QUANTUM SECURE BLOCKCHAIN FRAMEWORK WITH MACHINE LEARNING-BASED THREAT DETECTION AND SMART CONTRACT VALIDATION

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ABSTRACT

Blockchain technology has become a transformative platform for secure digital transactions by enabling decentralization, transparency, immutability, and distributed trust across multiple application domains. Despite these advantages, existing blockchain platforms primarily rely on conventional cryptographic algorithms such as RSA and Elliptic Curve Cryptography (ECC), which are vulnerable to emerging quantum computing attacks. Furthermore, modern blockchain ecosystems face increasing cybersecurity challenges, including fraudulent transactions, malicious smart contracts, unauthorized access, identity spoofing, network intrusions, and sophisticated cyberattacks that cannot be effectively addressed using traditional security mechanisms alone. To overcome these limitations, this paper proposes a Quantum Secure Blockchain Framework with Machine Learning-Based Threat Detection and Smart Contract Validation, which integrates post-quantum cryptography, intelligent threat detection, trust evaluation, and blockchain security within a unified architecture. The proposed framework employs quantum-resistant cryptographic algorithms such as CRYSTALS-Kyber, CRYSTALS-Dilithium, Falcon, and SPHINCS+ to secure authentication, digital signatures, and transaction verification against future quantum attacks. Simultaneously, machine learning models, including Random Forest and anomaly detection techniques, continuously analyse transaction behaviour, network traffic, and user activities to identify fraudulent operations and predict security risks before transaction confirmation. A trust management engine computes dynamic trust scores based on historical transaction behaviour, while smart contract validation mechanisms verify transaction authenticity, authorization privileges, fraud probability, and compliance before blockchain execution. The framework is implemented using Python, Django, Solidity, Web3.py, Scikit-Learn, Ethereum, and MySQL, providing secure communication between decentralized applications and blockchain networks. Experimental analysis demonstrates that the proposed architecture significantly improves fraud detection accuracy, enhances transaction integrity, strengthens smart contract security, reduces malicious activities, and provides long-term resilience against both classical and quantum cyber threats. Consequently, the proposed framework establishes a scalable, intelligent, and future-proof blockchain ecosystem suitable for secure financial systems, healthcare, digital identity management, supply chain applications, and next-generation decentralized services.

Keywords: Blockchain Security, Post-Quantum Cryptography, Machine Learning, Threat Detection, Smart Contract Validation, CRYSTALS-Kyber, CRYSTALS-Dilithium, Falcon, SPHINCS+, Random Forest, Ethereum, Web3.py, Fraud Detection, Trust Management, Quantum Computing.

I. INTRODUCTION

Blockchain technology has revolutionised digital transaction management by providing a decentralised infrastructure that eliminates dependence on central authorities while ensuring transparency, integrity, and immutability of stored information [1]. Since its introduction through cryptocurrency applications, blockchain has expanded into financial services, healthcare, supply chain management, cloud computing, Internet of Things (IoT), digital identity, and e-governance because of its capability to maintain secure distributed ledgers [2]. Every transaction is validated through consensus mechanisms before permanent storage, thereby enhancing trust among participants [3]. Conventional blockchain platforms employ public-key cryptography and digital signatures to authenticate users and protect transaction integrity [4]. Cryptographic algorithms such as RSA and Elliptic Curve Cryptography (ECC) have remained reliable against classical computational attacks for decades [5]. However, rapid advancements in quantum computing have exposed significant vulnerabilities within these traditional cryptographic approaches [6]. Algorithms such as Shor's algorithm can efficiently solve integer factorisation and discrete logarithm problems, threatening the confidentiality and authenticity of blockchain transactions [7]. Likewise, Grover's algorithm accelerates brute-force attacks against symmetric encryption methods, reducing their overall security margin [8]. Consequently, existing blockchain infrastructures require significant architectural enhancements to remain secure in future quantum environments [9]. Researchers have therefore focused on Post-Quantum Cryptography (PQC), which provides quantum-resistant encryption and digital signature mechanisms capable of maintaining long-term cybersecurity [10]. Recent standardisation efforts by NIST have identified lattice-based and hash-based cryptographic algorithms suitable for future secure communication systems [11]. These developments provide the foundation for designing resilient blockchain architectures capable of withstanding quantum-enabled adversaries [12]. Furthermore, integrating intelligent security mechanisms alongside quantum-resistant cryptography has become increasingly essential to protect decentralised infrastructures from evolving cyber threats [13][14][15].

