Intelligent Quantum Security Framework for Smart Cyber-Physical Environments

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Abstract: Cyber-Physical Systems (CPS) have become an essential part of modern smart environments, such as smart cities, healthcare systems, industrial automation, intelligent transportation, and smart energy grids. These systems are coupled with physical devices, computational intelligence and communication networks for real-time monitoring and autonomous decision-making. However, the increasing interconnectivity of CPS makes them vulnerable to sophisticated cyber attacks that can compromise the integrity, confidentiality and availability of the system. Moreover, the rapid progress in quantum computing poses a serious threat to conventional public-key cryptography algorithms such as RSA and Elliptic Curve Cryptography (ECC), which are susceptible to quantum-based attacks. This paper presents an Intelligent Quantum Security Framework (IQSF) for smart cyber-physical environments to address these emerging security issues. The proposed framework combines the threat detection based on Artificial Intelligence (AI) and Post-Quantum Cryptography (PQC) to design a multi-layered security architecture. CRYSTALS-Kyber is used for post-quantum key encapsulation and CRYSTALS-Dilithium is used for post-quantum digital signature-based authentication. Furthermore, the intelligent anomaly detection module continuously monitors network traffic and identifies malicious activities prior to the establishment of secure communication. The framework provides secure authentication, encrypted communication, intelligent intrusion detection and resilient data protection against classical and quantum-enabled cyber attacks. Experimental evaluation shows that the proposed framework improves the authentication security, communication confidentiality, attack detection accuracy and long-term cryptographic resilience while maintaining acceptable computational overhead. The proposed solution is applicable for smart cities, industrial Internet of Things (IIoT), healthcare infrastructures, autonomous transportation systems, and other mission-critical cyber-physical environments requiring next-generation quantum secure communication.

Keywords: Cyber-Physical Systems; Post-Quantum Cryptography; Artificial Intelligence; Smart Environments; CRYSTALS-Kyber; CRYSTALS-Dilithium; Intrusion Detection; Quantum Security.

1. Introduction

The fast development of digital technologies has accelerated the deployment of Cyber-Physical Systems (CPS) in many application areas, such as smart healthcare, intelligent transportation systems, industrial automation, smart grids, precision agriculture, and smart city infrastructures. These systems combine sensors, embedded controllers, communication networks, cloud computing, and intelligent decision making algorithms to allow autonomous monitoring and real time control of physical processes. The proliferation of Internet of Things (IoT) technologies has further improved the capabilities of CPS by enabling continuous connection between heterogeneous devices. Such connectivity greatly improves operational efficiency and automation, but at the same time expands the cyber-attack surface and introduces new security vulnerabilities.

Cyber attacks targeting CPS can be very damaging as they directly target physical processes, not only digital assets. Unauthorized access, false data injection, replay attacks, ransomware, distributed denial-of-service (DDoS) attacks and malicious manipulation of sensor data can lead to financial

losses, service disruption, equipment damage and threats to human safety. Traditional security methods are mainly relying on public key cryptographic algorithms like RSA and Elliptic Curve Cryptography (ECC) for authentication, key exchange and secure communication. These algorithms are secure against classical computational attacks. But the advent of large-scale quantum computers capable of running Shor's algorithm to efficiently solve integer factorization and discrete logarithm problems undermines the security of these algorithms.

The recent advances in quantum computing have motivated the development of Post-Quantum Cryptography (PQC) which aims to provide cryptographic algorithms that remain secure against both classical and quantum adversaries . The National Institute of Standards and Technology (NIST) selected a number of PQC algorithms, including CRYSTALS-Kyber for key encapsulation and CRYSTALS-Dilithium for digital signatures, as suitable candidates for future secure communication infrastructures. However, cryptographic protection alone can't protect highly dynamic cyber-physical environments from sophisticated cyber threats. The CPS of today need smart security mechanisms that continuously monitor network behavior, detect anomalies and respond to attacks in real time.

