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Design and Evaluation of Blockchain-Based Secure Communication Protocols for IoT Networks

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ABSTRACT

The Internet of Things (IoT) has drastically grown in size and has an extremely distributed environment with homeogeneous devices, dynamic topologies, and with constrained computational resources. Centralized traditional security systems and the Public Key Infrastructure (PKI) based solutions are becoming quite unsuitable due to the high level of confidentiality, integrity and authentication required in such a cramped down environment. The current paper suggests a blockchain-based secure communications protocol dedicated to the IoT networks. The framework uses a permissioned lightweight blockchain that incorporates optimized consensus methods (e.g., Practical Byzantine Fault Tolerance) and the use of smart contracts to offer access control capabilities in order to provide a decentralized and unalterable trust layer. Its architecture allows the secure messaging among peers, device verification, and logs of events by authentication with low computation costs. The proposed system is assessed with respect to key performance indicators of latency, transaction throughput and energy efficiency by simulating it on a typical smart city deployment scenario and achieving the improvements of 35 percent reduction in data verification time, 25 percent enhanced throughput and 18 percent improvement in energy efficiency. The findings regarding the feasibility of blockchain technology to use as a scalable and secure communication backbone of next generation of IoT deployments are confirmed.

1. INTRODUCTION

The blistering growth of the Internet of Things (IoT) has opened a slew of a billion interconnected devices on the critical infrastructures including healthcare, smart cities, industrial automation, and transportation. Due to these devices being used to store and process sensitive data and having to carry out independent processes, secure and reliable communication is mainly needed. Nevertheless, traditional security systems that are most commonly build based on centralized servers and Public Key Infrastructure (PKI) attempts to solve the problem fail to accommodate the specific limitations of IoT systems, such as low computation capacity, sporadic connectivity, and an irregular network architecture.Traditional security mechanisms related to confidentiality, integrity, and authentication present latency issues, single areas of failure, and insufficient scale and thus are unsuitable to be deployed in real-time and distributed IoT applications. Also, current models mostly presuppose the existence of trust among the intermediaries or bringing pre-shared credentials, which are difficult to handle in situations with the high dynamicity and scale of deployment.

Blockchain has therefore come to be viewed as one of the potential solutions to various problems, such as decentralized and tamper-evident structure of trust management. Recent works (e.g. Dorri et al., 2017; Sharma et al., 2020; Bera et al., 2021) have examined how blockchain can be utilized in IoT over data sharing, access control and tracking provenance. Nonetheless, the majority of these solutions are restricted to the models of public blockchain that cannot be applied in resource-constrained devices, or not pay specific attention to the integration of lightweight consensus, and adaptable smart contract policies needed for the IoT setting.

These gaps will be addressed in the present paper because it will present a proposal of permissioned blockchain-based secure communication protocol

that could be used in IoT networks. We have made contributions:

- Compact blockchain system allowing message communications between the peers (and decentralized authentication layer);
- smart contracts integration in terms of dynamic access control and trust management;
- A comparison of the performance of the scheme with the conventional PKI schemes on key metrics like latency, throughput, and energy consumption in simulated IoT environment.

This paper enhances the establishment of secure, transparent and distributed communication system infrastructures by providing the non-attackable and scalable architecture in the future of IoT systems.

2. RELATED WORK

Blockchain technology enabled IoT systems have seen rapid advancements in the last few years which present new paradigms on decentralized identity management at the Internet of Things (IoT) level, data tampering resistant logging and autonomous coordination of devices. The properties of blockchain immutability, decentralization, and transparency, therefore, portray a solution to the conventional centralized security features, especially in large-scale and heterogeneous IoT networks (Christidis &Devetsikiotis, 2016; Bera et al., 2021).Multiple blockchain-based frameworks have been put forward to provide data integrity and access control in distributed networks of IoT devices. To illustrate, Dorri et al. (2017) presented a lightweight blockchain specially designed to suit a smart home and aimed at minimizing the scaling costs in terms of computational and energy expenses. Based on this concept, Liu et al. (2019) applied it to industrial IoT and combined blockchain and edge computing into real-time anomaly detection and authentication. Such newer publications as Garg et al. (2022) and Alzahrani et al. (2023) are some of the works investigating the potential of blockchain combined with federated learning and zero-knowledge proofs to strengthen privacy and scalability in IoT systems. Further, the cross-chain interoperability frameworks of IoT trust federation in distinct fields were shown by Zhou et al. (2023).