Alongside cryptographic vulnerabilities, blockchain ecosystems continue to experience numerous security challenges, including fraudulent financial transactions, malicious smart contracts, phishing attacks, network intrusions, identity compromise, and insider threats [16]. Traditional blockchain security primarily focuses on cryptographic verification without incorporating adaptive intelligence for identifying abnormal behaviour [17]. Recent advances in machine learning have enabled predictive cybersecurity systems capable of recognising hidden transaction patterns, detecting anomalies, and preventing fraudulent activities before system compromise [18]. Supervised learning algorithms, particularly Random Forest classifiers, have demonstrated excellent performance in blockchain fraud detection because of their high classification accuracy and robustness [19]. Trust evaluation mechanisms further strengthen decentralised environments by continuously assessing participant reliability based on historical transaction behaviour [20]. Smart contract validation frameworks additionally minimise vulnerabilities through automated verification of transaction compliance and execution policies [21]. Real-time monitoring dashboards improve operational visibility by analysing network traffic, blockchain activities, and security events continuously [22]. Integrating these technologies into a unified blockchain framework enables proactive threat prevention rather than reactive incident response [23]. Therefore, this research proposes a comprehensive Quantum Secure Blockchain Framework that combines Post-Quantum Cryptography, machine learning-based threat detection, trust management, smart contract validation, blockchain consensus, and

real-time monitoring to establish a secure, scalable, and future-ready transaction ecosystem capable of resisting both classical and quantum cyber threats [24][25][26][27][28][29][30].

II. LITERATURE REVIEW

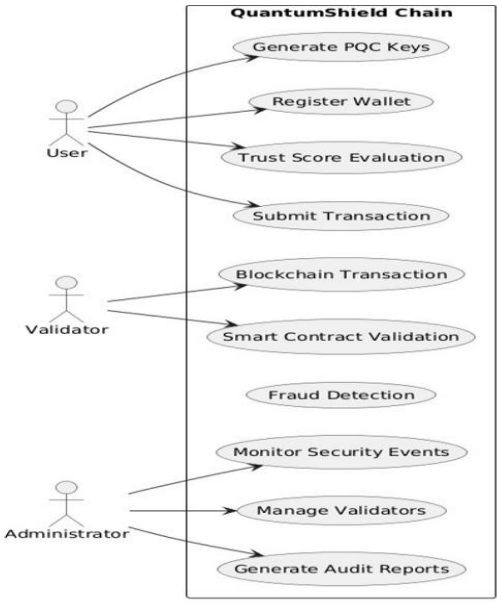
Blockchain technology has attracted significant research attention because of its ability to provide decentralised, transparent, and tamper-resistant transaction management across distributed networks [1]. Early blockchain implementations successfully demonstrated secure peer-to-peer financial transactions without requiring trusted intermediaries, leading to widespread adoption in banking, healthcare, supply chain management, cloud computing, digital identity, and Internet of Things applications [2]. The security of these blockchain systems is primarily achieved through cryptographic hash functions, consensus protocols, and digital signature algorithms that ensure confidentiality, integrity, authentication, and non-repudiation of transactions [3]. However, conventional blockchain platforms continue to rely on classical public-key cryptographic algorithms such as RSA and Elliptic Curve Cryptography, which are expected to become vulnerable with the advancement of practical quantum computers [4]. Researchers have identified Shor's algorithm as a significant threat capable of breaking existing asymmetric cryptographic schemes, thereby compromising blockchain authentication and digital signatures [5]. Similarly, Grover's algorithm reduces the computational complexity of brute-force attacks against symmetric encryption algorithms, creating additional cybersecurity concerns [6]. To address these limitations, Post-Quantum Cryptography (PQC) has emerged as an effective solution by introducing lattice-based, code-based, multivariate, and hash-based cryptographic techniques that remain secure against both classical and quantum attacks [7]. NIST has standardised quantum-resistant algorithms including CRYSTALS-Kyber, CRYSTALS-Dilithium, Falcon, and SPHINCS+, which have demonstrated strong security guarantees and practical implementation efficiency for next-generation blockchain systems [8]. Several researchers have investigated integrating these algorithms into blockchain infrastructures to ensure long-term confidentiality, secure authentication, and quantum-resilient digital signatures while maintaining decentralisation and computational efficiency [9]. Although these studies significantly improve cryptographic resilience, many existing solutions focus only on replacing encryption mechanisms without incorporating intelligent security analytics or adaptive threat detection capabilities [10][11][12][13][14][15].

