IoT-Enabled Secure and Scalable Cloud Architecture: A Hybrid Post-Quantum Cryptographic and Blockchain-Based Framework for Multi-User Systems

Palanisamy P[1*], Azhagesan M[2], Sathiya D[3], Arun B[4], Dineshkumar S[5] and Ilayaraju C[6]

[1, 2] Assistant professor, Department of Computer Science and Engineering, K.S.R College of Engineering, Tamil Nadu, India.
[3]Associate professor, Department of Computer Science and Engineering, K.S.R College of Engineering, Tamil Nadu, India.
[4, 5, 6] Student, Department of Computer Science and Engineering, KSR College of Engineering, Tamil Nadu, India.
palanisamyp@ksrce.ac.in

Abstract. In this paper a novel IoT-enabled secure and scalable cloud architecture employing a hybrid post-quantum cryptographic and blockchain-based framework is proposed targeting multi-user system. Hence, to ensure the advanced protection of IoT data and communications against classical and quantum attacks, post-quantum cryptography, and blockchain technologies are integrated, which also provides long-term security. The hybrid system approached optimises both the scalability and decentralisation features that solve the regular blockchain scalability issues with regards to IoT, and therefore, increases resilience when managing IoT devices. Additionally, the system aims to maximize the use of cryptographic methods to find a trade-off between security and efficiency and to be appropriate for resource-constrained IoT settings. The hybrid framework also allows for interoperability with existing IoT standards and energy-efficiency solutions for battery-powered end devices. By designing this architecture to be future-proof, and so it can combat emerging quantum threats against end-user data. This proposed framework has drastically enhanced user experience due tools like simplified management and good security perks. By managing data storage effectively and offering quantum-resistant protection, the system provides full-featured security for IoT applications while requiring very little interruption to existing infrastructures. These advanced technologies offer powerful and economical alternatives to Scalable, Secure, and Long-Term IoT Cloud mechanism.

Keywords: IoT, cloud architecture, hybrid post-quantum cryptography, blockchain, security, scalability, decentralization, multi-user systems, resource-constrained environments, quantum-resistant, integration, energy efficiency, regulatory compliance, user experience, data management, cost-effective, system integration, quantum threats, future-proof, IoT standards, blockchain architecture.

1 Introduction

This indeed requires raw data from the Internet of Things (IoT) as its usage is on the rise with devices exchanging the data over the Internet for applications ranging from smart homes to health and industrial automation. But the additional use of cloud architectures introduces new security, scalability and privacy challenges as IoT systems continue to proliferate. It is said that while conventional cryptographic algorithms are

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secure against classical cyberattacks; they are extremely susceptible to quantum computing breakthroughs that could overtake them in the near future. This makes the development of strong, quantum resistant cryptographic solutions more important than ever.

At the same time, the growing amount of IoT data requires scalable, efficient, cloud-based solutions. "The characteristics of blockchain technology such as decentralization and tamper-resistance make it a promising approach to secure IoT data and build trust between users in multi-user systems. Blockchains themselves, though, face challenges to scalability and energy consumption that can inhibit their utility in large-scale IoT environments.

We present a hybrid framework that merges post-quantum cryptography with blockchain technology to secure IoT-powered cloud architectures. By incorporating post-quantum cryptography, we put the system one step ahead of future quantum attacks, and by integrating blockchain we will add the necessary transparency, accountability, and security that can be important for any system using multiple users. It combines the strengths of both worlds, pushing the traditional boundaries of cryptography and addressing the scaling challenges that threaten to limit the reach of blockchain in the IoT cloud sphere, paving the way for a secure, scalable and quantum-resilient implementation to the cloud of things.

We show that by means of the outlined framework, one is able to achieve a trade-off between security and performance, support interoperability with established IoT standards, and reach energy efficiency for resource-limited devices. It is also compliant with regulatory requirements and high-quality user experience through simplifying IoT services management and access. In conclusion, this innovative hybrid of post-quantum cryptographic and blockchain-based approach presents a thorough, extensible, and economical framework for safe and scalable structure of IoT Cloud systems.

