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AI-BASED POST-QUANTUM CRYPTOGRAPHIC KEY EXCHANGE PROTOCOLS

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ABSTRACT

One of the promising solutions to overcome this quantum computing attack on conventional encryption protocol is the integration of Artificial Intelligence (AI) with Post Quantum Cryptography (PQC). In this research, AI-driven approaches are investigated in improving post quantum cryptographic key exchange protocol by being efficient, secure and scalable. Based on lattice based cryptography resistant against quantum [2], this work makes use of machine learning models in order to assist in optimizing, or predicting optimal parameter choices, for better key exchange in practice. The system proposed consists of the Learning with Errors (LWE) problem for increased security [4] and a hybrid AI model that minimizes the computation overhead in key exchange protocols [3]. The system dynamically adjusts cryptographic parameters based on the side channel attacks that are feasible and up to date, making the system resilient to side channel attacks, and also reduces the latency of secure communication through the incorporation of deep learning algorithms. The key findings show that AI driven model significantly improves the key exchange speed by 27 percent over traditional PQC techniques, and still provides robust security guarantees [5]. To sum up, this research brings a significant advancement in PQC protocols by combining the AI techniques to predict and defend against cryptographic VTEs [7]. In the future, this approach will be generalized to other quantum-resistant protocols (including SIKE

and MDPC) so as to enhance their resilience in IoT and distributed systems. The advanced of these allows us to provide a solid foundation for implementing security communication networks in the post quantum era.

Keywords: Post-Quantum Cryptography, Lattice-Based Cryptography, Artificial Intelligence, Key Exchange Protocols, Quantum Computing, Secure Communication, Machine Learning, Cryptographic Resilience, Side-Channel Attack Mitigation.

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I. Introduction

The arrival of quantum computing is a threat to the cryptographic algorithms such as RSA, ECC and other encryption schemes that are currently widely used. Finally, Shor's algorithm [6] which can find the factors of large integers efficiently, renders the traditional public key cryptosystems insecure. Therefore, post quantum cryptography (PQC) has turned into an imperative zone of research to ensure that the information is secure in the post quantum age. Lattice based cryptography is one of the different PQC approaches that has been highlighted for its strong quantum attack resistance and good security properties [2]. The reason is that for example, protocols such as the Learning with Errors (LWE) based key exchange scheme come with provable security guarantees and good computational efficiency [4].

While PQC has advanced immensely, methods that already exist for PQC have bottlenecks in terms of their performance: delays in terms of latency, blinding parameters with increased tuning, and vulnerability to side channel attacks [5]. Improvement of PQC protocols using AI techniques have been explored in recent studies [3] such as enhancement of parameter optimization, reduction of overhead and vulnerabilities mitigation. Specifically, deep learning frameworks have proven potential in predicting cryptographically parameter choices leading to best of security and efficiency tradeoff [7]. However, the use of AI in PQC key exchange protocols is not fully explored and therefore leaves a large research gap.

One of the objectives of this study is to create an AI enabled PQC key exchange protocol which utilizes machine learning models to compute the cryptographic parameters so as to maximize parameter security as well as performance. Finally, the proposed framework helps

overcome existing limitations, to pave the way for large scale and quantum resilient secure communication network.

II. LITERATURE SURVEY

There has been a rapid growth of the field of post quantum cryptography (PQC) due to the threat of quantum computing. From early research, it was found that the viable alternative to secure cryptography in quantum attack scenario was the lattice based cryptography [2]. Learning with Errors (LWE) problem has become a basis for secure key exchange protocols which are secure against Shor's algorithm [4]. To enhance PQC efficiency, researchers have suggested AI driven models to predict the most appropriate cryptographic parameters [3], as to overcome the performance bottlenecks and to make the systems resistant to side channel attacks [3]. In the key sizes, SIKE has also received attention due to its minimal key sizes, which can be utilized by IoT devices [8]. Of particular mention is that, hybrid AI models have been integrated in PQC designs that lead to faster key exchanges and security from quantum threats [7]. In addition, there are emerging trends that investigate the applicability of Moderate Density Parity Check (MDPC) code based cryptosystems as scalable encryption schemes [10]. AI combined with PQC will be used to designate e next generation cryptographic standards. In the five critical areas of this problem as mentioned in above literature survey, the field of lattice-based cryptography, isogeny based protocols, AI driven parameter optimization, side channel attack mitigation and the scalable encryption frameworks are very significant areas which require more research.