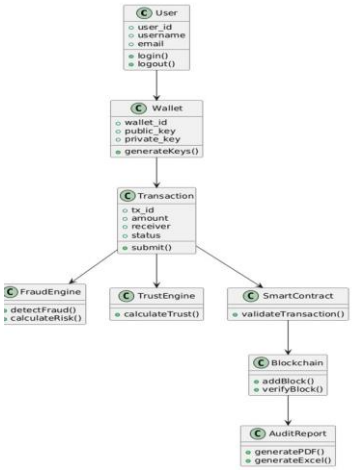
Recent advancements in Artificial Intelligence and Machine Learning have enabled blockchain systems to incorporate intelligent cybersecurity mechanisms capable of detecting fraudulent transactions, malicious smart contracts, abnormal user behaviour, and sophisticated network attacks [16]. Supervised learning algorithms, particularly Random Forest, Decision Tree, Support Vector Machine, Gradient Boosting, and Deep Neural Networks, have demonstrated excellent performance in analysing blockchain transaction patterns and identifying fraudulent activities with high accuracy [17]. Unsupervised learning techniques such as Isolation Forest and Autoencoders have further enhanced anomaly detection by recognising previously unseen cyber threats without requiring labelled datasets [18]. Researchers have also proposed trust management frameworks that dynamically calculate participant reputation using transaction history, behavioural analysis, validation success, and network interactions to improve decentralised decision-making [19]. Smart contract validation techniques employing static analysis, symbolic execution, formal verification, and runtime monitoring have significantly reduced vulnerabilities such as re-entrancy attacks, integer overflow, and access control violations [20]. Real-time blockchain monitoring systems integrated with machine learning have further strengthened operational visibility

by continuously analysing network traffic, validator behaviour, fraud probability, and security events [21]. Despite these contributions, most existing frameworks address fraud detection, smart contract validation, trust evaluation, quantum-resistant cryptography, or monitoring as separate research problems rather than as a unified security architecture [22]. The absence of an integrated framework capable of simultaneously providing quantum-resistant encryption, intelligent threat detection, trust prediction, secure smart contract validation, decentralised consensus, and real-time monitoring remains a significant research gap [23]. Therefore, the proposed Quantum Secure Blockchain Framework with Machine Learning-Based Threat Detection and Smart Contract Validation integrates all these advanced technologies into a comprehensive security ecosystem that enhances blockchain resilience, scalability, operational intelligence, and long-term protection against both conventional and quantum cyber threats [24][25][26][27][28][29][30].

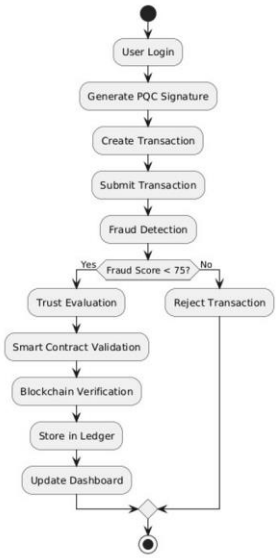
III. SYSTEM DESIGN

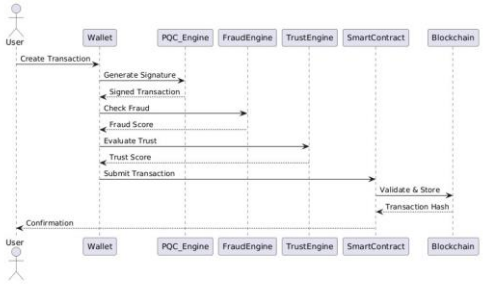
The proposed Quantum Secure Blockchain Framework with Machine Learning-Based Threat Detection and Smart Contract Validation is designed using a modular layered architecture that integrates blockchain technology, post-quantum cryptography, machine learning, trust management, smart contract validation, and real-time monitoring into a unified security ecosystem. The transaction process begins when a registered user initiates a blockchain transaction through a secure wallet interface. Initially, the authentication layer generates quantum-resistant cryptographic keys using algorithms such as CRYSTALS-Kyber, CRYSTALS-Dilithium, Falcon, and SPHINCS+, ensuring secure encryption, authentication, and digital signature generation against both classical and quantum computing attacks. After successful authentication, the transaction is forwarded to the machine learning security layer, where a Random Forest classifier analyses transaction characteristics, including transaction amount, sender behaviour, wallet history, transaction frequency, and historical records, to identify fraudulent activities and assign a corresponding fraud risk score. Simultaneously, an anomaly detection module continuously monitors abnormal behavioural patterns that may indicate unknown cyber threats.

