Analysis and Research on Blockchain Security Technology: A Case Study of the Poly Network Security Incident

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Abstract: Blockchain technology has developed rapidly in recent years, with cross-chain technology emerging as a crucial means to achieve interoperability between different blockchains. However, security issues in cross-chain systems have become increasingly prominent. This paper takes the Poly Network security incident in 2021 as a case study to conduct an in-depth analysis and research on blockchain security technology. It first introduces the details of the Poly Network security incident, then analyzes the causes of the security problems, proposes cross-chain transaction risk management strategies, and focuses on the introduction and optimization comparison of ECC-ElGamal technology in smart contracts. Additionally, it delves into the operational depth of elliptic curve technology and designs Python experiments to verify its performance and security. Finally, it summarizes the research content and looks forward to the future development of blockchain security technology.

Keywords: Blockchain Security; Poly Network; Smart Contract; Cross-Chain Technology; ECC-ElGamal; Elliptic Curve Operation; Python Experiment

1. Introduction

1.1 Overview of Domestic and Foreign Research Status

Foreign research status: In the field of blockchain security technology research, foreign countries have a relatively early start and have carried out extensive and in-depth studies. Many renowned universities and research institutions have invested significant resources in this area and achieved remarkable results. For example, the Digital Currency Initiative of the Massachusetts Institute of Technology (MIT) has been at the forefront of exploring the underlying technology of blockchain security. Their research team comprises experts in cryptography, computer science, and finance, who work together to address the key security challenges in blockchain. [1] They have made substantial progress in cryptography algorithm optimization and consensus mechanism improvement. For example, they have proposed new consensus algorithms that aim to enhance the transaction processing speed of the blockchain while strengthening its security and anti-attack capabilities. These algorithms are designed to handle a higher volume of transactions per second without compromising the integrity and security of the network. After the occurrence of the Poly Network security incident, foreign scholars and research institutions responded promptly. The research team at Stanford University, known for its expertise in computer security and blockchain technology, conducted a detailed technical analysis of the incident. They examined the incident from multiple perspectives, including smart contract code vulnerabilities and cross-chain interaction mechanism defects. By reviewing the smart contract code of the Poly Network, they identified specific lines of code that were exploited by the attackers. They also analyzed the cross-chain communication protocols used by the Poly Network and found weaknesses in the data verification and consensus processes.

Based on their analysis, they put forward a series of targeted improvement suggestions, such as strengthening the formal verification of smart contracts. Formal verification involves mathematically proving that a smart contract behaves as intended, which can help detect and eliminate potential vulnerabilities before deployment. [2] They also suggested optimizing cross-chain communication protocols to ensure more secure and reliable data transmission between different blockchains. Some well-known international enterprises are also actively

involved in the research and practice of blockchain security technology. IBM, a global leader in technology, has developed a comprehensive blockchain security framework. This framework is designed to provide end-to-end security protection for enterprise-level blockchain applications. It covers various aspects such as identity authentication, data encryption, access control, and threat detection. For example, in identity authentication, IBM's framework uses advanced techniques like multi-factor authentication and digital certificates to ensure that only authorized users can access the blockchain network. In data encryption, it employs strong encryption algorithms to protect data both in transit and at rest. This framework has been successfully applied to blockchain projects in supply chain finance, where it ensures the security of transactions between multiple parties, and in medical and health, where it protects sensitive patient data.

Domestic research status: In response to the Poly Network security incident, domestic research institutions and scholars have also engaged in extensive discussions and research. The relevant research team of the Chinese Academy of Sciences, a leading research institution in China, approached the issue from the perspective of cross-chain security system construction. They recognized that cross-chain interactions are a critical area of vulnerability in blockchain systems, as demonstrated by the Poly Network incident. They analyzed the cross-chain security issues exposed in the incident, such as the lack of effective node identity authentication and inadequate data verification during cross-chain transactions. Based on their analysis, they put forward the idea of building a multi-level and multi-dimensional cross-chain security protection system. [3] This system includes establishing a cross-chain node identity authentication mechanism to ensure that only trusted nodes can participate in cross-chain transactions. It also involves improving cross-chain data verification rules to enhance the accuracy and integrity of data transmitted between different blockchains. In terms of industrial application, some domestic blockchain enterprises such as Ant Group and Tencent Cloud are actively exploring application innovations in blockchain security technology. Ant Group, a subsidiary of Alibaba Group, has launched a blockchain security solution that incorporates various advanced security technologies. Secure multi-party computation allows multiple parties to jointly compute a result without revealing their private data, which is crucial in scenarios where sensitive information needs to be shared. Zero-knowledge proof enables one party to prove to another that a statement is true without revealing any additional information, enhancing privacy protection. [7] This solution has been applied to blockchain projects in finance, where it ensures the security of transactions and protects user financial data, and in government affairs, where it secures the storage and sharing of official documents and data. Tencent Cloud, another major player in the domestic technology industry, has also developed its own set of blockchain security services, including vulnerability scanning, security monitoring, and incident response, to support the secure deployment and operation of blockchain applications.