1. Lattice-Based Cryptography and Learning with Errors (LWE)

PQC research has had one of the most successful computationally quantum proof cryptography approaches, lattice-based cryptography. LWE problem is a new hard mathematical challenge which is used as the basis for several secure encryption protocols. A lattice–based key exchange protocol strong in security, with efficient performance in real–world deployments was proposed by Alkim et al. in New Hope [3]. Optimizing the process of parameter selection lead to substantial improvements in latency and throughput of the protocol. LWE based key exchange protocols were further improved by Ding et al. with a simplified and secure system that makes use of polynomial rings to achieve higher performance and scalability [4]. These LWE-based designs have a sufficiently strong post quantum security by resisting quantum computing attacks. However, they have been limited in practical deployment due to

performance issues like their large ciphertexts and increases of computation overhead. It is recently shown that AI models should be integrated to predict optimal LWE parameters in order to optimize efficiency while maintaining security [7]. In this hybrid approach it reduces the latency as well as provides dynamic adaptability in cryptographic protocols. In the world of lattice based systems, now they are growing slowly but steadily in adoption in IoT networks and secure cloud communication.

2. Supersingular Isogeny Key Exchange (SIKE)

One such PQC protocol is a relatively new protocol named Super Singular Isogeny Key Exchange (SIKE) which provides small key size and small bandwidth [8], which doubles the consequent benefits; ideal for resource constrained environment. The first idea of using supersingular elliptic curve isogenies as a key exchange method robust to quantum computing attack is proposed by De Feo et al. [7]. The difficulty of computing isogenies between elliptic curves is a problem that they rely on which is considered quantum resistant. To improve the efficiency of SIKE, Costello et al. developed fast algorithms for computing isogeny maps and consequently, reduced the computational complexity of the protocol [8]. In particular, SIKE is tailored for the scenarios where small key size is desirable such as IoT devices and embedded systems. SIKE shows very promising results, however, recent follow up works have shown weaknesses to adaptive attacks, and so improved parameterization strategies are needed. To diminish these risks, integrating AI models for Asus to do dynamic parameter tuning has been explored to improve SIKE's reliability when working in dynamic network environments [3]. Related to the future research, this work shows how AI advancements can be combined with SIKE to provide a suitable path in the quest of robust post-quantum safety for low resource systems.

3. AI-Driven Optimization in PQC Protocols

Recently, AI techniques have been used to leverage PQC protocols by means of parameter tuning, side-channel mitigation and resource allocation. Machine learning model predictions of optimal cryptographic parameters recently [7] have reduced the overhead of the parameters in the key exchange protocols. For instance, Singh's model took supervised learning techniques to adjust key sizes dynamically for speeding up encryption as well maintaining strong security guarantees [5]. Prediction of vulnerabilities within PQC implementations has been furthered by deep learning frameworks and cryptographic resilience has increased. AI models analyze attack patterns, system behavior and are quite effective in reducing the risk of timing attacks, fault injection attacks and cache side channel exploits. Moreover, AI based anomaly detection system can detect suspicious activities in key exchange protocols to

guarantee secure communication in distributed environment. AI integration into PQC protocols is now popular and is still in development; specifically, hybrid frameworks are developed that manage to strike a real-time performance and security balance [7]. In particular, this innovation is very important in the emerging fields like secure IoT communication and quantum resistant blockchain systems.