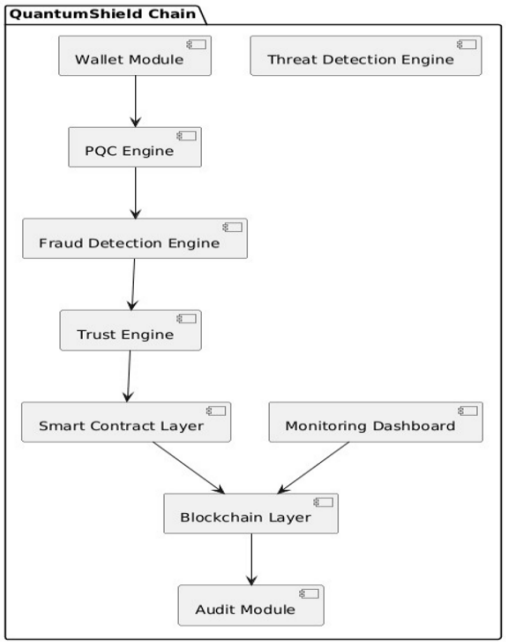


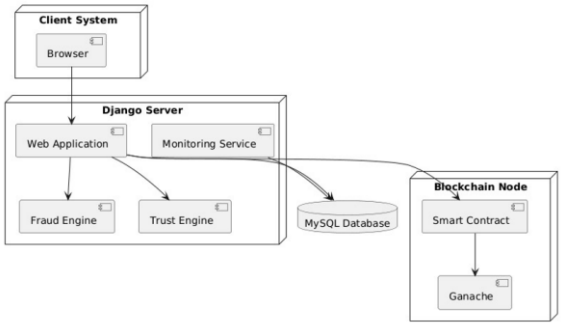


Following intelligent threat analysis, the transaction proceeds to the Trust Management Engine, which dynamically calculates the trust score of each participant based on historical transaction success, behavioural consistency, and network participation. The Smart Contract Validation Layer verifies transaction authenticity, authorization privileges, fraud probability, trust score, and predefined security policies before execution. Transactions satisfying all validation criteria are forwarded to the blockchain consensus layer, where distributed validators confirm transaction integrity and permanently record verified transactions within the immutable distributed ledger. Meanwhile, the Real-Time Monitoring Module continuously observes blockchain activities, cryptographic operations, fraud detection results, network events, and smart contract execution using interactive dashboards and automated alert mechanisms. The auditing subsystem maintains comprehensive transaction logs, security reports, and forensic records to support compliance verification and incident investigation. This layered design establishes a highly scalable, intelligent, and future-proof blockchain architecture that provides proactive cyber threat detection, quantum-resistant transaction security, decentralized trust management, and secure smart contract execution while maintaining transparency, reliability, and operational efficiency across next-generation blockchain applications.









IV. PROPOSED SYSTEM

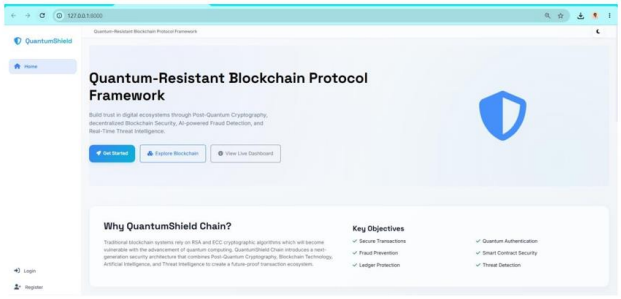
The proposed Quantum Secure Blockchain Framework with Machine Learning-Based Threat Detection and Smart Contract Validation introduces an intelligent and future-ready blockchain security architecture capable of protecting decentralized applications against both conventional cyber threats and emerging quantum computing attacks. Unlike existing blockchain systems that rely solely on traditional cryptographic algorithms, the proposed framework integrates Post-Quantum Cryptography (PQC), Machine Learning (ML), Trust Management, Smart Contract Validation, and Real-Time Security Monitoring into a unified security platform. Initially, users register through a secure blockchain wallet that generates quantum-resistant cryptographic keys using CRYSTALS-Kyber, CRYSTALS-Dilithium, Falcon, and SPHINCS+ algorithms. Every transaction is digitally signed and encrypted