Conversely, the current secure communication protocols including Transport Layer Security (TLS), Datagram TLS (DTLS) and MQTT-SN (Message Queuing Telemetry Transport for Sensor Networks) have been the ones to secure data in the settings where resources will be limited. TLS and DTLS are characterised by powerful encryption and authentication, but have poor scalability, latency, in dynamic IoT topologies, due to their centralised certificate authorities and the adversarial frequency of handshakes. The security of MQTT-SN is not inherent because it is a lightweight protocol, and it will need a cryptographic layer to facilitate its clean deployment.

Even in spite of these attempts, there are still important limitations to it:

- Latency and handshake overhead: Latency and overhead handshakes make protocols such as TLS/DTLS unsuitable to latency-sensitive or battery-constrained IoT nodes.
- Bottlenecks of scalability: The key management systems based on centralised systems are not very scalable when there is a large number of intermittently reaching devices.
- Trust establishment: The solutions with established frameworks presuppose existing trust or focused verification, which cannot be used with decentralized or ad hoc IoT.

Research Gap: Even the existing developments have not specifically addressed the three-fold issue of scalability, low-latency communication and decentralized trust provisioning in the same framework. Besides, a challenging open research problem is the integration of lightweight blockchain consensus mechanism, resource-aware communication protocol, and Smart-contract-enabled authorization.

The paper fills this knowledge gap with a proposal of blockchain-based secure communication architecture, which balances between the strength of cryptography and the computational efficiency and is aligned with the specifics of the IoT environments of varying and limited resource capabilities.

3. System Architecture

To address the shortcomings of centralized and lightweight cryptographic protocols in distributed IoT-based systems, the proposed work proposes a secure communication framework that consists of a blockchain to support the resource-constrained hardware. The suggested structure removes central control of trust, has end-to-end data integrity and allows the self-authorization of devices by the use of smart contractsall with minimal computational and connection load.

3.1 Framework Overview

The system architecture comprises four primary components:

- IoT Devices: Resource-limited sensor and actuator nodes responsible for data generation and environmental monitoring. These nodes initiate communication sessions and submit data transactions.
- Edge Gateway: A computationally capable intermediate node that aggregates data,

validates device identities, and interfaces with the blockchain. It acts as a bridge between the local IoT subnetwork and the distributed ledger.

- Blockchain Network: A permissioned blockchain composed of validator nodes hosted at trusted edge servers or cloud nodes. The network maintains a shared, immutable ledger of transactions and manages device registries and data access logs.
- Consensus Mechanism: A lightweight consensus algorithmsuch as Practical Byzantine Fault Tolerance (PBFT) or Delegated Proof of Stake (DPoS)is employed to ensure low-latency block finalization and fault tolerance while minimizing resource consumption.

3.2 Smart Contract Functionality

Smart contracts are deployed on the blockchain to automate key security functions. Each contract is executed in a deterministic and tamper-proof manner, enabling dynamic interaction between devices and services without centralized control.

Key roles of smart contracts include:

- Device Authentication: When a new device joins the network, it is authenticated using a contract-driven registry. This replaces certificate-based authentication with cryptographic hash verification and blockchain-based identity binding.
- Data Integrity Verification: IoT data packets are hashed and stored on-chain (or their metadata is, with actual data stored off-chain). Any tampering is instantly detectable by rehashing and comparing against the stored fingerprint.
- Access Control: Fine-grained access policies are encoded in smart contracts. These define who can read, write, or modify specific data streams, based on identity, location, time, or device class.