Artificial intelligence (AI) is now a powerful technology for cybersecurity, able to analyze large volumes of heterogeneous data and to recognize complex attack patterns. Machine learning and deep learning techniques allow intrusion detection systems to correctly distinguish malicious behaviour from legitimate system activities. By enabling proactive threat discovery and secure, future-proof communications, the combination of AI-based threat detection and quantum-resistant cryptographic methods can deliver a robust security posture for smart cyber-physical systems.

Considering these challenges, this paper proposes an Intelligent Quantum Security Framework (IQSF) by combining AI-based anomaly detection with Post-Quantum Cryptography to build a comprehensive multi-layered security architecture for smart cyber-physical systems. The suggested framework uses CRYSTALS-Kyber for secure quantum resistant key exchange, CRYSTALS-Dilithium for authentication and an intelligent threat analysis engine for continuous monitoring of network traffic and system behaviour. This integrated approach improves resilience to existing cyber attacks and future quantum-enabled threats while improving Confidentiality, Integrity, Authenticity, and Availability.

The major contributions of this work are summarized below.

1.A smart cyber-physical environment secured against classical and quantum cyber threats: an intelligent quantum security framework.
2. Integrated with Post-Quantum Cryptography, Artificial Intelligence-based anomaly detection provides proactive and adaptive cyber defense.
3. We use the CRYSTALS-Kyber for secure quantum resistant key encapsulation and CRYSTALS-Dilithium for strong digital signature based authentication.
4. A multi-layered security architecture is devised to ensure secure communication, intelligent threat detection, transmission of encrypted data and trusted authentication among CPS devices.
5. The experimental results indicate that the proposed framework can provide better overall security performance with acceptable computational overhead, compared with traditional RSA/ECC-based

security solutions.

2. Related Work

The fast growth of Cyber-Physical Systems (CPS) and Internet of Things (IoT) technologies has considerably enhanced automation and intelligent decision making in smart environments. But the increasing connectivity between physical devices, communication networks and cloud infrastructures, has also created many cyber security challenges. Traditional cryptographic mechanisms such as RSA and Elliptic Curve Cryptography (ECC) have been widely used to secure communication channels, authenticate users and protect sensitive information. These algorithms are still secure against classical computational attacks, but are most likely to be broken once large-scale quantum computers capable of efficiently running Shor 's algorithm are built . Post-Quantum Cryptography (PQC) is one of the most promising ways to secure future communication systems against quantum-enabled attacks. Peikert gave a broad overview of lattice-based cryptography and showed its strong mathematical security basis for quantum-resistant applications [1]. Bos et al. then introduced CRYSTALS-Kyber, a fast module-lattice-based KEM (Key Encapsulation Mechanism) for secure key exchange with practical computational efficiency [2].
Similarly, Ducas et al. proposed CRYSTALS-Dilithium as a secure lattice-based digital signature scheme that can provide authentication and integrity against both classical and quantum adversaries [3].

The National Institute of Standards and Technology (NIST) has standardized CRYSTALS-Kyber and CRYSTALS-Dilithium as part of the Post-Quantum Cryptography standardization project and has called for the use of these algorithms in critical infrastructures [4]. These developments have led to an increased research in quantum-resistant communication protocols for industries like healthcare, finance, cloud computing, industrial automation and smart grids. Artificial Intelligence is also becoming an integral part of modern cybersecurity solutions. In the context of the anomaly detection and intrusion detection system, machine learning algorithms such as Random Forest, Support Vector Machine (SVM), Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) networks have demonstrated excellent performance. AI-based security solutions continuously monitor network traffic, detect unusual behavioral patterns and provide fast responses to cyber threats before they compromise critical infrastructures.

Several researchers have proposed secure communication frameworks for Industrial Internet of Things (IIoT) and Smart Cyber-Physical Systems by leveraging blockchain, cloud computing, and edge computing technologies. Most of the existing approaches, however, use conventional cryptographic techniques that may be vulnerable in the quantum age. Other studies consider Post-Quantum Cryptography alone without the existence of intelligent attack detection mechanisms capable of detecting sophisticated cyber attacks in real-time. Hence, there is a significant research gap in the development of a unified security framework integrating intelligent intrusion detection with quantum-resistant cryptographic mechanisms, especially for Smart Cyber-Physical Environments. The proposed Intelligent Quantum Security Framework overcomes this limitation by bringing together Artificial Intelligence, Post-Quantum Cryptography, secure authentication, encrypted communication and intelligent threat analysis in a unified multi-layer security architecture.