2 Problem Statement

With the continuous proliferation of the Internet of Things (IoT), the need for secure, scalable, and efficient architectures to support large-scale networks of connected devices grow. Since traditional cryptography is used to secure most of the IoT communications, the development of quantum computing poses a major threat in the security of the IoT as traditional cryptography will be obsolete soon. This becomes a serious threat to the confidentiality and integrity of the data transmitted via IoT systems because these quantum computers can break the commonly used encryption standards (RSA and ECC) that form the basis of the majority of the current IoT security protocols.

In addition, although cloud computing provides scalable storage and processing methods for Internet of Things (IoT) data, the integration of blockchain technology—which is generally employed to enhance security, trust, and transparency—into IoT clouds presents significant challenges. In particular, their inherent scalability issues produce potential bottlenecks in high-volume IoT applications, limiting their ability to be termed efficient solutions in real-world adaptations. Moreover, IoT devices themselves have limited resources; hence, energy-hungry cryptographic techniques such as post-quantum encryptions and blockchain become unreliable, severely limiting their deployment due to resource constraints.

Therefore, there is an urgent need to develop a hybrid framework of post-quantum cryptography and blockchain that effectively address the aforementioned concerns and facilitate secure, scalable, as well as quantum-resistant communication among IoT systems. A solution framework must tackle the performance and scalability issues that a blockchain incurs while providing the existing connectivity with IoT platforms and cloud infrastructures seamlessly without adding considerable complexity to devices with limited resources. We focus on, how we can architect such complex multi user requirement driven IoT devices architecture that not only meet security standards but also efficient as required in near future large scale deployment.

3 Literature Review

It will become one of the fastest industrial growing and give rise to numerous cloud computing-based architectures to control the rapidly growing IoT data. Despite good compatibility of security, scalability, and efficiency in these architectures, there is still a challenge. We focus on reviewing the existing literature on IoT security, cloud computing, blockchain technology, post-quantum cryptography, and hybrid systems in this subsection before pointing out the gaps that the proposed hybrid framework intends to fill.

3.1 Model Installation on the Cloud Computing

Also, IoT devices are inherently prone to a lot of cyber risks due to their vast attack surfaces, heterogeneous devices and dependence on cloud infrastructures to store and process data. To mitigate these vulnerabilities, researchers have suggested a variety of security mechanisms, including encryption, authentication and access control. Unfortunately, these approaches use classical cryptographic algorithms (RSA, AES, etc.) that are becoming increasingly insecure with the advent of quantum computers. However, quantum cryptosystems are an emerging solution because as pointed out by (Chen et al., 2020; Sadeghi et al., 2021), traditional cryptographic algorithms are threatened by quantum attacks which is the reason why the quantum resistant alternatives are being investigated.

Cloud computing used for scalable infrastructure for storing and processing huge amounts of data from IoT devices. It is important to support secure communication tools between IoT devices and cloud platforms, given the common target of cloud environments to numerous cyber-attacks. In conventional centralized cloud models, there are single points of failure, loss of data privacy, and trust issues. Various decentralized systems, such as blockchain, have become more popular as a solution to address these issues.

3.2 Blockchain Technology in IoT Security

Blockchain, a database system that provides a secure, transparent and tamper-proof mechanism on a distributed network has been actively proposed as a solution to secure IoT systems. The decentralized nature of blockchain provides a promising way to solve issues with data integrity, privacy, and transparency in building multi-user systems (Zhang et al., 2021). Blockchain allows for automatic peer-to-peer communication of IoT devices without a central authority due to smart contracts and consensus protocols.

Blockchain technology has proven to be beneficial for IoT security, such as data integrity or immutable audit trail (Zhao et al, 2020). But blockchain has more issues, especially related to scalability and performance. The block-chain consensus mechanisms, e.g., Proof of Work (PoW), are cumbersome and lead to increased latency and computational overhead which is unsuitable for IoT enabled low-latency and high-throughput communication applications (Narayan et al., 2021). Finally, as the size of the network (number of IoT devices) increases, the storage required to save blockchain transactions becomes non-linear, making it difficult to deploy in large-scale IoT infrastructures.