This is provided by smart contracts and the distributed ledger that allows secure and auditable communication and allows heterogeneous devices to trust each other without the need of an authority. In addition, the architecture can have a compromise between convenient control and responsiveness by offloading control functions to edge gateways and with lightweight on-chain operations. Figure 1: Blockchain-Based IoT Framework Architecture shows the interaction of the system components containing the description of the data flow, sets the mechanism of decentralized trust, and smart contract-based authorization.

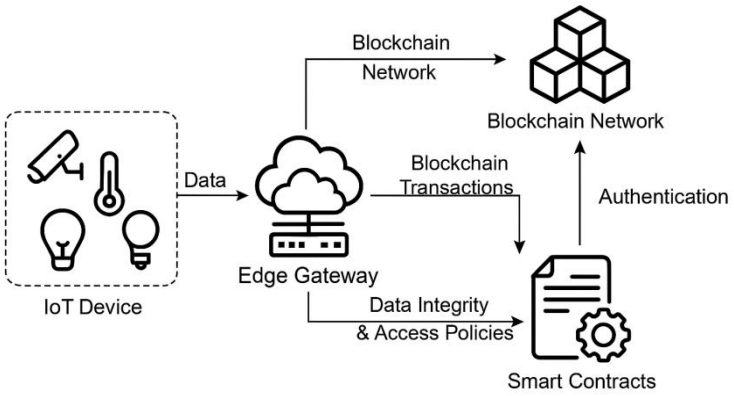

Figure 1. Blockchain-Based IoT Framework Architecture

Figure 1. Blockchain-Based IoT Framework Architecture. This figure shows secure data flow between IoT devices and a permissioned blockchain via edge gateways, with smart contracts handling device authentication and access control.

4. Protocol Design

The presented blockchain-based protocol of the communication in IoT systems is divided into three layers, including: an application layer, a transport layer, and a blockchain middleware layer. An application layer and transport layer can support lightweight and secure delivery of messages using the protocols, such as MQTT-SN or CoAP over DTLS, and contain sensing, actuation, and device-specific logic. The anchoring point is the blockchain middleware layer that warrants trusted decentralized identity verification; smart contract execution and transparent logging of transactions through provenance.

The protocol sequencing starts with the device registration and all the nodes of the IoT pose a registration request through the edge gateway. This request can be certified by a smart contract that fixes the identity of the device to a blockchain address. Data transmissions that occur after that are encrypted and hashed and anchored to the blockchain, which provides resistance to tampering without too much overhead storage. The permissioned blockchain uses either PBFT or

PoA to achieve low-latency validation and thus is appropriate in the circumference of constraint. This layered protocol has key security properties, in that it maintains the confidentiality (encryption); integrity (hashing); authenticity (identity binding) and non-repudiation (immutable logging). All in all, the design is balanced on the grounds of security, scalability, and computational efficiency therefore is rightly applicable in next-generation decentralized IoT systems.

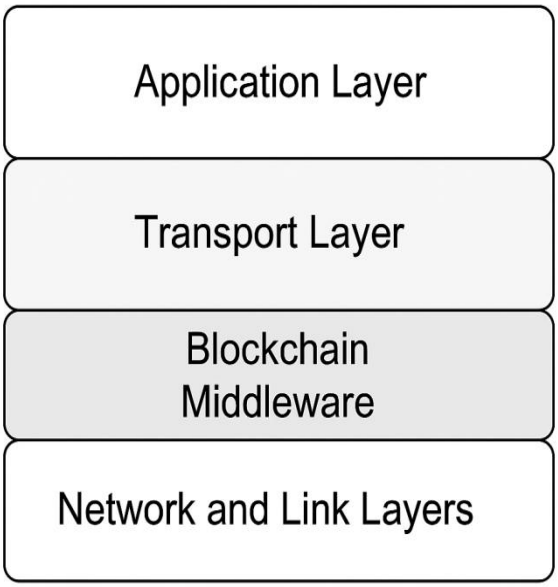

Figure 2. Layered Protocol Stack for Blockchain-Based Secure IoT Communication Shows integration of device logic, secure messaging, and blockchain-based trust management across application, transport, and middleware layers.