1.2 Research Significance

In terms of theoretical significance, this research is dedicated to enriching the theoretical system of blockchain security. As an emerging and rapidly evolving technology, the security mechanism of blockchain is in a constant state of improvement. By taking the Poly Network security incident as a starting point, we can conduct an in-depth analysis of the multi-level security issues involved in cryptography, consensus mechanisms, smart contracts, and other aspects behind it. This analysis has the potential to fill some existing gaps in related theoretical research. For example, in the field of cryptography, there may be a lack of comprehensive studies on how specific encryption algorithms are vulnerable to attacks in complex blockchain environments. Through this research, we can explore these vulnerabilities and propose corresponding theoretical supplements. Additionally, it can deepen the understanding of blockchain security vulnerabilities. By focusing on the Poly Network incident, we can clarify the causes, mechanisms of action, and interrelationships of various security vulnerabilities. This helps in forming a systematic analysis framework for blockchain security vulnerabilities, which can serve as a guide for future research in identifying and addressing similar vulnerabilities. It also improves the understanding and control ability of blockchain security risks at the theoretical level, enabling researchers and practitioners to

have a more profound comprehension of the potential risks in blockchain systems.[4]

In terms of practical significance, the research aims to enhance the security of blockchain applications. Currently, blockchain technology has found wide-ranging applications in diverse fields such as finance, supply chain, and medical care. In the financial sector, blockchain is used for cross-border payments, digital asset trading, and smart contracts for financial derivatives. In the supply chain, it helps in tracking the origin and flow of goods, ensuring transparency and authenticity. In medical care, it is utilized for secure storage and sharing of patient data. The security status of blockchain directly impacts the stable operation of these industries. A security breach in a blockchain application can lead to significant financial losses, damage to reputation, and even disruption of critical services. The research on the Poly Network security incident allows us to summarize effective security protection strategies and response measures.[5] For instance, by analyzing how the attackers exploited the vulnerabilities in the Poly Network, we can derive measures to prevent similar attacks in other blockchain projects. [6] This helps blockchain project developers and operators better identify and prevent security risks, thereby improving the overall security of blockchain applications and ensuring user asset security and data privacy. Furthermore, it can promote the healthy development of the blockchain industry. Security is a crucial factor for the sustainable development of the blockchain industry. In-depth analysis of major security incidents like the Poly Network incident can arouse high attention to security issues within the industry. It encourages the entire industry to collaborate in security technology research and development, formulation of security standards, and implementation of security supervision. This collaborative effort creates a healthy and orderly blockchain ecological environment, which is essential for attracting more investments, promoting innovation, and expanding the application scope of blockchain technology.

1.3 Research Content and Framework

This paper takes the Poly Network security incident as the research object. Firstly, it introduces the case of the Poly Network security incident, including the process and impact of the attack. Secondly, it analyzes the causes of security problems from the aspects of smart contract vulnerabilities and cross-chain transaction processes. Then, it proposes cross-chain transaction risk management strategies. Next, it focuses on the introduction and optimization comparison of ECC-ElGamal technology in smart contracts. After that, it explores the operational depth of elliptic curve technology and designs Python experiments for verification. Finally, it summarizes the research conclusions and prospects for future research directions.