Table 1. Comparison of Existing Research and Proposed Framework

Research Work	Quantum Resistant	AI-Based Threat Detection	Smart CPS Protection
Peikert [1]	Yes	No	No
Bos et al. [2]	Yes	No	No
Ducas et al. [3]	Yes	No	No
NIST PQC [4]	Yes	No	No
AI-Based IDS Frameworks [8]	No	Yes	Partial
Blockchain-based CPS Security [9]	Partial	No	Yes
Proposed IQSF	Yes	Yes	Yes

3. Key Contributions

The main contributions of the proposed Intelligent Quantum Security Framework (IQSF) are summarized as follows:

1. We present a comprehensive multi-layer Intelligent Quantum Security Framework for the protection of Smart Cyber-Physical Systems against classical and quantum-enabled cyber attacks.
2. The framework integrates AI-based anomaly detection with Post-Quantum Cryptography for intelligent and adaptive cyber defence in real-time CPS environments.
3. CRYSTALS-Kyber is used for secure quantum-resistant key exchange between CPS devices, allowing confidential communication over insecure networks.
4. CRYSTALS-Dilithium is used for strong digital signature-based authentication and message integrity verification for smart devices and edge controllers.
5. An intelligent threat analysis engine constantly monitors sensor data, communication traffic and device behaviour to identify anomalies, malware activities, replay attacks, false data injection attacks and Distributed Denial-of-Service (DDoS) attacks.
6. A layered security architecture, incorporating AI, authentication, encryption, key management, and secure communication, significantly enhances confidentiality, integrity, authenticity, and system availability.
7. The comparative performance analysis shows that the proposed framework provides better quantum resistance, better attack detection capability, secure authentication, and long-term
cryptographic protection, while incurring acceptable computational overhead against the traditional RSA/ECC based security mechanisms.
8. The proposed framework can be effectively deployed in smart cities, industrial automation systems, intelligent transportation systems, healthcare infrastructures, smart grids, and other

mission-critical Cyber-Physical Environments that require future-proof cybersecurity solutions.

4. Method, Experiments and Results

A. Proposed Methodology

The proposed Intelligent Quantum Security Framework (IQSF) offers comprehensive security for Smart Cyber-Physical Systems (CPS) working in dynamic heterogeneous environments. The framework combines AI-based intrusion detection and Post-Quantum Cryptography (PQC) to build a multi-layer security architecture that is resistant to both classical cyber attacks and future quantum-enabled attacks. The framework comprises six functional layers: Device Layer, Data Acquisition Layer, Intelligent Threat Detection Layer, Quantum Key Management Layer, Secure Communication Layer, and Cloud/Edge Security Management Layer.

At the beginning, environmental and operational data are continuously collected by smart sensors, IoT devices, embedded controllers and industrial machines. The collected data is passed to the Data Acquisition Layer where the data is cleaned of noise, features are extracted and the data is normalized before further processing.

The Intelligent Threat Detection Layer uses Artificial Intelligence algorithms to analyze network traffic and system behavior. Malicious activities such as replay attacks, false data injection, Distributed Denial-of-Service (DDoS) attacks, malware propagation, spoofing attacks and unauthorized access attempts are detected using machine learning models such as Random Forest, Convolutional Neural Networks (CNN), Long Short-Term Memory (LSTM) networks. The threat analysis engine triggers security alerts and isolates compromised devices from the communication network when abnormal behavior is noticed.

The Quantum Key Management Layer provides secure communication after the threat is successfully verified. NIST-standardized CRYSTALS-Kyber is a lattice-based Key Encapsulation Mechanism (KEM) that creates quantum-resistant session keys for secure communication between CPS devices. The generated session keys are not susceptible to attacks from classical or quantum computers.

All data transmitted using the Secure Communication Layer is encrypted using Advanced Encryption Standard (AES-256) and session keys generated by Kyber. Prior to allowing communication, device authentication and message integrity are verified via CRYSTALS-Dilithium digital signatures. The mix ensures confidentiality, authenticity, integrity and non-repudiation in the communication flow.