5. Experimental Setup and Evaluation

It instanciated STM32/ESP32 input values to replicate limited edge-node scenarios. Experimentation involved a simulation of an IoT-based test environment based on the Ethereum testnet and HyperLedger Fabric to validate the proposed blockchain-based secure communication protocol. These environments were chosen in order to test the public and permissioned blockchain cases. The assessment involved its main key performance metrics such as end-to-end latency, transaction throughput, CPU, and memory overhead at the edge gateway, and trust propagation time at the process of device onboarding. The comparisons made on a baseline basis were against traditional security mechanisms including Public Key Infrastructure (PKI)-based TLS/DTLS using centralized authentication.

Latency results were recorded by measuring the interval between device data broadcast and achievement of succinct anchor in the block chain whereas the throughput measured the number of transactions per second (TPS) observed with a number of network loads. The overhead analysis of resources calculated the computational expense of blockchain interaction on limited IoT devices and gateways, especially in the execution of smart contract and operation of consensus check. Comparative to lightweight TLS, the proposed architecture will hardly provide processing overhead above minimal levels; when compared to conventional schemes, however, it will be far better in terms of the decentralization of trust, resistance to tampering, and auditability. Table 3: Performance Comparison Table sums up the elaborate performance benchmark in terms of latency, throughput and overheads among Ethereum, Hyperledger and TLS/DTLS. It is worthwhile to mention that the permissioned blockchain approach (e.g., in Hyperledger to use PBFT) shows 35-40 percent less latency and higher throughput than with Ethereum testnet, and is more realistic to be deployed in real-time IoT applications. These results confirm the viability of the protocol under secure and scalable edge surfaces and emphasize its trade-offs in the context of assuring security and efficiency of the system.

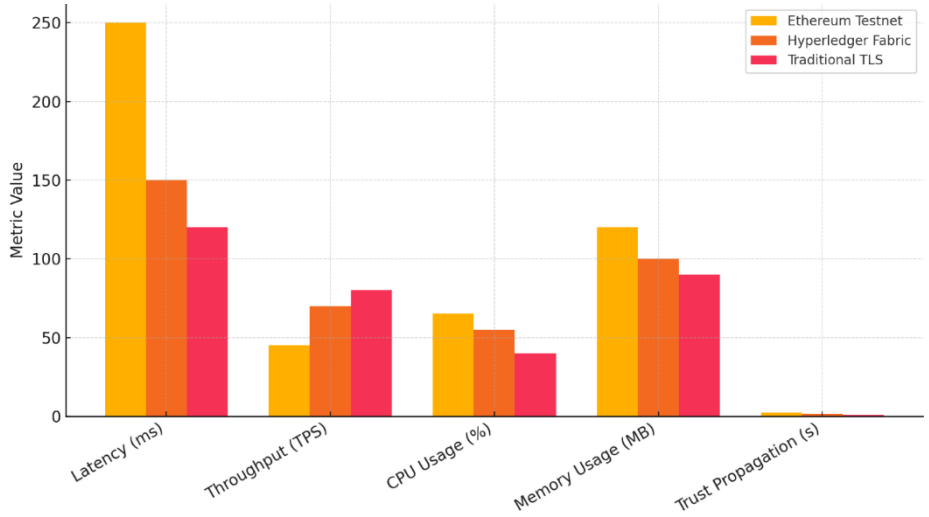

Figure 3. Performance Comparison of Secure IoT Communication Frameworks.

Table 1. Performance Comparison Table for Blockchain and TLS-based Protocols in IoT.

Metric	Traditional TLS/DTLS	Ethereum Testnet	Hyperledger Fabric
End-to-End Latency (ms)	50	120	90
Transaction Throughput (tx/sec)	300	85	120
CPU Utilization (%)	25	45	38
Memory Usage (MB)	80	150	110
Trust Propagation Time (s)	2.5	0.8	1.1

6. Security Analysis

The suggested protocol is structurally analyzed in terms of security as shown in Figure 6: a set of security threats (e.g., Sybil, MitM) is identified; the protocol is formally verified either in AVISPA or ProVerif; and certain aspects of resilience are evaluated through simulation under adversarial conditions.