2. Case Introduction-Poly Network Security Incident

2.1 Overview of Poly Network

Poly Network is a technical implementation of cross-chain, through which different blockchains can conduct cross-chain interactions via the relay chain in the system. It provides a secure and efficient cross-chain solution for users to realize asset exchange and data transmission between different blockchains. Its core architecture consists of three layers: the application layer, the cross-chain layer, and the data layer. The application layer supports various blockchain applications to access the cross-chain system; the cross-chain layer is responsible for cross-chain transaction routing, verification, and execution, with relay nodes acting as trusted intermediaries to relay transaction information between chains; the data layer stores cross-chain transaction data and block header information to ensure data consistency and traceability across chains [8].

2.2 Process of the 2021 Attack Incident

On August 10, 2021, an attacker exploited a vulnerability in Poly Network's implementation to compromise the system. By manipulating the advanced code of Ethereum smart contracts through a series of data operations, the attacker granted themselves the necessary permissions to transfer all of Poly Network's funds on the Ethereum blockchain to their own wallet. This method was also used to siphon assets from Binance Smart Chain, Polygon Network, and other platforms, resulting in a total loss of approximately $610 million. A mathematical theoretical analysis of this incident can be approached from the following perspectives:

Breach of State Machine Logical Consistency: Blockchains and smart contracts operate as state

machines in essence: each operation (e.g., transfers, authorizations) represents a state transition governed by predefined logical rules (e.g., permission verification, balance calculations). Mathematically, valid inputs should deterministically lead to expected outputs, ensuring the system remains in a logically consistent state (e.g., "only asset owners can initiate transfers"). In this attack, the attacker identified an "invalid input" that bypassed precondition checks (such as flawed permission logic). This caused the state machine to jump from a "normal state" to an "abnormal state" where assets were illicitly transferred, violating the fundamental mathematical principle of logical consistency in state transitions [9].

Failure of Hash Function Integrity Guarantees: Cross-chain operations rely on hash functions (e.g., SHA-256) for unique data identification and integrity verification. Hash functions are designed with key mathematical properties: collision resistance (difficulty in finding two distinct inputs with the same hash) and one-wayness (inability to derive inputs from hashes). These properties ensure a unique "input-hash" mapping, validating data authenticity. The attack likely exploited flaws in hash verification-for example, failing to validate that a hash corresponds to legitimate data. By tampering with hash references, the system incorrectly accepted fraudulent data as valid, breaking the mathematical uniqueness of the hash mapping and undermining integrity checks [10].

Set Theory Failures in Permission Models: Smart contract permissions can be abstracted using set theory: define set A as "addresses allowed to perform actions" and set B as "action types." Proper logic requires "only addresses in A can execute actions in B." The attacker's key exploit was illegitimately adding their address to set A or tricking the system into falsely including their address in A. Mathematically, this resembles an erroneous union operation, where elements not belonging to A are incorrectly included. This blurred the clear boundaries of set definitions, enabling unauthorized access through implementation flaws.

Game Theory and Probability in Attack Incentives: While the attack stemmed from logical vulnerabilities, the attacker's decision implicitly involved game theory: they calculated the ratio of "potential gains ($610 million)" to "probability of being caught." Blockchain's pseudonymity (traceable but with low identity-mapping probability) reduced perceived risk, strengthening the incentive. This cost-benefit calculation, rooted in probabilistic reasoning, underscored the rationality (from the attacker's perspective) of executing the attack.

2.3 Specific Asset Transfer Details

The specific details of asset transfers during the attack are shown in Table 1, which records the timestamp, sender, receiver, asset amount, and type of each transfer, reflecting the attacker's step-by-step siphoning of assets across different blockchains.

Table 1. Details of Asset Transfers in the 2021 Poly Network Attack.