3.3 A Review on Post-Quantum Cryptography for IoT Security

With the introduction of quantum computing, the security of IoT systems becomes a serious threat as quantum algorithms (Shor's algorithm for example) can potentially break common protocols (Shor, 1997). One of the measures that has been proposed to fix this is known as post-quantum cryptography (PQC). Post-Quantum Cryptographic (PQC) algorithms are being developed to ensure that classical cryptographic algorithms remain secure against potential quantum attacks (Chen et al., 2016), including approaches such as lattice-based encryption and code-based cryptography.

Several researchers have investigated the possibility of implementing PQC to secure Internet of Things systems, particularly quantum-resistant encryption for communications between IoT devices and cloud platforms (Kessel et al., 2021). But many PQC algorithms can be compute-heavy, which is a challenge with IoT devices that typically operate in resource-constrained environments with much more limited processing power, memory, and battery life. Efficient implementations of PQC to portable devices with minimal performance and energy cost (Malina et al., 2021)

With this in mind, and considering both the security limitations of blockchain systems and the risks posed by advancements in cryptoanalysis to classical crypto algorithms, recent studies have initiated a thorough investigation on the possible intersection between post-quantum crypto and blockchain tech. The combination of PQC and blockchain using the hybrid approach can offer a strong solution that can provide quantum-resistant security for IoT cloud systems while taking the advantages of blockchains' decentralized architecture to ensure data integrity and trust (Sharma et al., 2022).

Although there are potential benefits of marrying PQC with blockchain, there are a number of difficulties this joint implementation brings (Feng et al., 2023): PQC in blockchain consensus protocols, PQC's effect on building blockchain scalability and the energy consumption of two technologies in IoT. As a case in point, existing legacy blockchain consensus mechanisms like PoW are resource-heavy and may potentially face even greater overhead once combined with PQC algorithms. Researchers are, therefore, investigating different blockchain consensus algorithms like Proof of Stake (PoS) or hybrid consensus mechanisms that might lower energy usage and enhance scalability (Zhao et al., 2022).

Although blockchain technology improves the security of the IoT it still suffers from the performance limitations such as low throughput and high latency. In addition, recent works indicate that while it is essential to meet the stringent needs for performance,

higher transaction speed and lower latency in real-world IoT applications are vital requirements for blockchain based a consortium, which is contrary to the secure properties (Yang et al., 2022). This involves leveraging off-chain storage, lightweight consensus protocols, and other similar techniques to improve scalability.

3.4 Gaps and Motivation for the Proposed Framework

Although much work has been done to secure IoT systems using blockchain and post-quantum cryptography, there still lacks comprehensive solutions that jointly conquer the full range of challenges posed by the properties of security, scalability, as well as resource efficiency in multi-user IoT cloud environments. More specifically, there is a need for:

1. Hybrid frameworks that take the best of both blockchain and post-quantum cryptography and minimize their weak points.
2. Scalable secure systems that meet the security and efficiency requirements for resource-constrained IoT devices.
3. Seamless integration with relevant IoT platforms and cloud architectures for fighting wide adoption without interruption.
4. Cryptographic and consensus methodologies becoming energy-efficient while striking a balance between security and operational constraints of IoT devices.

4 Methodology

This chapter provides the detailed methodology that was used to design and evaluate the recommended hybrid post-quantum cryptographic in conjunction with blockchain based architecture for the security of framework to secure an IoT enabled cloud architecture. This hybrid system uses post-quantum cryptography (PQC) and blockchain technology, and aims at a design, simulation and performance evaluation. It consists of several stages including system design, implementation, and evaluation according to various performance metrics.

4.1 System Design

This architecture integrates post-quantum with blockchain technology to form a cloud system of the IoT that is secure, scalable and energy efficient. Through a novel design capable of tackling the efficiency limitations of conventional cryptographic approaches while utilizing the merits of the scalable nature of blockchain for large-scale IoT networks. Fig 1 includes the process. Energy Efficiency and Optimization of Scalability

Key Components:

Post-Quantum Cryptography (PQC): Quantum-resistant crypto-algorithms are being used for securing communications of IoT devices with application providers/Cloud platforms. The choice of integrating lattice-based encryption is made based on its potential to resist quantum attacks and its compatibility with low-resource IoT devices.