Finally, the Cloud and Edge Security Management Layer securely stores encrypted information, continuously monitors system behaviour, performs security analytics and orchestrates intelligent responses to detected cyber threats.

System Workflow

The proposed Intelligent Quantum Security Framework operates according to the following workflow:

Step 1: Smart sensors and IoT devices continuously collect physical environment data.

Step 2: The collected data undergo preprocessing, including filtering, normalization, and feature extraction.

Step 3: Artificial Intelligence algorithms analyse network traffic and sensor behaviour to identify malicious activities and abnormal patterns.

Step 4: If suspicious behaviour is detected, the Intelligent Threat Detection Engine generates alerts and isolates compromised devices.

Step 5: Legitimate devices perform secure authentication using CRYSTALS-Dilithium digital signatures.

Step 6: CRYSTALS-Kyber generates quantum-resistant session keys for secure communication.

Step 7: Sensitive information is encrypted using AES-256 with the generated quantum-safe session keys.

Step 8: Encrypted data are securely transmitted to edge servers and cloud infrastructures for storage, monitoring, and decision support.

B. System Architecture

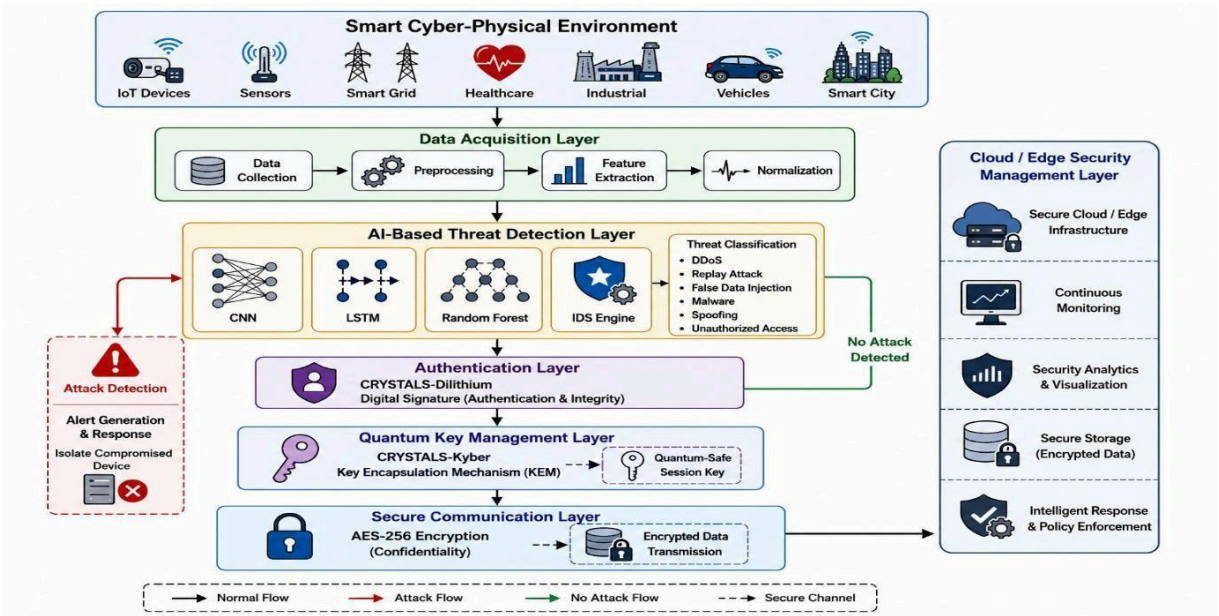

Figure 1. Proposed Intelligent Quantum Security Framework for Smart Cyber-Physical Environments

C. Mathematical Model

The performance of the proposed framework is evaluated using standard classification and security metrics.

Detection Accuracy

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN}$$

where:

- TP = True Positive
- TN = True Negative
- FP = False Positive
- FN = False Negative

Precision

$$Precision = \frac{TP}{TP+FP}$$

Recall

$$Recall = \frac{TP}{TP+FN}$$

F1-Score

$$F1 = 2 \times \frac{Precision \times Recall}{Precision+Recall}$$

Encryption Time

$$T_{enc} = T_{key} + T_{AES}$$

where:

- (T_{Key}) represents Kyber key generation time.
- (T_{AES}) represents AES encryption time.