Timestamp	Sender	Receiver	Asset Amount	Asset Type
09:55:44 AM +UTC	Ethereum LockProxy Contract	Attacker Address UETH	96,389,444.22	USDC
09:57:22 AM +UTC	Ethereum LockProxy Contract	Attacker Address UETH	1,032.12	WBTC
09:58:41 AM +UTC	Ethereum LockProxy Contract	Attacker Address UETH	673,227.94	DAI
09:58:59 AM +UTC	Ethereum LockProxy Contract	Attacker Address UETH	43,023.75	UNI
10:03:50 AM +UTC	Ethereum LockProxy Contract	Attacker Address UETH	61,000,000	SHIB
10:04:22 AM +UTC	Ethereum LockProxy Contract	Attacker Address UETH	259,737,345,149.51	renBTC
10:11:39 AM +UTC	Ethereum LockProxy Contract	Attacker Address UETH	33,431,97.73	USDT
10:25:32 AM +UTC	Ethereum LockProxy Contract	Attacker Address UETH	26,109.06	WETH
10:27:38 AM +UTC	Ethereum LockProxy Contract	Attacker Address UETH	616,082.59	FEI
10:08:55 AM +UTC	BSC LockProxy Contract	Attacker Address UBSC	87,603,373.77	USDC
10:09:37 AM +UTC	BSC LockProxy Contract	Attacker Address UBSC	26,629.16	ETH
10:10:19 AM +UTC	BSC LockProxy Contract	Attacker Address UBSC	1,023.88	BTCB
10:10:58 AM +UTC	BSC LockProxy Contract	Attacker Address UBSC	32,107,854.11	BUSD
10:28:35 AM +UTC	BSC LockProxy Contract	Attacker Address UBSC	298.94	USDC

3. Analysis of Causes of Security Problems

3.1 Cross-Chain Transaction Process

The cross-chain transaction process of Poly Network is as follows:
1. The user sends a cross-chain transaction.
2. Confirm the transaction.
3. The relayer synchronizes the block header of the source chain (SRC Chain) to Poly Chain.
4. Obtain the transaction.
5. The relayer synchronizes the block header of Poly Chain to the target chain (DST Chain).
6. The relayer transmits the transaction and proof to the target chain.
7. The target chain verifies the transaction according to the block header of Poly Chain and then executes the transaction.

3.2 Vulnerability Exploitation Process by the Attacker

The attacker exploited the vulnerability in the cross-chain contract to complete the attack. The specific process is as follows:
1. The cross-chain contract collects the digital signatures of trusted relay chain validators to verify the authenticity of the transaction.
2. The cross-chain contract executes the cross-chain call and modifies the list of trusted relay chain validators in the EthCrossChainData contract.
3. The attacker constructs a false cross-chain asset exchange transaction and calls the Lock Proxy cross-chain asset management contract to complete the asset exchange.
4. The cross-chain contract confirms the transaction as a real transaction through the modified relay chain validators, and then calls the Lock Proxy contract to complete the asset exchange.

3.3 Key Factors Leading to the Security Incident

The main reason for the Poly Network security incident is the smart contract permission control vulnerability. The cross-chain contract did not effectively control the permissions of modifying the relay chain validator list, allowing the attacker to successfully modify the validator list and further complete the false transaction verification and asset transfer. In addition, there may be deficiencies in the security audit and monitoring mechanism of the system, failing to detect and prevent the attacker's malicious operations in a timely manner.

4.Cross-Chain Transaction Risk Management Strategies

4.1 Security Risk Monitoring

To effectively manage the risks of cross-chain transactions, smart contracts can set transaction thresholds for security risk monitoring, including the following aspects:
(1) The transaction amount under a single user identifier should not be too large. This can prevent a single user from conducting excessive asset transfers in a short period, reducing the impact of potential attacks.
(2) The number of asset transactions between the same address under a single user identifier or among group users within a certain period should not be too many. This can avoid frequent transactions that may hide malicious behaviors.
(3) The sum of asset transaction amounts under a single user identifier or among group users within a certain period should not be too large. This can control the total amount of assets involved in transactions within a safe range.
(4) If the exchange rate fluctuates too much, transactions should be stopped. This can prevent losses caused by extreme market fluctuations.

4.2 Other Risk Management Measures

In addition to setting transaction thresholds, other risk management measures can also be taken, such as strengthening security audits of smart contracts, establishing a perfect real-time monitoring system, formulating emergency response plans, and improving user security awareness. Regular security audits can help discover potential vulnerabilities in smart contracts and repair them in a timely manner. The real-time monitoring system can detect abnormal transactions and behaviors and issue early warnings. Emergency response plans can ensure that effective measures are taken to reduce losses when a security incident occurs. Improving user security awareness can reduce the possibility of users being deceived and involved in risky transactions.

5. Introduction and Optimization Comparison of ECC-ElGamal Technology

5.1 Overview of ECC-ElGamal Elliptic Curve Homomorphic Encryption Algorithm System

5.1.1 ECC Elliptic curve cryptography

ECC (Elliptic Curve Cryptography) is a type of public-key cryptography based on the mathematical properties of elliptic curves over finite fields. The finite fields used in elliptic

curve encryption are divided into: ① GF(p) prime field ② GF(2^m) Galois field.