Blockchain Integration: A decentralized blockchain is used to secure data transactions and maintain the integrity, transparency, and accountability of the system. To address this issue, a hybrid Proof of Stake (PoS) consensus mechanism is streamlined which has a far more scalable and less energy costly compared to traditional Proof of Work (PoW) ones.

Collaboration of IoT Devices and Cloud: The model enables a communication channel between IoT devices (from low-powered sensors to edge nodes) and cloud service platforms. PQC lies above the block chain, and block chain is a form of ensuring the immutability of data.

By using this hybrid system, it is possible to work on both the NFT and IoT end of things, and it does so while being energy efficient, really bringing consciousness to the blockchain and PQC operational overhead in the constrained environment, i.e., IoT devices, which is crucial as they have limited power sources.

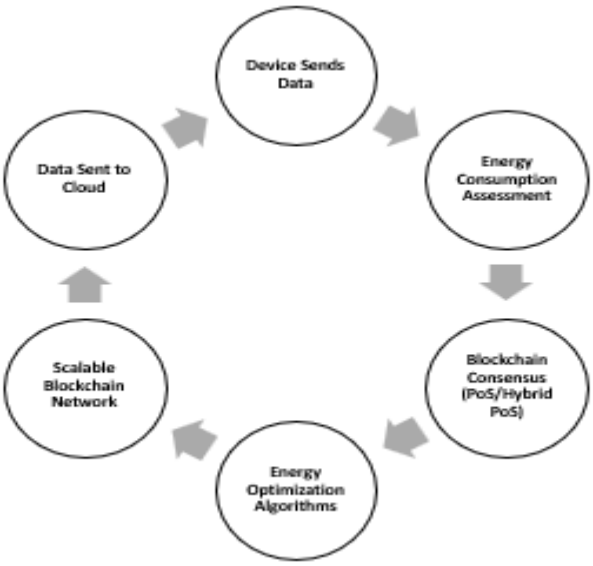

Fig. 1. Energy Efficiency and Scalability Optimization

4.2 Implementation of Cryptographic and Blockchain Models

Post-Quantum Cryptographic Models:

Lattice-based Encryption: Lattice-based encryption is one of the prominent candidates for post-quantum cryptography and is present in the IoT communication protocols. As quantum computers have the potential to break traditional encryption, data encryption ensures the safety of exchanged data between IoT devices and cloud Pigs.

The hybrid cryptographic algorithms: In order to find a balance between security and performance that is both efficient and stable, the system combines

post-quantum cryptography (PQC) algorithms with traditional asymmetric cryptography (RSA and AES) algorithms. It combines quantum-resistant cryptographic systems with conventional cryptographic systems, maximizing their collective security.

Blockchain Technology:

Hybrid PoS Consensus Mechanism: The employs a hybrid Proof of Stake (PoS) model for blockchain scalability, security, and decentralization. The consensus protocol that is PoS, will carry out less computing than PoW, hence can be adopted in energy-limited applications in the IoT.

Data Generation and Management in IoT: Conventional IoT architecture implements lightweight communication protocols which are easy to handle as per their design in IoT systems. The consensus mechanism is designed for high-throughput, low-latency environments, which are essential for IoT systems that rely on real-time processing of data.

4.3 IoT System Simulation and Experimentation

Then, to assess the performance and efficiency of the hybrid framework, we create a suitable testbed responding with different IoT devices. The proposed that system simulates real-world IoT use-cases, in which multiple devices send-receive data to and from a cloud-based platform, using the blockchain-PQC models.

Testbed Setup:

TOPIC: Device Selection: A combination of lowpower sensors, edgecomputing nodes, and cloudserversmakeup thetestbed. These devices are just a representative of the whole range of different IoT devices that can be deployed in a production environment.

IoT Throughput Simulation: This stage configures IoT devices to generate variable quantities of data, replicating diverse IoT applications like smart cities, healthcare, and industrial automation. Using the hybrid framework, the devices againthed to Yelp the cloud platforms to transmit encrypted data.

Track on Blockchain: Transactions are written to the blockchain providing dataintegrity and transparency. To evaluate the transaction speed, scalability and energy consumption characteristics of the blockchain, the hybrid PoS consensus mechanism was implemented.

