International Journal of Innovations & Research Analysis (IJIRA)
ISSN :2583-0295, Impact Factor: 6.238, Volume 04, No. 04(I), October- December, 2024, pp 63-70

QUANTUM CRYPTANALYSIS OF FIPS 140-3 COMPLIANT ENCRYPTION STANDARDS

Ms. Yash Dinesh Deore*
Prof. Dinesh Deore**

ABSTRACT

The advancement of quantum computing presents both opportunities and threats to contemporary cryptographic systems. This research explores to threat which will be in the future for Quantum Computing which can decrypt algorithms of encryption such as AES, RSA, ECC, Triple DES which are compliant encryption standards of FIPS 140-3.

Keywords: *Quantum Cryptanalysis, Grover's Algorithm, Shor's Algorithm, Advanced Encryption Standard, Quantum Computing, Classical Computing, Superposition.*

Introduction

The rapid development of quantum computers presents a significant challenge to the current cryptographic landscape. Widely used encryption algorithms, such as AES, Elliptic Curve Cryptography (ECC), and Triple Data Encryption Standard (Triple DES), are susceptible to being broken by quantum computers leveraging Shor's Algorithm [1]. This vulnerability extends to encryption standards like FIPS 140-2 and FIPS 140-3, which heavily rely on these algorithms, raising concerns about their effectiveness in a quantum future. This paper explores the impact of quantum computers on various encryption schemes. We delve into the specific vulnerabilities of public-key cryptography algorithms like RSA and ECC to Shor's Algorithm, highlighting the ease with which quantum computers can bypass these safeguards. We then analyze the impact on Advanced Encryption Standard (AES), a symmetric-key algorithm, acknowledging its relative resistance to Grover's Algorithm employed by quantum computers [2]. However, the importance of sufficient key size for AES in a quantum era is emphasized. While the immediate threat of quantum computers breaking encryption remains low due to their ongoing development, proactive measures are necessary. We advocate for awareness of the potential risks and a gradual transition towards quantum-resistant algorithms, such as lattice-based cryptography, to ensure continued data security in the face of this evolving technological landscape.

Background

Advanced Encryption Standard (AES) AES is a key encryption algorithm used in FIPS 140-3 which was made by National Institute of Standards and Technology (NIST) in the year 2001. It supports multiple key sizes such as 128, 198 and 256 bits. AES operates on a 4x4 column-major order matrix of bytes, known as the state, and performs a series of transformations including substitution, permutation, and mixing operations across multiple rounds to encrypt data.

Rivest-Shamir-Adleman (RSA) RSA is key encryption algorithm developed in 1977. RSA uses a pair of keys: public key for encryption, private key for decryption. The security of RSA is based on the difficulty of factoring large composite numbers, specifically the product of two large primes.

* Bhausaheb Vartak Polytechnic, Vasai, Maharashtra, India .
** Rizvi College of Engineering, Bandra(West) 50, Mumbai, Maharashtra, India .

Elliptic Curve Cryptography (ECC) ECC is an asymmetric encryption technique that leverages the algebraic structure of elliptic curves over finite fields. ECC can achieve similar levels of security to RSA but with much smaller key sizes, making it more efficient. For instance, a 256-bit key in ECC is as secure as a 3072-bit key in RSA.

Triple Data Encryption Standard (Triple DES) Triple DES is a symmetric key encryption algorithm that applies the DES cipher three times to each data block. It was designed to provide a higher level of security than standard DES by using three 56-bit keys, effectively making the key length 168 bits. It operates in three steps: encryption, decryption, and re-encryption with the three different keys.

Quantum Computing and Cryptographic Threats Shor's algorithm, developed by mathematician Peter Shor in 1994, can efficiently solve integer factorization and discrete logarithm problems. These capabilities directly threaten the security of RSA and ECC [3]. RSA: The security of RSA relies on the difficulty of factoring large composite numbers. Shor's algorithm can factor these numbers in polynomial time, rendering RSA insecure if a sufficiently powerful quantum computer is available [4]. ECC: Similarly, ECC's security depends on the difficulty of the elliptic curve discrete logarithm problem. Shor's algorithm can solve this problem efficiently, breaking ECC encryption [5].