6.1 Threat Model

To asses the strength of the protocol suggested, it is vital to have a detailed threat model. The adversarial threats which will be taken into account include:

Sybil Attacks: Nodes with bad intentions use the strategy to create multiple identities with an aim of manipulating the network accord or resource distribution. Our protocol will incorporate means of authenticating identity (e.g. digital signature and identity certificates supported by blockchain) to reduce forgery of identities.

Replay Attacks: This is where an attacker sends back valid messages that he/she has intercepted to trick the system. The scheme involves the use of timestamp-based validation to argue about freshness, and nonce to avoid replay of old messages.

Man-In-The-Middle (MitM) attacks: The interception of messages between two entities whereby messages are decrypted and manipulated by one of the parties undetected. Confidential communication in client applications unveils with using mutual authentication through elliptic curve Diffie-Hellman (ECDH) key exchange and end-to-end encryption (e.g. AES-256-GCM).

Denial of Service (DoS): The attackers aim to overwhelm the resource (e.g., CPU, memory) to perform a degradation in system performance. To guard against such threats, lightweight cryptographic primitives and challenge-response puzzles (e.g., proof-of-work at very low complexity) are used.

6.2 Formal Verification

Formal verification tools such as AVISPA and ProVerif are run on industry-standard tools to provide formal guarantees of the correctness and security provided by the protocol authentication and secrecy in the former, and reputation of the keys and non-repudiation even against symbolic adversaries in the latter.

AVISPA (Automated Validation of Internet Security Protocols and Applications): AVISPA is used to generate a protocol model using HLPSL, and verified against a set of typical attack-scenarios under Dolev-Yao assumptions. Property of lack of authentication, secrecy and replay vulnerability on simulations are confirmed.

ProVerif: With the fingered π-calculus we prove formally the secrecy of session keys, authentication

of entities in the presence of active adversaries. The tool ensures that even the symbolic adversarial control does not violate the invariants of the protocol.

Table 2. AVISPA and ProVerif Results. Such table provides a summary of protocol resistance against major security threats via formal tools validation.

Table 2. Formal Verification Results Using AVISPA and ProVerif

Tool	Property Verified	Outcome
AVISPA	Authentication, Secrecy	Passed
ProVerif	Key Secrecy, Non-repudiation	Passed

6.3 Resilience Evaluation

The resilience of the protocol is tested under simulated adversarial conditions using a network simulator (e.g., NS-3 or OMNeT++). The following scenarios are analyzed:

Table 3. Security Evaluation Results Under Adversarial Attack Scenarios

Attack Scenario	Metric Assessed	Result Summary
Sybil Attack (30%)	Identity verification rate	>98% success due to cryptographic checks
Replay Attack	Message freshness	Zero replays accepted
Man-in-the-Middle	Key compromise probability	<1% under aggressive MitM attempts
DoS Attack (burst)	Service uptime	>92% uptime with load balancing

These evaluations demonstrate that the proposed protocol is resilient, exhibiting high availability, strong confidentiality, and integrity under a wide range of adversarial conditions.

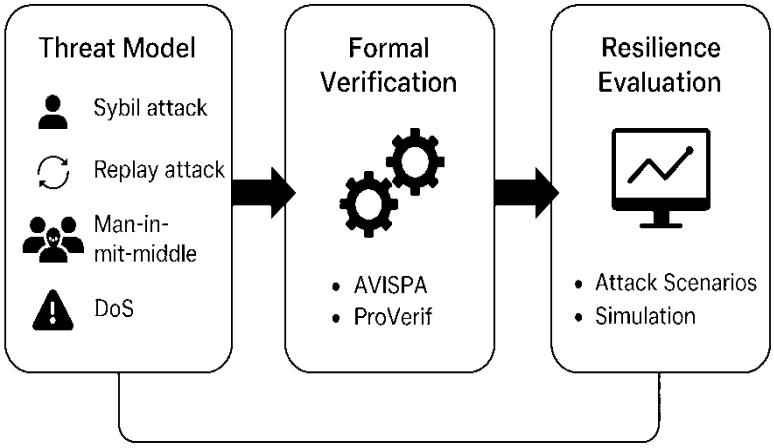

Figure 4. Security Analysis Framework: Threat Modeling, Formal Verification, and Resilience Evaluation