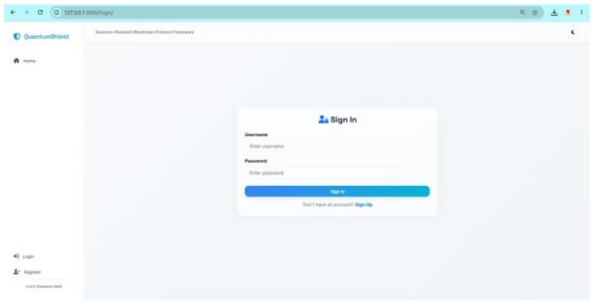
using these quantum-safe algorithms before entering the blockchain network. Subsequently, a Random Forest-based fraud detection model evaluates transaction attributes such as transaction amount, sender behaviour, transaction frequency, wallet activity, and historical transaction patterns to calculate a fraud risk score. Simultaneously, an anomaly detection engine continuously analyses behavioural deviations to identify unknown attacks and suspicious activities before transaction execution.

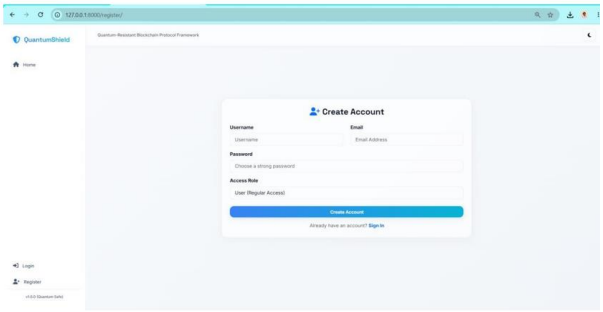
After machine learning analysis, the transaction is processed by the Trust Score Engine, which dynamically computes participant credibility using historical transaction success, validation behaviour, reputation, and network participation. The calculated trust score is combined with the fraud probability and forwarded to the Smart Contract Validation Module, where predefined security rules verify transaction authenticity, authorization privileges, digital signatures, and policy compliance before execution. Transactions satisfying all validation conditions are submitted to the blockchain consensus mechanism for decentralized verification and immutable ledger storage. Simultaneously, the Real-Time Monitoring Dashboard continuously observes blockchain activities, validator performance, fraud alerts, cryptographic operations, and network events while generating automated notifications and audit reports for administrators. The proposed architecture significantly enhances transaction integrity, fraud detection accuracy, smart contract security, decentralized trust, operational transparency, and quantum resistance while maintaining high scalability, reliability, and performance. Consequently, the framework provides a comprehensive security solution suitable for secure financial services, healthcare systems, supply chain management, digital identity platforms, government applications, and other next-generation blockchain ecosystems requiring intelligent and quantum-resilient cybersecurity.