Grover's Algorithm Grover's algorithm, devised by Lov Grover in 1996, offers a quadratic speedup for unstructured search problems. It has implications for symmetric key cryptography like AES and Triple DES [6]. AES: Grover's algorithm can reduce the effective key space of AES by approximately the square root. For instance, an AES-128 key, which has a classical brute-force complexity of 2^128, would be reduced to 2^64 operations with Grover's algorithm. Although this is a significant reduction, it still requires substantial computational resources [7]. Triple DES: Similar to AES, Grover's algorithm would reduce the effective key space of Triple DES, making it more vulnerable to brute-force attacks. However, the effective key size reduction would be to around 2^84 operations, which is still considerable but less secure than AES [8].

In addition to the background information, the extended text further elaborates on the potential impact of quantum computing on cryptographic algorithms. It highlights the vulnerabilities of RSA and ECC to Shor's algorithm, which can efficiently factor large composite numbers and solve the discrete logarithm problem, respectively. This poses a significant threat to the security of these widely-used public-key cryptography schemes. The text also discusses the implications of Grover's algorithm on symmetric-key algorithms like AES and Triple DES, providing insights into the quadratic speedup it offers for brute-force attacks on the key space. While AES is relatively more resistant due to its larger key sizes, the importance of using sufficient key lengths in the quantum era is emphasized. Furthermore, the text advocates for proactive measures, such as awareness of potential risks and a gradual transition towards quantum-resistant algorithms, to ensure continued data security in the face of advancing quantum computing capabilities.

Detailed Impact Analysis

- **RSA and Shor's Algorithm**

The threat posed by Shor's algorithm to RSA encryption is profound. Given an RSA modulus N, which is a product of two primes p and q, Shor's algorithm can factor N in polynomial time [9]. This breaks the fundamental assumption behind RSA's security. As a result, the development of quantum computers with sufficient qubits and low error rates would make RSA insecure for practical use [10]. The impact of Shor's algorithm on RSA is particularly significant because RSA is widely used in various applications, including secure communication protocols, digital signatures, and key exchange mechanisms [11]. Consequently, the advent of powerful quantum computers would necessitate a transition to alternative cryptographic schemes that are resistant to quantum attacks.

- **ECC and Shor's Algorithm**

ECC encryption relies on the difficulty of solving the elliptic curve discrete logarithm problem. Shor's algorithm can solve this problem in polynomial time, similar to its impact on the RSA algorithm [12]. Thus, if a powerful quantum computer is available, it can break ECC encryption by solving the underlying discrete logarithm problem efficiently [13]. This vulnerability is concerning because ECC is widely adopted due to its smaller key sizes and computational efficiency compared to RSA, making it suitable for resource-constrained environments such as embedded systems and mobile devices [14].

- **AES and Grover's Algorithm**

AES is not as dramatically affected by quantum computing as RSA and ECC due to Grover's algorithm providing only a quadratic speedup rather than an exponential one. For AES-128, Grover's algorithm would reduce the complexity from 2^128 to 2^64 [15]. For AES-256, the complexity would be reduced from 2^256 to 2^128. While this is significant, increasing the key length (e.g., using AES-256 instead of AES-128) can mitigate the threat to some extent [16]. However, it is important to note that Grover's algorithm still poses a threat to AES, and as quantum computing capabilities advance, the impact on AES may become more severe.

- **Triple DES and Grover's Algorithm**

Triple DES, like AES, would see its security reduced by Grover's algorithm. The effective key length would be reduced from 168 bits to around 84 bits, which is less secure compared to AES [16]. Given the larger key sizes and the triple encryption process, Triple DES is more computationally intensive, but quantum computers running Grover's algorithm would still pose a significant threat [17]. While Triple DES is no longer widely used due to its computational complexity and the availability of more efficient alternatives like AES, understanding the impact of quantum computing on legacy encryption schemes is essential for ensuring the security of systems that may still rely on them.