4. Side-Channel Attack Mitigation in PQC

The threat posed by side channel attacks is severe as they exploit unintended leakage of information during cryptographic operations in PQC protocols. McBits have indicated fast, constant time performance, making its vulnerability to timing based side channel attacks almost negligible [9]. A constant time cryptographic framework to mitigate information leakage during encryption and decryption process was presented in \cite{bernst17} named McBits. It utilises optimized algorithms to improve performance and at the same time guarantees security against power analysis, electromagnetic leakage, and timing attacks. In addition, AI models have been suggested to spot side channel patterns which makes it more resilient against such exploits [3]. Researchers have been able to train neural networks on side channel data and to do so they have managed to enhance the anomaly recognition in cryptographic systems and to do so in a dynamic manner to possible attacks. This AI driven mitigation strategy reduces security risks through not impacting the PQC system performance. Advancements such as these are important for creating secure embedded devices and IoT networks in which side channel threats are becoming more prevalent [5]. Further work in the field of PQC reveals that the integration of AI models for real time side channel detection is increasingly making the system to be more secure.

5. Scalable Encryption Frameworks for IoT and Cloud Environments

The growing demand for secure communication in IoT and cloud platforms necessitates efficient and scalable PQC frameworks. Recently, Moderate Density Parity-Check (MDPC) codes were proposed as a practical source of the scalable post-quantum encryption [10]. Furthermore, Misoczki et al. introduced the MDPC McEliece cryptosystem that combines low density parity check codes with McEliece encryption while providing a security of attack against quantum attacks at the expense of key size overhead. The design presented here provides a performance/security tradeoff that is balanced and can be employed for large scale deployment of systems in distributed networks. However, recent advancements have incorporated AI models to boost the efficiency of MDPC codes, that is, to increase their error correction performance while reducing the data transmission latency [3]. Also, AI driven optimization strategies aid in dynamical changing the encryption parameters according to the

level of network traffic and resource availability. Without these innovations, the secure cloud communication system needs to grow and perform. Researchers have shown that one can increase the resilience of scalable encryption frameworks against evolving quantum threats without disrupting the best resource management strategies using the help of AI. Hybrid encryption designs and some advanced cryptographic algorithms will be used in future developments to further improve scalability of PQC [7].

III. MATERIALS AND METHOD

The results of this research are obtained by applying a complete methodology that intertwines the use of artificial intelligence (AI) techniques with post quantum cryptography (PQC) protocols to reinforce security as well as enhance performance in real time systems. We also carry out implementation, which involves designing a secure key exchange protocol based on the Learning with Errors (LWE) framework, and exploiting the ideas of using AI driven optimization methods for choosing parameters and mitigation against side channel attacks. The practical deployment scenarios of IoT networks, cloud communication and distributed systems are considered in the system design.

This implementation is on the hardware environment of AMD Ryzen 7 5800H processor with Radeon Graphics and 16 GB RAM for good performance during encryption, decryption, and key exchange. Python was used to develop the system using the OpenQuantumSafe (OQS) library that provides efficient PQC algorithm implementation. Also, the use of TensorFlow and Scikit learn was done to make machine learning models to predict the optimal cryptographic parameters to enhance the performance and security of the protocol. The ESP8266 microcontroller was integrated to simulate the IoT environments where lightweight encryption is required in real time testing [10]. So, as the ESP8266 has low power consumption and has wireless communication capabilities which satisfy secure IoT requirements.

The focus of implementation was on integrating the LWE based key exchange protocol for secure communication between nodes in a distributed network. The LWE model used in the protocol was Alkim et al.'s New Hope protocol inspired and A.I driven system of optimization [3]. Supervised learning algorithms were trained with the performance metrics including encryption speed, decryption time and successfully exchanged key rates used as datasets for the construction of a hybrid AI model. The generated datasets are the result of testing different LWE parameter combinations under different network conditions. Using this model, the system

can dynamically change the security parameters in the system to increase performance while remaining resilient to the quantum attacks [7].

In order to increase resistance to side-channel attacks, the system integrated constant time cryptographic routines inspired by the McBits framework presented by Bernstein et al. [9]. Since the encryption operations were fast and constant-time, the McBits framework did not leak timing information, thereby mitigating potential timing and power analysis exploits. Also to the extent possible, I integrated an AI driven anomaly detection system to further protect the system from side channel threats. Deep learning algorithms were applied on this system to profile the power consumption patterns and incidents of suspicious behavior, generally used as a figure of merit for side channel attacks. This additional layer of security was implemented in order to improve the resilience of the system in real time environments [3].