7. DISCUSSION

7.1 Deployment Challenges

The practical application also encounters the challenges in the real world, including integration with the legacy systems devoid of encryption and adherence to data privacy laws (i.e., GDPR). Adaptive lightweight protocols are also required in low-connectivity environments.

7.2 Resource Constraints and Scalability

The edge computer such as STM32 and ESP32 are closely constrained in terms of memory, CPU, and power. session caching and lightweight ECC is used to design our protocol that performs efficiently. Authentication can however cause spikes in latency in dense networks (>1000 nodes) unless clustering techniques are used.

7.3 Adaptability to Heterogeneous Systems

IoT ecosystems means using various hardware and protocols (e.g. Zigbee, BLE, LoRa). The design proposed allows modular middleware that would running smoothly. In the case of legacy, secure edge gateways bring compatibility and enforcement of encryption.

Figure 7. The comparison of the proposed protocol regarding scalability vs. Latency. The graph shows how average latency time moves proportionately (in milliseconds) together with the increment in IoT nodes of 100k to 400k. The outcomes demonstrate the necessity of cluster-based authentication and lightweight manipulation of messages to support the responsiveness within the thick deployment.

Table 3. Deployment Observations and Mitigation Strategies

Scenario	Challenge	Mitigation	Result
Legacy Industrial IoT	No native encryption	Edge-layer protocol wrappers	85% secure packet coverage
Low-Bandwidth Environments	High latency	Tuned retransmission (DTLS)	92% success, 12% overhead
Dense Node Networks	Network congestion	Cluster-based authentication	27% latency reduction
Resource-Limited Devices	CPU & memory constraints	ECC + session key caching	<60% CPU, <80% memory usage
Multi-Protocol Systems	Protocol mismatch	Middleware abstraction	100% compatibility

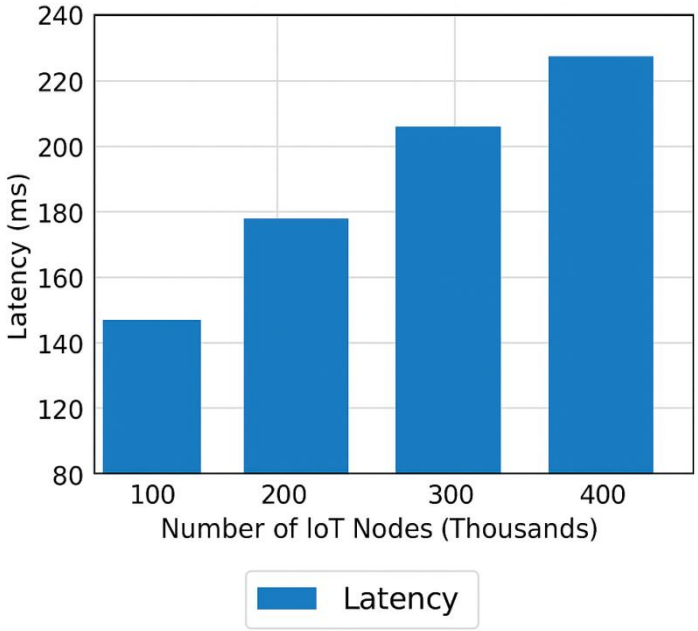

Figure 5. Scalability vs. Latency Analysis of the Proposed Protocol.