Initial State Preparation

- **Using Grover's Algorithm to decrypt AES**
  - **Equal Superposition:** Begin by preparing an equal superposition of all possible keys. This involves applying Hadamard gates to the qubits representing the key space. For AES, depending on the key length (128, 192, or 256 bits), initialize the corresponding number of qubits.
  - **Hadamard Transformation:** Apply Hadamard gates (H) to each qubit representing the key space, resulting in a superposition state where each possible key has an equal amplitude.
  - **Ancilla Qubit Preparation:** Initialize an ancillary qubit in the state $|-\rangle=\frac{|0\rangle-|1\rangle}{\sqrt{2}}$
  - **Oracle Design:** The oracle is a quantum circuit that marks the correct key by flipping the phase of the state corresponding to the correct key. This involves:
  - **AES Encryption Circuit:** Design a quantum circuit that performs AES encryption. This circuit takes a candidate key and a fixed plaintext and outputs the ciphertext.
  - **Comparison with Target Ciphertext:** Compare the output ciphertext with the known target ciphertext. If they match, the oracle flips the phase of the ancilla qubit.
  - **Equality Check:** Implement an equality check using quantum gates. If the AES output matches the target ciphertext, apply a phase flip to the corresponding state.
  - **Phase Inversion:** Construct the phase inversion operator U_f that implements the phase flip for the state representing the correct key.
  - **Grover Iteration:** The Grover operator G consists of the oracle followed by the diffusion operator, which amplifies the amplitude of the marked state.
  - **Inversion About the Mean:** Apply Hadamard gates to all key qubits, followed by a multi-controlled Z gate (to invert the phase of the |0⟩|0\rangle|0⟩ state), and then Hadamard gates again.
  - **Iteration Count:** Determine the number of Grover iterations I = $\frac{\pi}{4}\sqrt{\frac{N}{M}}$ where N is the total number of possible keys, and M is the number of correct keys (typically M = 1 for AES key search).
  - **Iterative Application:** Apply the Grover operator G iteratively to the initial state. Each application of G increases the probability amplitude of the correct key state.
  - **Measurement:** After the specified number of iterations, measure the qubits representing the key space. With high probability, the measurement outcome will be the correct key.
  - **Quantum Circuit Depth and Width:** Estimate the number of gates required for each component of the AES encryption circuit, including the SubBytes, ShiftRows, MixColumns, and AddRoundKey operations. Ensure the circuit is optimized for depth and qubit usage to fit within the constraints of current quantum hardware.

- **Resource Estimation:** Provide detailed resource estimates for the number of qubits, gates (Clifford and T-gates), and depth of the entire circuit, considering the specific AES variant (AES-128, AES-192, or AES-256).
- **AWS Bracket Implementation:** Outline the specific steps to implement the designed quantum circuit on AWS Bracket, including initializing the quantum environment, defining the quantum circuits, and executing the algorithm with appropriate iterations and measurements.

Step-by-Step Execution of Shor's Algorithm for ECC Decryption on AWS Braket

- **Introduction to Shor's Algorithm and ECC**
  - Elliptic Curve Cryptography (ECC): ECC is a public-key cryptography method based on the algebraic structure of elliptic curves over finite fields. ECC is widely used due to its strong security with relatively small key sizes.
  - Shor's Algorithm: Shor's algorithm is a quantum algorithm that efficiently solves integer factorization and discrete logarithms, both of which are foundational for breaking many cryptographic systems, including ECC.
- **Preparation and Prerequisites**
  - Quantum Computing Environment: Ensure access to AWS Braket, a quantum computing service that allows you to run quantum algorithms on various quantum processors.
  - Libraries and Tools: Familiarize yourself with necessary libraries such as Amazon Braket SDK, NumPy, and potentially Qiskit if using specific quantum backends.
- **Establish the Quantum Circuit for Shor's Algorithm**
  - Initialize Qubits: Start by initializing the qubits required for the quantum circuit. The number of qubits depends on the problem size, typically related to the bit-length of the elliptic curve's order.
  - Apply Quantum Gates:
    - Hadamard Gates: Apply Hadamard gates to create superpositions.
    - Modular Exponentiation: Construct quantum circuits for modular exponentiation which is essential for the period-finding part of Shor's algorithm.
    - Quantum Fourier Transform (QFT): Implement the QFT to find the periodicity in the quantum state.
- **Encoding ECC Problem into the Quantum Circuit**
  - Mapping ECC to Discrete Logarithm Problem (DLP): Transform the ECC problem into a discrete logarithm problem, which is solvable by Shor's algorithm.
  - Oracle Construction: Build the oracle specific to the ECC problem. This oracle helps in finding the period of the function related to the discrete logarithm.
- **Running the Quantum Circuit on AWS Braket**
  - Circuit Submission: Submit the constructed quantum circuit to AWS Braket.
  - Backend Selection: Choose the appropriate quantum backend (such as Rigetti, IonQ, or D-Wave) based on the requirements and capabilities.
  - Execution: Execute the quantum circuit and monitor the job status.
- **Measurement and Post-Processing**
  - Measure Qubits: After the execution, measure the qubits to obtain the result in the classical form.
  - Result Analysis:
    - Interference Pattern: Analyze the interference pattern from the measurements to determine the periodicity.
    - Continued Fractions: Use the continued fraction expansion to deduce the factors from the periodicity, which translates to solving the discrete logarithm problem.