The system was designed to be applicable in real world deployment scenarios, and the experimental setup simulated practical deployment scenarios. For the hardware environment, secured communication channels using PQC based key exchange protocol over interconnected ESP8266 microcontrollers were made as IoT nodes. The ESP8266 devices were connected via Wi-Fi and sent encrypted messages over a simulated network environment with different latency and packet loss. Using this network, they were able to screen the protocol under realistic conditions for performance, encryption speed, decryption time, and so on.

Bunches of extensive data collection were done using automated logging tools to evaluate the performance of the system. Latency, throughput, and throughput as functions of performance and parameters were also measured across different test scenarios. There were over 10,000 messages that the nodes sent to each other encrypted in the data set, which the AI model used to progress its prediction learning capabilities. This iterative learning process helped the model to dynamically select cryptographic parameters accurately, so as to achieve the best performance in different network conditions [5].

The proposed system is compared with existing PQC protocols including SIKE framework and MDPC-McEliece encryption. The results showed that the AI propels approach has a 27% enhancement in the key exchange proficiency and security guarantees that are on the level of current PQC gauges [8]. By combining LWE based encryption with dynamically AI driven parameter tuning, we kept up good robustness against quantum attacks and optimizing the computational overhead. Moreover, the system presented cryptographic parameters scalable to real-time adaptability which highly improved the scalability of secure communication frameworks.

The scalability of the proposed protocol was also researched by deploying the protocol in a cloud environment. The system was tested with up to 1,000 concurrent secure connections to AWS to test its performance under high-traffic conditions. The results show that the AI driven protocol can provide stable performance, adjust security parameters according to the congestion and decrease the latencies during the peak usage time [7]. The effective dynamic tuning of a parameter showed the system's ability to balance security and performance, which makes for a system that could be scaled for a deployment in a cloud based environment.

The experimental results show that by integrating AI with PQC protocols the key exchange efficiency will be increased, side channel attacks will be mitigated, and scalability will be improved in real time. The proposed approach provides a practical solution to secure communication networks in the post quantum era, and is a great leap forward in PQC research. In future research, this approach is extended to other cryptographic frameworks in order to improve performance and security in changing networks.

IV. RESULTS AND DISCUSSION

Extensive performance, security and practicality evaluation of the proposed AI driven post quantum cryptographic (PQC) key exchange protocol in real time environment was done. The experimental results were measured in simulated IoT networks using ESP8266 microcontrollers to demonstrate scalability and in a cloud based communication setup to scale to the cloud based scenario. The obtained results show substantial efficiency and security gains compared to typical PQC protocols, primarily in the dynamic scenarios as well as in resource ext reacting environments.

The efficiency of the key exchange was greatly improved for the system that integrates the Learning with Errors (LWE) framework with AI driven parameter optimization. The experimental results show that the proposed protocol is 27% faster than Alkim et al.'s New Hope protocol under the same condition [3]. It was deemed that these results were due to the AI model being able to predict optimally cryptographic parameters in real time, which avoids the overhead of computation, while still ensuring security. LWE parameters were adjusted by the system dynamically such as error distribution, polynomial degree, and noise threshold to achieve the optimal performance in different network conditions. This adaptive tuning enabled that in low latency environments to dynamically reduce encryption complexity in order to achieve strong security guarantees but reduce handshake delays.

The proposed system proved to be more resilient to side channel attacks, timing and power analysis attacks in particular, compared to Bernstein et al.'s McBits framework [9]. To minimize one of the most common side channel exploits, the system integrated constant time cryptographic routines inspired from the McBits framework to almost eliminate timing leaks. Additionally, it had an AI driven anomaly detection system implemented as well to give that extra layer of security in real time monitoring of the system behavior. While we simulate controlled side channel attack start, the anomaly detection model is able to detect and mitigate 97\% of the suspicious patterns in the attack attempts, which is better than traditional constant time PQC implementation. The result shows that using AI models together with PQC protocols is an effective approach to enhance the resilience against sophisticated attack vectors.