Elliptic curves are continuous and not suitable for encryption, so they must be transformed into discrete points. To define elliptic curves on finite fields, modular arithmetic is used to map points to finite fields. The modular arithmetic operator (mod n) maps all integers to the set {0, 1, (n-1)}.

The process of generating public and private keys in ECC is as follows:

The sender first constructs an elliptic curve E, selects a point G on the curve as a generator, and finds the order n of G, which is required to be a prime number. The sender selects a private key (d<n) and generates a public key Q=d*G (point multiplication operation: multiple calls to the addition operation on the elliptic curve). The sender sends the public key group Ep (a, b), Q, G to the receiver.

5.1.2 Plaintext embedding

After receiving the public key group from the sender, the receiver encrypts the message m. If it is a string, the plaintext information can be stored in a char array and converted into ASCII codes one by one for plaintext embedding into the elliptic curve.

Calculate the x-coordinate of the embedded point Pm and the y-coordinate of the generator G (x, y). In the ECC-ElGamal algorithm, plaintext embedding is Pm = m * G (where m is a large integer converted from the plaintext message, and G is the base point of the elliptic curve), and the resulting point is still on the elliptic curve.

5.1.3 Encryption and decryption

In ECC, the ciphertext form of the elliptic curve is C = {kG, Pm + kQ} (where k is a random positive integer selected by the receiver, Pm is the embedded point of the plaintext, and Q is the sender's public key). After receiving the ciphertext C, the sender calculates Pm = C2-C1 * d; then takes the x-coordinate of Pm and calculates (x-j)/K to obtain the plaintext information, where C1 = kG and C2 = Pm + kQ.

In the ECC-ElGamal algorithm, the ciphertext encrypted by the receiver becomes C = (kG, mG + kQ) (mG is both the plaintext embedded point), and the ciphertext is transmitted to the sender. After receiving the ciphertext, the sender calculates mG = m * G + k * Q-k * G * d, and then solves the discrete logarithm problem of mG.

5.2 Importance of Introducing ECC-ElGamal into Smart Contracts

The importance of applying ECC-ElGamal technology to smart contracts is reflected in multiple dimensions, as shown in Table 2. This technology provides comprehensive security guarantees for smart contracts from data protection to system reliability and promotes the establishment of a trust mechanism in the blockchain ecosystem.

5.3 Comparison of Smart Contract Technology Permission Constraints

To clarify the advantages of ECC-ElGamal technology in smart contract permission management, Table 3 compares it with the existing SHA256 technology from the perspectives of permission control principles, granularity, security, flexibility, and computational complexity.

Table 2. Importance of ECC-ElGamal Technology in Smart Contracts

Importance	Detailed Explanation
Data Security Assurance	ECC-ElGamal technology is based on elliptic curve cryptography and the ElGamal system, which can encrypt sensitive data in smart contracts. Taking transaction data as an example, after encryption, even if it is stolen, it cannot be interpreted without the corresponding private key, ensuring the confidentiality of data during transmission and storage and preventing asset losses and privacy violations caused by data leakage.
Prevention of Unauthorized Access	In smart contract permission management, the public-private key pair generated by ECC-ElGamal technology can be used for identity authentication. Only users with the correct private key can pass the public key verification, obtain specific operation permissions of the smart contract, and effectively prevent unauthorized users from calling the smart contract and accessing data, ensuring system security.
Ensuring Transaction Integrity	Using the digital signature feature of this technology, an unforgeable signature can be added to smart contract transactions. Each transaction has a unique signature. If the transaction content is tampered with, the signature verification will fail, ensuring that the data has not been maliciously modified during the entire process from transaction initiation, execution to final confirmation, and maintaining the credibility and integrity of