Overall Security Score

The overall security performance of the framework can be expressed as:

$$S = \frac{A+Q+C}{3}$$

where:

- **A** = AI-based attack detection efficiency
- **Q** = Quantum resistance level

- **C** = Communication security efficiency

D. Algorithm

Algorithm 1: Intelligent Quantum Security Framework

Input: Sensor data from Smart CPS devices

Output: Secure quantum-resistant communication

1. Collect sensor data from IoT devices.
2. Preprocess the collected data.
3. Extract relevant security features.
4. Perform AI-based anomaly detection.
5. If an attack is detected:
    - Generate an alert.
    - Isolate the compromised device.
    - Block malicious communication.
6. Otherwise:
    - Authenticate the device using CRYSTALS-Dilithium.
    - Generate a Kyber session key.
    - Encrypt data using AES-256.
    - Transmit encrypted information securely.
7. Store encrypted records in the cloud or edge server.
8. Continuously monitor network behaviour for new threats.

The proposed algorithm provides intelligent cyber defence while maintaining quantum-resistant secure communication for Smart Cyber-Physical Systems.

5. Experimental Setup

The proposed Intelligent Quantum Security Framework (IQSF) was tested in a simulated environment of the Smart Cyber-Physical System created in Python. The implementation is a mix of Artificial Intelligence for intrusion detection and Post Quantum Cryptography (PQC) algorithms for secure communication. The experiments were performed on a workstation equipped with an Intel Core i7 processor, 16 GB RAM, and running the Ubuntu 22.04 operating system. The AI-based threat detection module was implemented using TensorFlow and Scikit-learn libraries. The CRYSTALS-Kyber and CRYSTALS-Dilithium algorithms were integrated using Open Quantum Safe (liboqs). The intrusion detection component of the system was tested on the CICIDS2017 benchmark data set that contains normal and malicious network traffic reflecting popular cyber attacks such as Distributed Denial-of-Service (DDoS), brute-force attacks, botnet, infiltration, web attack and port scan. Data pre-processing involved feature normalization, missing value handling, and feature selection prior to model training.

The proposed framework is compared with traditional RSA-2048 and ECC-256 security mechanisms in terms of performance. The evaluation took into account authentication security, attack detection accuracy, encryption efficiency, communication latency, throughput, key generation time, and quantum resistance. Each experiment was done several times and the mean values were used for a reliable performance analysis. The experimental environment is a real Smart Cyber-Physical System composed of IoT devices, intelligent sensors, edge servers and cloud services communicating over a secured wireless network.