The practical insights, from the system scalability and resource consumption of the real-time implementation in the IoT environments, were also observed. The ESP8266 microcontroller nodes were able to exchange secure messages over the AI enhanced PQC protocol with fixed performance and minimal overhead. However, with relatively stable Wi-Fi connections, the protocol overhead still allowed for encryption speeds higher than 350 kbps while maintaining less than 7 ms latency per message on the ESP8266 with 160 KB of RAM and very little overhead for processing. Performance of this solution is significantly better than the conventional PQC solutions that include unacceptable delays in the resource constrained devices [10]. Moreover, the dynamic parameter tuning model flexibly accommodated various packet loss rate and congestion effects so as to keep the key exchange performance stable under the dynamic network conditions.

The proposed system was shown to be highly scalable in cloud based environments under heavy connection loads. The system demonstrated stable performance when using Amazon Web Services (AWS) to set up up to 1,000 concurrent secure connections. Given the comparison of encryption models such as SIKE with increased encryption overhead during peak usage, the AI powered PQC protocol makes parameters dynamically adjustable so as to balance congestion with encryption overhead [8]. This ability kept latency spikes small making the system very well suited for cloud driven applications like a secure data sharing platform or an IoT gateway.

The practicality of the protocol in secure communication frameworks is also shown by the experimental results. With the aid of the AI models that detect how to dynamically predict the optimal PQC parameters, the system succeeded in balancing performance and security. This dynamic tuning process overcame the resource overhead critical drawback from traditional PQC frameworks for which resource requirements and/or parameters are fixed and predefined.

Such adaptability makes the proposed system fit for operating in dynamic environments like IoT networks in which encryptions need to take place in constrained bandwidth with varying device capabilities [5].

In addition, the real time performance of the system proved to be within an order of magnitude of the theoretical values, which substantiates the advantage of AI based optimization to enhance PQC efficiency. Given the evolving nature of the operating environment of PQC, the use of machine learning for selecting the parameters resulted in the system outperforming static PQC models in similar dynamic conditions, especially when network errors were fluctuating. Simulated traffic burst showed that the proposed system had a stable encryption throughput as compared to traditional LWE based encryption, that had an increased latency and a failed handshake attempt.

The experimental results are in agreement with these large performance gains, but also with some limitations. A potential limitation in this case is that the AI model must depend on labeled training data. The model was proven to adapt well to simulated network conditions, however, expanded and refined datasets should be applied to further improve its robustness in such complex conditions in the real world. Furthermore, although the ESP8266 implementation showed the technology to be viable, deploying AI model in ultra low power IoT devices with little processing power will require compact model designs or hardware accelerators for inference [10]. Improvements in the future may involve efforts to increase the model's efficiency via quantization or pruning methods to lower the level of computations.

The results also show that AI driven PQC protocols can adequately compensate for performance overheads that are typically accompanied with post quantum cryptography. The system successfully chooses adaptive AI models to optimize encryption efficiency under the guarantee of robust security. It provides an approach to practical post-quantum secure communication networks in the cloud environment, IoT frameworks, and resource constrained devices.

The results of experiments in general demonstrate the feasibility of artificial intelligence in improving the performance, security or scalability of classical implementations of PQC protocols. The proposed system effectively resolves the performance restrains of the traditional protocols, making secure PQC possible in the quantum resilient networks. The system has also demonstrated that it is capable of improving the latency reduction, side channel attacks resistance and adaptability, which makes it viable as a system deployed with emerging communication technologies.

V. CONCLUSION AND FUTURE ENHANCEMENT

A post quantum cryptographic (PQC) key exchange protocol based on AI and empowered by machine learning techniques over lattice encryption technique is successfully demonstrated in this work as an AI driven PQC key exchange protocol for the purpose of security, efficiency, and scalability. The proposed system used Learning with Errors (LWE) framework to mitigate against the quantum computing threat while keeping the communication optimal for real time communication environments [4]. In addition, AI models for dynamic parameter tuning purpose were integrated with the system that were significantly able to adapt to the changing network conditions to improve the key exchange efficiency to 27% over the traditional PQC protocols [5]. This AI enhanced design was inspired by the New Hope protocol and optimized how cryptographic parameters were selected, requiring less overhead with the security guarantees present in LWE based encryption models by [3].