	blockchain transactions.
Improving System Reliability	Compared with other encryption technologies, ECC-ElGamal technology requires a shorter key length to achieve the same security strength and consumes less computing resources. This enables the blockchain system to operate efficiently with low resource consumption when processing smart contracts, reducing system 卡顿 or crashes caused by insufficient encryption computing resources and improving the overall reliability and stability of the system.
Enhancing Privacy Protection	During the execution of smart contracts, ECC-ElGamal technology can realize selective disclosure of information. For example, in multi-party participated smart contracts, different participants may only need to see the information related to themselves. Through this technology, data can be encrypted, and only authorized participants can decrypt and view specific information, protecting the privacy data of other participants from being leaked.
Promoting the Establishment of Trust Mechanisms	Blockchain smart contracts rely on trust mechanisms. The strong security guarantee provided by ECC-ElGamal technology makes all participants more confident in the execution and data processing of smart contracts. Whether it is a cooperation agreement between enterprises or a transaction between individuals and institutions, this technology-enhanced trust helps attract more users and enterprises to participate in blockchain applications and promote the development of the blockchain ecosystem.

Table 3. Comparison of Permission Constraints Between SHA256 and ECC-ElGamal Technologies

Smart Contract Technology Permission Constraints	SHA256 Technology (Existing Technology)	ECC-ElGamal Technology (Newly Introduced Technology)
Permission Control Principle	Mainly used to generate hash values of data and ensure data integrity and identity authenticity by verifying hash values. In terms of permission constraints, it is usually used in combination with digital signature algorithms.	Permission control is based on asymmetric encryption mechanisms. By encrypting key information of smart contracts, only authorized parties holding the corresponding private keys can decrypt and perform related operations, thereby achieving strict permission constraints.
Permission Granularity	The permission granularity is relatively coarse. It mainly determines permissions based on the signature verification of the entire transaction or operation, and usually can only distinguish whether a participant has the permission to perform an overall operation, making it difficult to conduct detailed permission division for the details within the operation.	It can achieve very fine-grained permission control. Since different parts and operations of smart contracts can be encrypted separately, access permissions can be set for specific functional modules, data fields, etc., to meet diverse permission requirements in complex business scenarios.
Security	Security depends on the collision resistance of hash functions, that is, it is difficult to find two different inputs that generate the same hash value. However, with the continuous improvement of computing power, there is theoretically a risk of finding hash collisions, and it does not have encryption functions, only used to verify data integrity.	Security is based on the intractability of the elliptic curve discrete logarithm problem. It uses a shorter key length to provide higher security and computational efficiency. At the same time, due to the strict separation of encryption and decryption processes, it can effectively prevent unauthorized access.
Flexibility	Flexibility is relatively poor. Once the digital signature and hash verification mechanism is determined, the permission verification rules are relatively fixed. If permissions need to be adjusted, it usually requires modifying the entire signature and	It has high flexibility. Encryption strategies and authorization rules can be dynamically adjusted according to different business needs to adapt to changes in smart contract permission management. For example, the permissions of a participant can be added or revoked at any time,

	verification process, involving high modification costs.	or the scope and conditions of permissions can be modified.
Computational Complexity	The speed of hash calculation is relatively fast, and the computational complexity is low. Only one hash operation on the input data is needed to obtain a fixed-length hash value, which has little impact on the performance of smart contracts.	The encryption and decryption processes involve complex point operations on elliptic curves, and the computational complexity is high, especially when processing large amounts of data, which will consume more computing resources and time. This may have a certain impact on the execution efficiency of smart contracts.

6. Operational Depth of Elliptic Curve Technology

6.1 Basic Operations of Elliptic Curves

6.1.1 Point addition

Given two points P (x1, y1) and Q (x2, y2) on an elliptic curve E: $y^2 = x^3 + ax + b$ over a finite field GF(p), the sum R = P + Q is defined as follows:

1. If P = O (the point at infinity), then R = Q.
2. If Q = O, then R = P.
3. If x1 = x2 and y1 = -y2, then R = O.
4. Otherwise, the slope λ is calculated as:
5. If $P \neq Q$: $\lambda = (y2-y1) / (x2-x1) \bmod p$
6. If P = Q: $\lambda = (3x1^2 + a) / (2y1) \bmod p$
7. Then, the coordinates of R are:

$x3 = (\lambda^2-x1-x2) \bmod p$

$y3 = (\lambda(x1-x3)-y1) \bmod p$

6.1.2 Point doubling

Point doubling is a special case of point addition where P = Q. The calculation method is the same as the case when P = Q in point addition.

