiable off-chain storage	Higher retrieval latency
ZKP	~122	Strong privacy-preserving verification	Computationally intensive

VII. CONCLUSION

This study has presented a formally verified Blockchain-Based Security Model (BSM) for secure personal data sharing. The model integrates Chaincode-as-a-Service (CCaaS) for modular execution, Intel SGX enclaves for trusted computation, InterPlanetary File System (IPFS) for decentralized storage, and optional Zero-Knowledge Proofs (ZKPs) for privacy-preserving verification. Through symbolic analysis with the Dolev–Yao adversary model in ProVerif, the BSM was shown to satisfy confidentiality, integrity, authentication, authorization, and auditability requirements. In parallel, experimental evaluation demonstrated that low-latency execution can be maintained in CCaaS and SGX components, with ZKPs offering configurable privacy enhancements.

The novelty of this work lies in unifying modular smart contract execution, hardware-assisted protection, off-chain storage, and formal verification into a single deployable framework. The contributions of the study can be summarized as follows:

- It delivers provable security guarantees for a multi-layer blockchain system,
- It aligns privacy-by-design principles with global compliance obligations, and
- It provides a deployment blueprint that can be adapted across domains such as healthcare, finance, and e-government.

While the results are encouraging, the study also opens avenues for future research. Extending the model with post-quantum cryptographic schemes will address resilience against emerging quantum threats. Compositional verification with tools such as Tamarin can capture more complex system behaviours, while multi-chain interoperability would strengthen trust frameworks that span institutional or jurisdictional boundaries.

Beyond its technical achievements, the work has practical and societal relevance. The BSM offers organizations a means to implement GDPR-and HIPAA-compliant data sharing with reduced audit overhead. By embedding formal verification into the design, it enhances confidence for users and service providers, supports regulators in evaluating compliance, and contributes to trustworthy digital ecosystems. In doing so, this study not only advances the state of blockchain security research but also provides a foundation for building privacy-preserving infrastructures capable of supporting sensitive cross-domain data sharing. This formally verified BSM thus provides a foundation for building future blockchain infrastructures that are both technically rigorous and societally trustworthy.

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