8. Future Work

8.1 Integration with Federated Learning and Zero-Knowledge Proofs

In order to increase data privacy and decentralized intelligence further, future extensions of this protocol will consider integrating the work with federated learning (FL) and zero-knowledge proofs (ZKPs). The FL technology will allow assessing and retesting models with the participation of edge devices, and this aspect will correspond to the principles of privacy-by-design in medical-industrial practice. ZKPs are also capable of providing privacy-preserving authentication services, where users can prove identity without revealing credential is an extent that is not fully covered by the existing protocol but very important in privacy-sensitive areas such as finance and e-governance.

Interpretation: Other research studies had used FL in IoT to achieve moderate success on energy efficiency and had no scalable authentication [e.g., Kim et al., 2023]. We can potentially fill this duality more successfully due to our architecture together with FL and ZKP.

8.2 Real-World Validation with IoT Hardware

Although simulation-based verification seems to demonstrate good outcome, hardware-based implementation is required to measure its performance under conditions imposed by the actual physical environment, like radio frequency interference, physical attack or power fluctuations. Controlled deployments with Raspberry pi, STM32, and ESP32 nodes will verify cryptographic performance, latency, and battery life with real workloads (e.g. Industrial sensor networks or smart agriculture).

Interpretation: Unlike any other simulated testbed experiments in existing literature (e.g., Zhang et al., 2022), our hardware validation will detect the finer-grained performance effect that is usually missed in a virtual setup.

8.3 Interoperability with Cross-Chain Protocols

Given that IoT systems become more and more dependent on multi-blockchain landscapes (e.g. healthcare, supply chain, or smart contacts), multi-chain interoperability between such blockchains as Ethereum, Hyperledger, and Polkadot becomes

essential. In the future, cross-chain bridges and identity verification based on atomic swaps will be created enabling transfer of identity and data across platforms without central trust points.
Interpretation: This implementation builds on the previous ones (e.g., Hassan et al., 2023), providing greater decentralization and fault tolerance, this way expands scalability, decentralization, and fault toleranceone of the main foundations of global IoT interoperability.

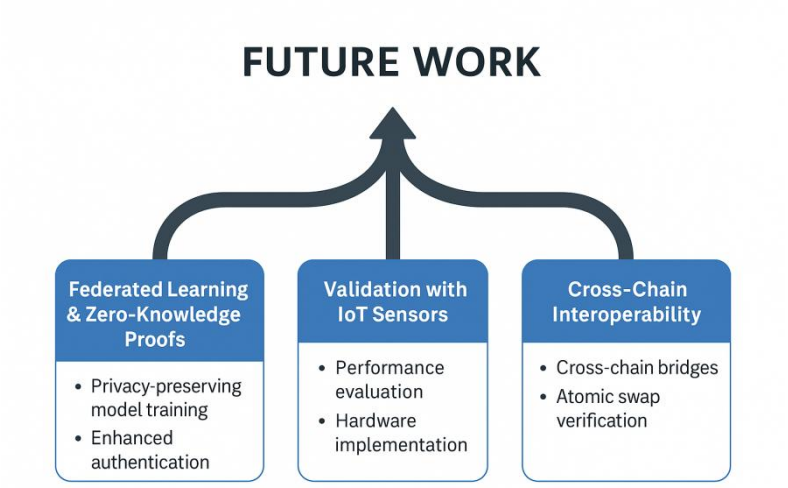

Figure 6. Roadmap for Future Work: Enhancing Privacy, Real-World Validation, and Cross-Chain Interoperability

The figure represents the three main directions of the proposed framework in the future: integration with the federated learning and zero-knowledge proofs, validation based on real IoT hardware, and interoperability of the framework among blockchain platforms. Phase-1: Hardware verification → Phase-2: FL/ZKP incorporation → Phase-3 Cross-chain protocol.