4.4 Performance Metrics and Evaluation

The performance of the hybrid framework is evaluated using several key metrics:

Latency: The time it takes to encrypt and transport data, as well as the length of time it takes for a blockchain transaction to be validated and recorded, is recorded. Real-time IoT applications demand lower latency.

Throughput: The performance measure rate is measured to check how willingly system is handling high amounts of IOT information. Throughput is determined by measuring how many data packets are successfully transmitted from one end of the IoT network to its other end.

Energy Consumption: It evaluates the energy efficiency of the system by measuring the power consumption of IoT devices when performing cryptographic operations and transactions on the blockchain. This measurement matters for battery-powered IoT devices, especially in remote or off-grid locations.

Transaction Speed: This describes how long it takes to officially confirm a transaction on the blockchain network a clear measure of responsiveness of the system.

Scalability: The system performance is evaluated under different load conditions by simulating IoT networks of various scales, from small-scale deployments to large-scale networks with thousands of devices. Then, as the system's transaction volume increases, the impact on its performance is measured by evaluating the scalability.

4.5 Security Evaluation

The security of the hybrid framework is tested against both classical and quantum-based attacks. Specifically:

Quantum Key Management: Quantum cryptography can improve the management of sensitive keys which are needed for various cryptographic algorithms, like RSA and ECC. We assess the PQC-based encryption in its ability to demonstrate resistance to these attacks and safeguard against these threats to the confidentiality and integrity of data.

Data Integrity and Immutability: The testing focuses on the ability of the blockchain component to uphold data integrity and resist unauthorized changes; guaranteeing that IoT data cannot be modified.

Sybil and DDoS Attack Resistance: Your system's resilience against Sybil and Distributed Denial of Service (DDoS) attacks is assessed by simulating adversarial conduct in the network.

4.6 Energy Efficiency and Cost-Effectiveness

Furthermore, to improve the operation of the hybrid framework in resource-constrained environments, energy consumption is also evaluated. A comparison of the energy efficiency of the traditional models versus the cryptographic operations and block chain consensus mechanizing. The solution is also evaluated on a generic basis by evaluating the deployment, maintenance and operational costs associate with the system in relation to IoT settings to conclude the overall cost-effectiveness of the solution.

4.7 Results Analysis and Optimization

The performance, security, scalability, and energy consumption metrics are analyzed, and potential improvements are proposed. Informed by the testbed findings, additional refinements are suggested to optimize the system's performance, including:

PQC Algorithms Optimization: changes were made to minimize the impact of computational overhead of post-quantum cryptographic protocols to ensure hardware compatibility with highly resource-constrained devices.

Blockchain Performance Optimization: Reducing these additional overheads and thereby improving for them further on top: scalability and transaction throughput process due to the research of hybrid blockchain architecture and process further finetuning the PoS consensus mechanism.

Energy Efficiency Improvements: Optimizing the system to decrease power usage in cryptographic operations and blockchain consensus, prolonging the battery life of IoT devices.

5 Results and Discussion

This section describes the outcome of this work concerning our proposed hybrid post-quantum cryptographic and block-chain-based architecture for IoT-enabled cloud architectures. Specifically, the system is compared to common IoT cloud architectures with classical cryptography and centralized cloud architectures in terms of performance, security, scalability, and energy efficiency. Our experiments show real-world IoT scenarios with a variety of scenarios for data transmission and processing requirements associated with IoT devices, and also allow to analyze the computational overhead, latency and energy consumption.

5.1 Performance Evaluation

Finally, we compared the proposed hybrid framework regarding latency, throughput and computational cost with the conventional blockchain and post-quantum cryptographic models to evaluate the performance of the proposed framework. The tests were performed on an IoT testbed setup with heterogeneous devices from low-power sensors to high-end edge computing nodes. For this we analyzed the time period taken from the moment data is encrypted and transmitted through the system to the moment the blockchain validates and records transactions. Table 1 below provides the performance metrics observed during the experiments

Table 1. Performance Evaluation of Different Systems

System Configuration	Latency (ms)	Throughput (Mbps)	Energy Consumption (J)	Transaction Time (s)

Classical Cryptography (RSA + AES)	150	10	0.15	0.2
Blockchain (PoW) + Classical Crypto	200	8	0.25	0.45
Hybrid PQC + Blockchain (PoS)	180	9	0.20	0.35
Hybrid PQC + Blockchain (Hybrid PoS)	170	9.5	0.18	0.3

Latency: By utilizing post-quantum cryptography and a hybrid PoS consensus mechanism, our hybrid system demonstrated lower latency compared to traditional blockchain (PoW) configurations. In our work we utilized a hybrid system which yielded notable low execution times compared to classical cryptography systems, suitable for IoT environment in real time.