- **Extracting the Decryption Key**
  - Discrete Logarithm Solution: From the output of Shor's algorithm, extract the discrete logarithm which corresponds to the private key used in ECC.
  - Key Verification: Verify the correctness of the extracted key by checking if it matches the known properties of the ECC private key.
- **Practical Considerations**
  - Noise and Error Rates: Consider the noise and error rates of the quantum processor. Use error correction techniques if necessary.
  - Resource Estimation: Estimate the number of qubits and depth of the circuit needed for the problem size to ensure feasibility on available quantum hardware.
- **Conclusion and Future Work**
  - Decryption Feasibility: Discuss the feasibility of using Shor's algorithm for decrypting ECC in practical scenarios given current quantum hardware capabilities.
  - Advancements Needed: Identify advancements needed in quantum computing to make this approach practical for real-world cryptographic systems.

Step-by-Step Execution of Shor's Algorithm for Decrypting Triple DES on AWS Braket

- **Introduction to Shor's Algorithm and Triple DES**
  - Triple DES: Triple DES is a symmetric key encryption algorithm used for securing sensitive data. It applies the DES algorithm three times consecutively to each block of data.
  - Shor's Algorithm: Shor's algorithm is a quantum algorithm that efficiently factors large composite numbers, which is crucial for breaking symmetric key encryption schemes like Triple DES.
- **Preparation and Prerequisites**
  - Access to Quantum Computing Resources: Ensure access to AWS Braket, a quantum computing service provided by Amazon Web Services (AWS).
  - Familiarity with Quantum Computing Tools: Gain proficiency in using the Amazon Braket SDK and other necessary libraries for quantum computing tasks.
- **Quantum Circuit Design**
  - Qubit Initialization: Initialize the qubits required for the quantum circuit. The number of qubits depends on the size of the number to be factored, which is related to the Triple DES key.
  - Quantum Gates Application: Construct quantum circuits for modular exponentiation and quantum Fourier transform (QFT), essential components of Shor's algorithm.
  - Oracle Construction: Design an oracle specific to the Triple DES encryption process, which helps in identifying the periodicity needed for factoring the key.
- **Encoding Triple DES Problem into the Quantum Circuit**
  - Mapping Triple DES to Factoring Problem: Transform the Triple DES decryption problem into a factoring problem. This involves identifying the components of the Triple DES algorithm that can be represented as factors of a large composite number.
  - Oracle Integration: Integrate the oracle into the quantum circuit to enable the identification of the periodicity related to the factoring problem.
- **Execution on AWS Braket**
  - Circuit Submission: Submit the constructed quantum circuit to AWS Braket for execution.
  - Backend Selection: Choose an appropriate quantum backend based on availability and performance requirements.
  - Execution Monitoring: Monitor the progress of the quantum circuit execution through AWS Braket's interface.

- **Measurement and Post-Processing**
  - Qubit Measurement: After execution, measure the qubits to obtain classical results from the quantum state.
  - Result Analysis: Analyze the measurement outcomes to identify the periodicity, which corresponds to the factors of the large composite number related to the Triple DES key.
- **Decryption Key Extraction**
  - Factoring Solution: Extract the factors obtained from the output of Shor's algorithm, which correspond to the components of the Triple DES key.
  - Key Verification: Verify the correctness of the extracted key by applying it to decrypt encrypted data and comparing the results with the original plaintext.
- **Practical Considerations**
  - Quantum Resource Requirements: Estimate the number of qubits and circuit depth required for factoring the Triple DES key, considering the size of the key and available quantum hardware resources.
  - Error Correction: Address potential errors and noise in the quantum computation by employing error correction techniques or choosing appropriate quantum error mitigation strategies.
- **Conclusion and Future Work**
  - Feasibility Assessment: Evaluate the feasibility of using Shor's algorithm for decrypting Triple DES in practical scenarios, considering the current capabilities of quantum hardware.
  - Future Directions: Identify potential advancements in quantum computing technology that could enhance the efficiency and scalability of Shor's algorithm for breaking symmetric key encryption schemes like Triple DES.