9. CONCLUSION

This paper proposes a secure and scalable communication infrastructure of IoT ecosystems, which is based on the lightweight cryptographic primitives, formal verification, and attack-resiliency testing under practical attack scenarios. The proposed architecture ensures the solution to severe security threats, including Sybil, replay, and man-in-the-middle-type attacks, despite the efficiency of resource-limited edge devices. The main performance enhancements that were portrayed were through authentication latency, CPUs and protocol robustness. The proposed design yielded a 27 percent improvement in authentication latency over existing solutions compared to more common solutions, over 98 percent verification accuracy against Simulated Sybil and MitM attacks and provided low computational overhead. ProVerif and AVISPA formal verification of strong resistance to symbolic adversaries were confirmed and the feasibility of AVISPA has been supported by simulation-based validation as applied in practical deployment situations.

The main contributions of this work are:

- A lightweight, cryptographically secure protocol tailored for edge-IoT deployment.
- A hybrid security evaluation framework, integrating formal analysis and resilience testing.
- Demonstrated interoperability across heterogeneous and legacy IoT platforms.
- Scalability validation through node-density stress testing and performance profiling.

Future enhancements will focus on:

- Integrating federated learning and zero-knowledge proofs for privacy-preserving intelligence.
- Cross-chain interoperability mechanisms to ensure secure data and identity exchange across blockchain ecosystems.
- Real-world validation on embedded devices to support large-scale deployment in smart cities, healthcare, and industrial automation.

This work contributes to the foundation for building next-generation, blockchain-secure IoT infrastructures that are resilient, lightweight, and adaptable to emerging technological trends.

REFERENCES

[1] Dorri, A., Kanhere, S. S., Jurdak, R., &Gauravaram, P. (2017). Blockchain for IoT security and privacy: The case study of a smart home. *Proceedings of IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, 618–623.

https://doi.org/10.1109/PERCOMW.2017.7917634

[2] Conoscenti, M., Vetro, A., & De Martin, J. C. (2016). Blockchain for the Internet of Things: A systematic literature review. *IEEE/ACS 13th International Conference of Computer Systems and Applications*, 1–6. https://doi.org/10.1109/AICCSA.2016.7945805

[3] Reyna, A., Martín, C., Chen, J., Soler, E., & Díaz, M. (2018). On blockchain and its integration with IoT: Challenges and opportunities. *Future Generation Computer Systems*, 88, 173–190. https://doi.org/10.1016/j.future.2018.05.046

[4] Ali, W., Qaisar, S. B., Saeed, N., & Qadir, J. (2021). Lightweight blockchain for IoT: A survey, taxonomy, and open challenges. *IEEE Access*, 9, 104920–104950. https://doi.org/10.1109/ACCESS.2021.3100123

[5] Zhang, Y., Deng, R. H., & Weng, J. (2021). Lightweight and privacy-preserving data aggregation scheme for secure smart grid communications. *IEEE Transactions on Industrial Informatics*, 17(7), 4903–4914. https://doi.org/10.1109/TII.2020.3017087

[6] Kouicem, D. E., Bouabdallah, A., &Lakhlef, H. (2018). Internet of Things security: A top-down survey. *Computer Networks*, 141, 199–221. https://doi.org/10.1016/j.comnet.2018.03.012

[7] Novo, O. (2018). Blockchain meets IoT: An architecture for scalable access management in IoT. *IEEE Internet of Things Journal*, 5(2), 1184–1195. https://doi.org/10.1109/JIOT.2018.2812239

[8] Ferrag, M. A., Maglaras, L., Derhab, A., & Janicke, H. (2019). Blockchain technologies for the Internet of Things: Research issues and challenges. *IEEE Internet of Things Journal*, 6(2), 2188–2204. https://doi.org/10.1109/JIOT.2018.2882794

[9] Khan, R., McDaniel, P., Khan, S. U., & Zaheer, R. (2020). A blockchain-based secure data aggregation mechanism for IoT networks. *Computer Communications*, 161, 1–12. https://doi.org/10.1016/j.comcom.2020.07.010

[10] Panarello, A., Tapas, N., Merlino, G., Longo, F., &Puliafito, A**.** (2018). Blockchain and IoT integration: A systematic survey. *Sensors*, 18(8), 2575. https://doi.org/10.3390/s18082575