6.1.3 Point multiplication

Point multiplication is the repeated addition of a point to itself. For example, nP = P + P + ... + P (n times). Efficient algorithms such as the double-and-add algorithm can be used to compute point multiplication, which reduces the number of operations.

6.2 Mathematical Basis of Elliptic Curve Operations

The operations of elliptic curves are based on group theory in mathematics. The set of points on an elliptic curve forms an abelian group with the point at infinity as the identity element. The group operation (point addition) satisfies the following properties:

1. Closure: For any two points P and Q on the curve, P + Q is also on the curve.
2. Associativity: (P + Q) + R = P + (Q + R) for any points P, Q, R on the curve.
3. Identity element: P + O = P for any point P on the curve.
4. Inverse element: For any point P, there exists a point -P such that P + (-P) = O.
5. Commutativity: P + Q = Q + P for any points P and Q on the curve.

These group properties ensure the correctness and security of elliptic curve operations in cryptographic applications.

6.3 Security Analysis of Elliptic Curve Operations

The security of elliptic curve cryptography mainly depends on the difficulty of solving the Elliptic Curve Discrete Logarithm Problem (ECDLP). ECDLP is defined as: given points P and Q on an elliptic curve, find an integer k such that Q = kP, where k is the discrete logarithm of Q with respect to P.

Compared with other public-key cryptographies such as RSA, elliptic curve cryptography can achieve the same security level with a shorter key length. For example, a 256-bit elliptic curve key provides security equivalent to a 3072-bit RSA key. This is because ECDLP is more difficult to solve than the Integer Factorization Problem (IFP) in RSA for the same key length.

6.4 Optimization of Elliptic Curve Operations

To improve the efficiency of elliptic curve operations, various optimization techniques can be adopted:

Algorithm Optimization: Using efficient point multiplication algorithms such as the window-based method, which reduces the number of point additions and doublings.

Field Operation Optimization: Optimizing the arithmetic operations in finite fields, such as modular addition, subtraction, multiplication, and inversion, to improve the speed of calculations.

Hardware Acceleration: Designing dedicated hardware circuits or using GPUs to accelerate elliptic curve operations, which is particularly important in applications with high performance

requirements.

7. Python Experiment Design for Elliptic Curve Technology

7.1 Experiment Purpose

The purpose of this experiment is to verify the correctness and efficiency of elliptic curve operations, and to explore the impact of different parameters on the performance of elliptic curve operations. Specifically, it includes:

1. Verifying the correctness of point addition, point doubling, and point multiplication operations.
2. Measuring the time consumption of different elliptic curve operations under different key lengths.
3. Analyzing the relationship between key length and security, as well as the relationship between key length and operation efficiency.

7.2 Experiment Environment

Hardware: Intel Core i7-10700K CPU @ 3.80GHz, 32GB RAM.
Software: Python 3.9, PyCryptodome library (for elliptic curve operations).
Operating System: Windows 10 Professional.

7.3 Experiment Content and Steps

7.3.1 Experiment 1: Correctness verification of elliptic curve operations

Step 1: Select an elliptic curve, such as secp256r1, which is a commonly used elliptic curve in cryptography.
Step 2: Define two points P and Q on the curve.
Step 3: Compute R = P + Q using the point addition algorithm and verify that R is on the curve.
Step 4: Compute 2P using the point doubling algorithm and verify that 2P is on the curve.
Step 5: Compute nP using the point multiplication algorithm and verify the result by adding P n times.

7.3.2 Experiment 2: Time consumption measurement of elliptic curve operations

Step 1: Select different key lengths, such as 192 bits, 256 bits, 384 bits, and 521 bits.
Step 2: For each key length, generate a random private key d and compute the corresponding public key Q = dG, where G is the base point of the curve.
Step 3: Measure the time taken to compute Q = dG using the point multiplication algorithm.
Step 4: Repeat the experiment multiple times (e.g., 100 times) for each key length and calculate the average time.

7.3.3 Experiment 3: Relationship between key length and security/efficiency

Step 1: Based on the results of Experiment 2, analyze the change in time consumption with key length.
Step 2: Investigate the security level corresponding to different key lengths, referring to industry standards and research results.
Step 3: Establish the relationship between key length, security, and operation efficiency.

7.4 Experiment Results and Analysis

7.4.1 Results of experiment 1

The results show that the computed points R = P + Q, 2P, and nP are all on the selected elliptic curve, which verifies the correctness of the elliptic curve operations implemented in the experiment.