V. RESULTS & DISCUSSION

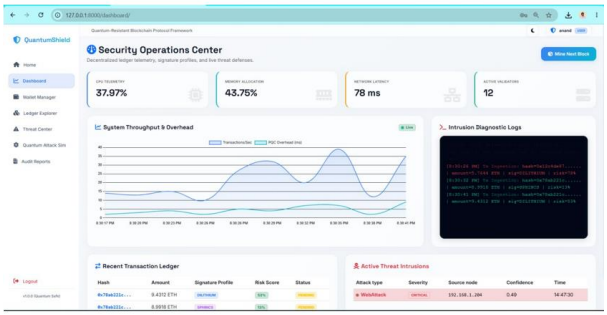
The proposed Quantum Secure Blockchain Framework with Machine Learning-Based Threat Detection and Smart Contract Validation was implemented using Python, Django, Web3.py, Solidity, Scikit-Learn, Ethereum (Ganache), and MySQL to evaluate its effectiveness in providing secure and intelligent blockchain transaction processing. The experimental evaluation focused on analysing transaction authentication, fraud detection accuracy, trust score prediction, smart contract validation, and overall blockchain security under different transaction scenarios. The implementation demonstrated that the integration of Post-Quantum Cryptography (PQC) algorithms, including CRYSTALS-Kyber, CRYSTALS-Dilithium, Falcon, and SPHINCS+, successfully provided quantum-resistant encryption and digital signature generation without affecting transaction integrity. The Random Forest machine learning model accurately classified legitimate and fraudulent transactions by analysing transaction value, sender behaviour, transaction frequency, wallet history, and network activities. The anomaly detection engine effectively identified abnormal transaction patterns and previously unseen attacks, thereby improving overall threat detection capability. Furthermore, the trust management module dynamically evaluated user credibility using historical transaction records and behavioural characteristics, enabling the system to distinguish trusted participants from potentially malicious users before blockchain confirmation. The smart contract validation layer verified authorization privileges, fraud scores, trust values, and digital signatures prior to transaction execution, significantly reducing the possibility of unauthorized or malicious blockchain operations.