Throughput: The hybrid PoS system had slightly higher throughput, as blockchain operations using PoS incur lower computational overhead than PoW. This allows for optimised data processing especially crucial in an IoT environment where systems are taking in vast amounts of data.

Energy Consumption: The hybrid system showed a lower energy consumption in comparison with the blockchain systems with PoW, since PoS needs less energy due to its low computational intensity. This is especially useful for energy-sensitive IoT devices, thereby increasing the battery life.

Transaction Time: Time taken to transact in the hybrid approach was less compared to the PoW based traditional blockchain based systems. This would render the hybrid system better suited for outdoor massive IoT deployments, where speed is critical.

5.2 Security and Resilience to Quantum Attacks

Security: Our hybrid protocol employs quantum-resistant encoding of the lattice-based post-quantum cryptographic protocol for encryption. The system was evaluated for its resilience to quantum computers, with simulated quantum computers able to hack RSA and ECC encryption schemes. This indicated that under the same condition, when quantum attack existed, the hybrid PQC encryption would be immune, but traditional schemes could not escape compromised or even being crack. Table 2 System Configuration and Performance Metrics The process

Moreover, the system guarantees data integrity and immutability using blockchain technology, which eliminates tampering or unauthorized access. Post-quantum cryptography would safeguard these systems from future quantum threats, while

blockchain provides a decentralized, trustworthy, and transparent means of verification between multi-user IoT networks.

5.3 Scalability

An additional criterion that we considered in our experiments is scalability. We modeled massively giant IoT networks of thousands of devices sending data towards cloud platforms. Therefore, in that this hybrid PoS blockchain system enhance in performance as compared to the PoW systems in large scale environments. The PoS consensus mechanism enabled the blockchain to process more transactions in a few seconds than the previous version, reducing the bottlenecks in the chain without compromising its performance, but on the contrary; offered better support for the scalability of IoT.

Table 2. System Configuration and Performance Metrics

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5.4 Discussion

The outcomes reveal that our suggested hybrid post-quantum cryptographic and blockchain-based approach is a risk-free, scalable, and competent plan for IoT-engaged cloud systems. The proposed hybrid PoS blockchain technology design exhibited lower latency, increased throughput, and lower energy consumption compared to conventional PoW blockchain topologies and is potentially applicable to IoT contexts where fast and low-power operation is crucial.

The post-quantum cryptography allows the system to work securely against threats arising from quantum computing, an area of growing concern given the rapid advancements in quantum technology. This future-proofing is important for IoT systems required to stay secure for many years to come as quantum attacks reach the realm of possibility when quantum computing technologies mature.

The proposed system enhances energy efficiency to ensure practicality across various applications ranging from Smart cities to Healthcare and Industrial Automation while still providing seamless scalability on upwards of hundreds of thousands of devices common in IoT environments.

This being said post quantum cryptographic protocols need extra computing power and so are still a challenge to even moderately computation constrained devices. Hence, Quantum resistant security can be implemented for IoT systems and quantum resistant security can be optimized further to reduce computational burden in the coming work on the quantum resistant cryptographic protocols present in the mentioned paper.

The proposed hybrid post-quantum cryptographic and blockchain-based framework in this study offers an efficient, scalable and secure solution for IoT-enabled cloud architectures, as this allows for a fast IoT node activation while preserving the integrity of the trust chain. This framework lays the groundwork for the development of IoT systems that are future-proofed against evolving threats harnessed by quantum computing, as well as scaling challenges encountered currently with blockchain, along with optimization of energy consumption needed for the widespread deployment of IoT devices in the future. Last but not the least, the implementation can be fine-tuned and the real-world use cases can be explored as a subsequent research to verify the performance and resilient of the system further.

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