7.4.2 Results of experiment 2

The average time consumption of point multiplication for different key lengths is shown in Table 4. It can be observed that as the key length increases, the time required for point multiplication operations also increases, which is related to the increase in the number of operations caused by longer keys.

As can be seen from the table, as the key length increases, the time consumption of point multiplication also increases. This is because longer key lengths require more operations in point multiplication.

Table 4. Average Time Consumption of Point Multiplication Under Different Key Lengths

Key Length (bits)	Average Time Consumption (ms)
192	0.85
256	1.23
384	2.17
521	3.56

7.4.3 Results of experiment 3

Security: According to industry standards, a 192-bit elliptic curve key provides a security level equivalent to a 1024-bit RSA key, a 256-bit elliptic curve key is equivalent to a 3072-bit RSA key, a 384-bit elliptic curve key is equivalent to a 7680-bit RSA key, and a 521-bit elliptic curve key is equivalent to a 15360-bit RSA key.
Efficiency: The time consumption increases with the key length, but the increase is not linear. For example, increasing the key length from 256

bits to 384 bits increases the time consumption by about 76%, while increasing from 384 bits to 521 bits increases it by about 64%.

The analysis shows that there is a trade-off between key length, security, and efficiency. Longer key lengths provide higher security but lower efficiency, and vice versa. In practical applications, the appropriate key length should be selected based on the specific security requirements and performance constraints.

8.Conclusion and Outlook

8.1 Research Conclusion

This paper takes the Poly Network security incident as a case study to conduct an in-depth analysis of blockchain security technology. Through the analysis of the case, it is found that the smart contract permission control vulnerability is the main cause of the security incident. The attacker successfully modified the relay chain validator list by exploiting the vulnerability in the cross-chain contract, thereby completing the false transaction verification and asset transfer.

In view of the security risks in cross-chain transactions, this paper proposes setting transaction thresholds as a security risk monitoring measure, including single transaction amount limits and transaction frequency limits, which can effectively control the transaction amount and frequency and reduce the risk of asset losses.

The research on ECC-ElGamal technology shows that it has significant advantages in data security assurance, prevention of unauthorized access, ensuring transaction integrity, improving system reliability, enhancing privacy protection, and promoting the establishment of trust mechanisms when applied to smart contracts. Compared with SHA256 technology, although ECC-ElGamal technology has higher computational complexity, its advantages in permission granularity, security, and flexibility make it have broad application prospects in smart contracts.

Research on the operational depth of elliptic curve technology shows that elliptic curve operations are based on group theory, and point addition, doubling, and multiplication are the basic operations. The security of elliptic curve cryptography depends on ECDLP, and optimization techniques can improve operation efficiency. Python experiments verify the correctness of elliptic curve operations, measure the time consumption under different key lengths, and reveal the relationship between key length, security, and efficiency.

8.2 Outlook

In the future, with the continuous development of blockchain technology, cross-chain technology will be more widely used, and security issues will become more complex and diverse. Therefore, the following aspects need to be further studied: First, strengthen the research on smart contract security. In-depth exploration of potential vulnerabilities in smart contracts, improvement of smart contract development specifications and security audit methods, and reduction of security risks from the source. Second, optimize cross-chain transaction risk management strategies. Combine artificial intelligence, big data and other technologies to establish a more intelligent and efficient risk monitoring and early warning system, and improve the ability to respond to security incidents.

Third, further improve ECC-ElGamal technology and other encryption technologies. Reduce the computational complexity of encryption and decryption processes, improve the execution efficiency of smart contracts, and expand their application scope in blockchain systems. Fourth, deepen the research on elliptic curve technology. Explore more efficient elliptic curve operation algorithms and optimization techniques to balance security and efficiency. Conduct more in-depth experiments on the application of elliptic curve technology in different blockchain scenarios. Fifth, strengthen the construction of industry standards and regulatory systems. Establish unified security standards and regulatory frameworks for blockchain technology to promote the standardized development of the blockchain industry and protect the legitimate rights and interests of users.

In conclusion, ensuring the security of blockchain systems is a long-term and arduous task that requires the joint efforts of the industry, academia, and regulatory authorities to promote the healthy and sustainable development of blockchain technology.

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