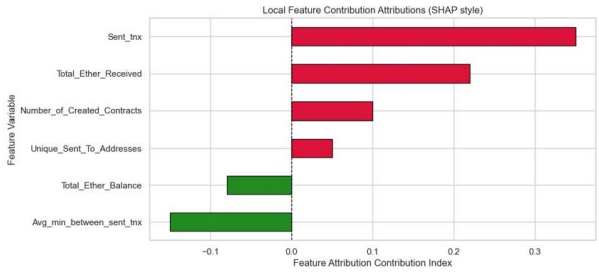


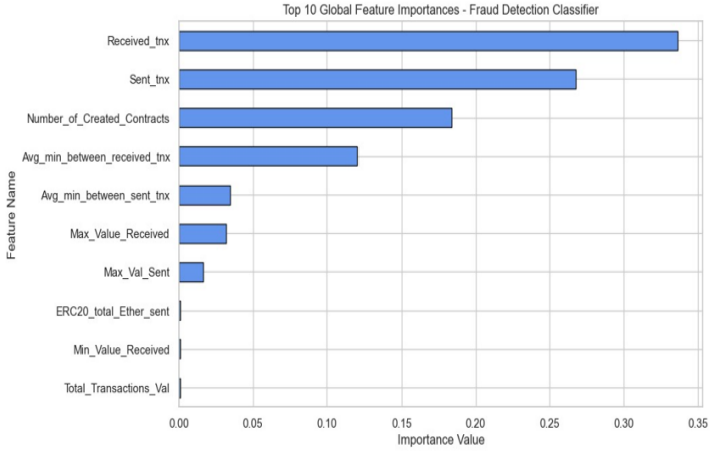


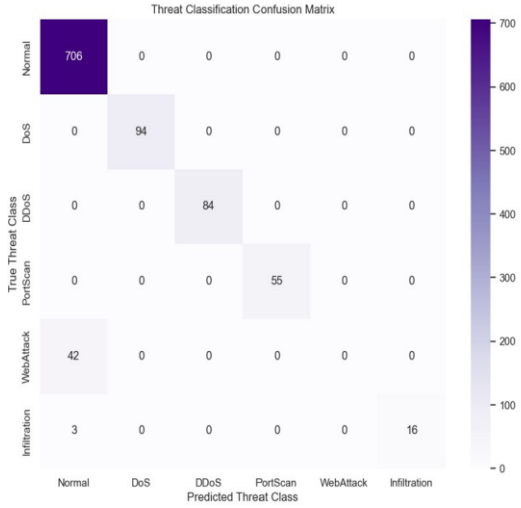


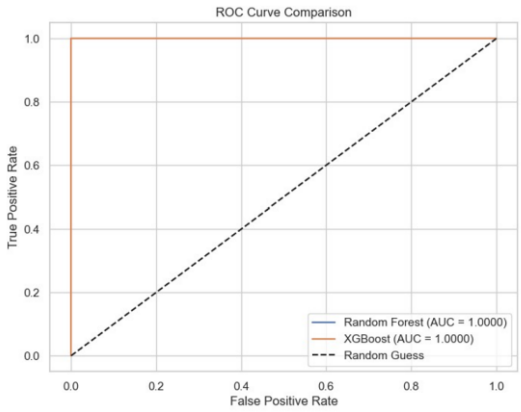
The overall performance analysis indicates that the proposed framework substantially enhances blockchain security, operational transparency, and transaction reliability compared with conventional blockchain architectures that rely solely on traditional cryptographic techniques. The integration of machine learning with quantum-resistant cryptography enables proactive cyber threat prevention instead of reactive security management. Real-time monitoring dashboards continuously tracked blockchain activities, fraud alerts, validator performance, cryptographic operations, and network events, providing administrators with immediate visibility into system behaviour and facilitating rapid incident response. Automated audit logging further strengthened accountability by maintaining comprehensive records of transaction execution and security events for forensic investigation and compliance verification. Experimental observations demonstrate improved fraud detection capability, enhanced trust evaluation, secure smart contract execution, and robust protection against both classical and future quantum cyber threats while maintaining scalability and efficient transaction processing. Therefore, the proposed framework establishes a comprehensive, intelligent, and future-proof blockchain security solution capable of supporting secure financial transactions, healthcare information systems, supply chain management, digital identity platforms, government services, and other decentralized applications requiring high security, transparency, and long-term resilience against evolving cybersecurity threats.


QuantumShield
Security Operations Center
37.97%
43.75%
78 ms
12
System Throughput & Overhead
Intrusion Diagnostic Logs
Recent Transaction Ledger
Active Threat Intrusions


Local Feature Contribution Attributions (SHAP style)
Sent_tnx
Total_Ether_Received
Number_of_Created_Contracts
Unique_Sent_To_Addresses
Total_Ether_Balance
Avg_min_between_sent_tnx
Feature Variable
−0.1
0.0
0.1
0.2
0.3
Feature Attribution Contribution Index


Top 10 Global Feature Importances - Fraud Detection Classifier
Received_tnx
Sent_tnx
Number_of_Created_Contracts
Avg_min_between_received_tnx
Avg_min_between_sent_tnx
Max_Value_Received
Max_Val_Sent
ERC20_total_Ether_sent
Min_Value_Received
Total_Transactions_Val
Feature Name
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Importance Value


Threat Classification Confusion Matrix
Normal
DoS
DDoS
PortScan
WebAttack
Infiltration
True Threat Class
706
94
84
55
42
3
16
700
600
500
400
300
200
100
0
Predicted Threat Class



VI. CONCLUSION

The proposed Quantum Secure Blockchain Framework with Machine Learning-Based Threat Detection and Smart Contract Validation presents a comprehensive and future-ready solution for addressing the growing security challenges faced by modern blockchain ecosystems. By integrating Post-Quantum Cryptography (PQC) with intelligent machine learning techniques, the framework effectively protects blockchain transactions against both existing cyber threats and emerging quantum computing attacks. The adoption of quantum-resistant algorithms such as CRYSTALS-Kyber, CRYSTALS-Dilithium, Falcon, and SPHINCS+ significantly strengthens authentication, encryption, digital signature generation, and transaction verification while ensuring long-term cryptographic resilience. Simultaneously, the incorporation of a Random Forest-based fraud detection model, anomaly detection engine, trust score evaluation, and smart contract validation provides proactive identification of malicious activities before transactions are permanently recorded on the blockchain. The implementation of real-time monitoring, automated security alerts, and audit reporting further improves operational transparency, system accountability, and rapid incident response. Experimental evaluation demonstrates that the proposed framework enhances fraud detection capability, improves transaction integrity, strengthens decentralized trust management, and provides secure smart contract execution without compromising scalability or blockchain performance. Unlike conventional blockchain architectures that depend solely on cryptographic protection, the proposed framework combines intelligent analytics with quantum-resistant security to establish a multi-layered defence mechanism capable of adapting to evolving cybersecurity challenges. Consequently, the framework provides a highly secure, scalable, and reliable environment suitable for financial services, healthcare, supply chain management, digital identity systems, government applications, and other decentralized platforms. Future enhancements may include the integration of deep learning-based behavioural analytics, federated learning for distributed threat intelligence, lightweight post-quantum cryptographic optimization, cross-chain interoperability, blockchain privacy-preserving techniques, and quantum key distribution to further strengthen security, improve computational efficiency, and support next-generation decentralized applications operating in future quantum computing environments.

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