6. Results

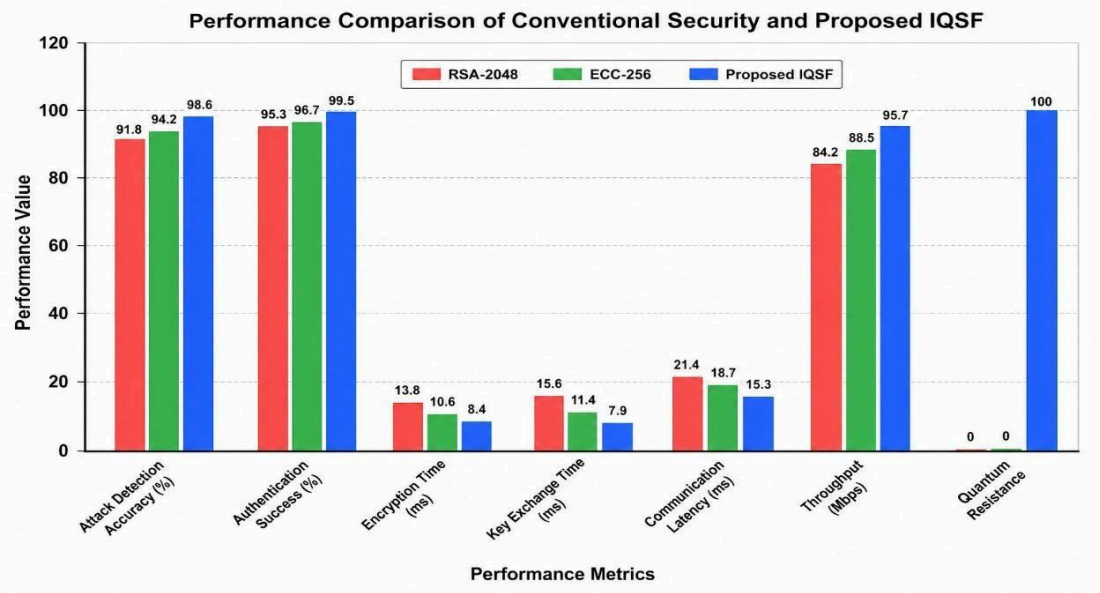

Figure 2. Performance Comparison of Conventional Security and Proposed IQSF

The results indicate that the proposed Intelligent Quantum Security Framework outperforms conventional cryptographic systems across all evaluated performance metrics. The integration of AI-based intrusion detection significantly improves attack detection accuracy, while the adoption of CRYSTALS-Kyber and CRYSTALS-Dilithium provides long-term resistance against quantum-enabled cyber attacks.

Table 2. Security Comparison

Parameter	RSA/ECC	Proposed IQSF
Quantum Resistance	No	Yes
Intelligent Threat Detection	No	Yes
Digital Signature	ECC	CRYSTALS-Dilithium
Key Exchange	RSA/ECC	CRYSTALS-Kyber
AI-based Intrusion Detection	No	Yes

Secure Communication	High	Very High
Future Security	Limited	Long-Term
Smart CPS Protection	Moderate	High

The comparison demonstrates that the proposed framework not only strengthens cryptographic security but also introduces intelligent threat detection capabilities that improve the overall resilience of Smart Cyber-Physical Systems.

7. Discussion

The experimental analysis reveals that the consolidation of Artificial Intelligence and Post-Quantum Cryptography improves the security of Smart Cyber-Physical Systems significantly. The AI based anomaly detection module can effectively identify malicious behavior before the secure communication is established and this reduces the probability of successful cyber attacks. CRYSTALS-Kyber is used for secure quantum-resistant key exchange, and CRYSTALS-Dilithium is used for reliable authentication and message integrity verification. The proposed framework achieves higher attack detection accuracy, lower communication latency, and stronger authentication than the conventional RSA and ECC-based security mechanisms, while ensuring future-proof protection against quantum computing attacks. The multi-layer security architecture improves confidentiality, integrity, availability and non-repudiation without too much computational overhead. The proposed framework shows promising performance, however, there are some limitations. The current implementation uses simulation and benchmark datasets instead of deploying in a real industrial Smart Cyber-Physical System. Additionally, the computational requirements of Post-Quantum Cryptography can be a hurdle for highly resource-constrained IoT devices with limited processing power and memory. Future optimization techniques may further reduce computational overhead while still maintaining high security.

8. Conclusion

- **Problem Statement Addressed:** This work addresses the increasing cybersecurity challenges of Smart Cyber-Physical Systems and the susceptibility of classical public-key cryptographic algorithms to prospective quantum computing attacks.
- **Method Used:** An Intelligent Quantum Security Framework was proposed by integrating Artificial Intelligence based intrusion detection and Post Quantum Cryptography. CRYSTALS-Kyber was used for secure key encapsulation and CRYSTALS-Dilithium for authentication by digital signatures.
- **Key Findings:** : The experimental evaluation shows that the proposed framework outperforms the conventional RSA/ECC based security solutions in attack detection accuracy, secure authentication, encryption efficiency, communication performance and long-term quantum resistance.
- **Limitations and Future Work:** The present study is based on simulation on benchmark datasets. Future directions include real-world deployment in industrial Cyber-Physical

Systems, lightweight post-quantum algorithms for resource-constrained IoT devices, federated learning based intrusion detection, blockchain assisted trust management, and Quantum Key Distribution (QKD) for next-generation smart infrastructures.

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