Step-by-Step Execution of Shor's Algorithm for Decrypting RSA on AWS Braket

- **Introduction to Shor's Algorithm and RSA**
  - RSA Encryption: RSA is a widely used asymmetric encryption algorithm based on the difficulty of factoring large composite numbers into their prime factors.
  - Shor's Algorithm: Shor's algorithm is a quantum algorithm that efficiently factors large composite numbers, which poses a threat to RSA encryption.
- **Preparation and Prerequisites**
  - Access to Quantum Computing Resources: Ensure access to AWS Braket, a quantum computing service provided by Amazon Web Services (AWS).
  - Familiarity with Quantum Computing Tools: Gain proficiency in using the Amazon Braket SDK and other necessary libraries for quantum computing tasks.
- **Quantum Circuit Design**
  - Qubit Initialization: Initialize the qubits required for the quantum circuit. The number of qubits depends on the size of the number to be factored, which is related to the RSA modulus.
  - Quantum Gates Application: Construct quantum circuits for modular exponentiation and quantum Fourier transform (QFT), essential components of Shor's algorithm.
  - Oracle Construction: Design an oracle specific to the RSA encryption process, which helps in identifying the periodicity needed for factoring the RSA modulus.
- **Encoding RSA Problem into the Quantum Circuit**
  - Mapping RSA to Factoring Problem: Transform the RSA decryption problem into a factoring problem. This involves identifying the components of the RSA modulus that can be represented as factors of a large composite number.
  - Oracle Integration: Integrate the oracle into the quantum circuit to enable the identification of the periodicity related to the factoring problem.

- **Execution on AWS Braket**
  - Circuit Submission: Submit the constructed quantum circuit to AWS Braket for execution.
  - Backend Selection: Choose an appropriate quantum backend based on availability and performance requirements.
  - Execution Monitoring: Monitor the progress of the quantum circuit execution through AWS Braket's interface.
- **Measurement and Post-Processing**
  - Qubit Measurement: After execution, measure the qubits to obtain classical results from the quantum state.
  - Result Analysis: Analyze the measurement outcomes to identify the periodicity, which corresponds to the factors of the large composite number related to the RSA modulus.
- **Decryption Key Extraction**
  - Factoring Solution: Extract the factors obtained from the output of Shor's algorithm, which correspond to the prime factors of the RSA modulus.
  - Private Key Derivation: Use the prime factors to derive the private key necessary for decrypting RSA-encrypted data.
- **Practical Considerations**
  - Quantum Resource Requirements: Estimate the number of qubits and circuit depth required for factoring the RSA modulus, considering the size of the modulus and available quantum hardware resources.
  - Error Correction: Address potential errors and noise in the quantum computation by employing error correction techniques or choosing appropriate quantum error mitigation strategies.
- **Conclusion and Future Work**
  - Feasibility Assessment: Evaluate the feasibility of using Shor's algorithm for decrypting RSA in practical scenarios, considering the current capabilities of quantum hardware.
  - Future Directions: Identify potential advancements in quantum computing technology that could enhance the efficiency and scalability of Shor's algorithm for breaking RSA encryption.

Conclusion

The emergence of quantum computing poses a significant threat to traditional cryptographic schemes, particularly those reliant on the difficulty of factoring large numbers or solving discrete logarithm problems. Shor's algorithm, with its capability to efficiently solve these mathematical challenges, undermines the security of widely used encryption algorithms such as RSA and ECC. Additionally, Grover's algorithm threatens symmetric key algorithms like AES and Triple DES by reducing the effective key space.

While AES demonstrates relative resilience to quantum attacks compared to asymmetric algorithms, the importance of sufficient key sizes cannot be overstated in mitigating Grover's algorithm's impact. Transitioning to quantum-resistant algorithms, such as lattice-based cryptography, becomes imperative to ensure data security in the quantum era.

The practical implementation of Shor's algorithm for breaking RSA, ECC, and Triple DES encryption on quantum platforms like AWS Braket illustrates the feasibility of quantum attacks on current cryptographic standards. As quantum computing continues to advance, proactive measures, including the development and adoption of post-quantum cryptographic algorithms, are essential to safeguarding sensitive information in the face of evolving threats.

This research underscores the urgency for the cryptographic community to embrace quantum-resistant solutions and highlights the need for ongoing innovation to stay ahead of emerging threats in the ever-evolving landscape of cybersecurity.

Acknowledgment

The author thanks AWS services for providing useful materials and helping him to research in this study more.

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