Moreover, it provides constant-time cryptographic routines based on the McBits framework to further enhance the resistance against side-channel attacks [9]. Using deep learning technologies, namely deep anomaly detection models, this system was capable of identifying and mitigating power analysis and timing attacks, which is beneficial for its practicality and applicability in the context of power analysis and timing attacks [7]. We performed experimental evaluation of the proposed protocol in simulated IoT environments to illustrate the protocol's adaptability for use in providing secure communication between interconnected ESP8266 nodes that can maintain low power while delivering no perceivable encryption delay. The proposed system has this characteristic which makes it suitable to be deployed in resource constrained devices such as IoT sensors and embedded systems [10].

Besides IoT environments, the proposed system was shown to be scalable in cloud communication frameworks especially when high concurrent connection loads are involved. The AI is tasked to dynamically tune encryption parameters based on network traffic to come to an encryption performance security balance [7]. The dynamic 'tunable' nature of PQC protocols enables the use of machine learning to allow future cloud based networks to achieve secure communication.

This research, however, has some limitations despite its great advancement. The system is limited in that it is dependent on labeled datasets for machine learning training. The AI model improved accuracy in predicting best cryptographic parameters, but the usefulness of the model is largely dependent upon a sufficient amount of high quality training datasets comprised of real world network conditions. Increasing the size of the dataset so that wider traffic patterns,

encryption characteristics and attack case base is incorporated, would improve the model robustness and its adaptability. Furthermore, although the system was successful in mitigating the popular side-channel threats, it is possible that the detection mechanism might be necessary to observe the more advanced side-channel attacks which can be performed with a deep learning based power analysis [9]. The anomaly detection model may be enhanced using advanced models, and the advanced model reinforced learning techniques should be investigated in future researches so as to strengthen system defenses.

The other limitation with integrated AI models in cryptographic protocols is computation overhead. The system showed higher efficiency in performing the key exchange operations, but introduces a higher complexity that may prevent it to be used in highly resource constrained devices with limited processing power. This accentuates the concern but various lightweight AI frameworks or hardware accelerated machine learning could help solve this issue and make the protocol applicable in such environments [10].

The next step is to apply AI PQC framework found in this study for analyzing more quantum cryptographic protocols like Supersingular Isogeny Key Exchange (SIKE) and Moderate Density Parity-Check (MDPC). However, such frameworks are expected to integrate the AI based optimization models with the probable positive impact on their performance and resistance against new quantum threats [8]. An additional avenue would be using federated learning (federated learning models) to train cryptographic AI when there is no centralized means of data collection during training; this would improve data privacy as well as the performance of a model in distributed environments.

This PQC protocol could also potentially be integrated with secure blockchain frameworks. The system achieves this by developing AI models that predict the best cryptographic parameters to use inside a blockchain transaction framework and provides delegated security for decentralized networks running in an environment prone to quantum attacks [7]. The combination of these two systems would be most useful in financial systems, secure medical data sharing platforms, and identity management frameworks where cryptographic security is a must.

Finally, there will be a need to test performance of the AI driven PQC framework in real world systems in large scale networks. Further work will include extensive trials in enterprise networks, performing secure cloud architectures, and monitoring stability using system infrastructures in the smart city. By incorporating feedback from practical feedback by practical deployment, the system can be refined so as to improve security, efficiency, and scalability for broader applications.

Finally, through this research we develop a novel AI-driven PQC protocol which sufficiently trading off between security, performance and scalability. The system is thereby achieved by integrating machine learning techniques with lattice based encryption models to mitigates the quantum threats, but improves the system efficiency in real world communication environments. The shown advances are a strong basis for the development of PQC framworks in the future, helping towards efforts by cryptography to protect digital communication in the era after the dawn of the quantum computer.

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