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Construction and Security Protection of a Private Computation System Based on Quantum Cryptography-Blockchain Integration

Xiao Zhang

School of Computer Science, Guangdong University of Technology, Dongguan, Guangdong, 523000, China

ABSTRACT
As digitalization advances, data has become a core production factor. Data encryption computing and protection hold significant implications for national security, economic development, and social governance. This study addresses the current landscape characterized by frequent global data breaches, prominent conflicts between efficiency, security, and usability, security gaps in emerging scenarios, and the intensive introduction of data security regulations worldwide. The research categorizes technologies based on their lifecycle, analyzes encryption strategies according to application scenarios, and assesses risks from security threat perspectives. Findings indicate that a multi-layered protection architecture has emerged, with breakthroughs in privacy-preserving computing and advancements in frontier technologies like post-quantum cryptography. This study provides guidance for enterprise technology selection, facilitates industrial standard development, supports critical information infrastructure upgrades, and lays the foundation for building a trustworthy digital society and promoting secure digital economic development.

KEYWORDS
Data encryption computing; Privacy-preserving methods; Post-quantum cryptography; Quantum key distribution (QKD)

1 Introduction

Driven by the digital wave, data has become a core production factor for global economic development and social governance. However, the tension between unlocking its value and ensuring its security has grown increasingly prominent. Data encryption computing and protection technologies have evolved from mere technical tools into strategic pillars safeguarding national security, economic stability, and social trust. According to the 2024 Verizon report, global data breaches are growing exponentially, with small and medium-sized enterprises (SMEs) accounting for 43% of attack targets. The average cost per breach reaches $4.35 million, while a multinational healthcare group suffered the leakage of 5 million patient records due to encryption vulnerabilities. Concurrently, nations are intensifying data security regulations. China's Data Security Law mandates end-to-end encryption for critical data throughout its lifecycle, while the EU's GDPR imposes fines of up to 4% of global revenue for violations. This compliance pressure propelled the global encryption technology market to $78 billion in 2024, with finance, government, and healthcare accounting for over 60% of demand. Yet behind technological evolution and application expansion, conflicts between efficiency, security, and usability grow increasingly pronounced: Fully homomorphic encryption slows neural network inference significantly compared to plaintext computation; RSA/ECC traditional encryption relied upon by 80% of global enterprises faces potential threats from quantum computing's Shor algorithm; differential privacy in medical image analysis (when privacy parameter $\varepsilon=1$) reduces lesion detection accuracy by 8-12%. At the management level, cross-regional operations must simultaneously comply with multiple standards like GDPR, China's Grade 2.0 Information Security Protection, and HIPAA. A multinational bank was fined $230 million due to conflicting policies. Emerging security gaps—such as low-power IoT devices struggling to support AES-256 encryption and delays in hybrid cloud key synchronization—further exacerbate data security risks. Building an efficient, secure, and adaptable encryption protection system has become an urgent necessity for digital economic development.

A multi-tiered technical architecture spanning foundational encryption to cutting-edge privacy computing has emerged globally. While research achievements provide crucial support for data security, significant disparities and room for improvement remain. International research laid the theoretical foundation for modern cryptography: Diffie and Hellman introduced public-key cryptography concepts and the Diffie-Hellman key exchange algorithm in 1976, while Rivest et al.'s RSA algorithm—still widely used in SSL/TLS and other scenarios—was proposed in 1978. In cutting-edge domains, NIST designated CRYSTALS-Kyber and CRYSTALS-Dilithium—both lattice-based cryptosystems—as the first post-quantum cryptographic standards in 2022. The fourth round of post-quantum cryptography proposals commenced in 2023, with formal standards slated for release in 2024. MIT researchers enhanced the NTRU Prime algorithm, tripling its key generation speed. DeepMind's 2024 neural cryptography framework further optimizes encryption parameters via GANs, tripling image encryption's resistance to differential attacks. Domestic research focuses on building autonomous technology systems and scenario-based innovation: Feng Dengguo systematically analyzed elliptic curve cryptography fundamentals and supported SM2 algorithm engineering applications; Wang Xiaoyun dissected SM4 algorithm's Feistel structure design principles, providing methodology for domestic symmetric cryptography; Ren Kui's 2015 cloud computing data lifecycle security framework reduced storage verification complexity from O(n) to O(1), adopted by Huawei and H3C and incorporated into national standards; Mao Ming's team achieved international standardization

breakthroughs with optimized SM3 hash algorithms, reaching 2557.72 Gb/s throughput while reducing power consumption by 42%; In cutting-edge research, Li Mengdong and Wang Xiaoyun designed the subversion-resistant SM9 algorithm (SR-SM9), which immunizes against subversion attacks with only a 0.6% increase in computational cost. Pan Jianwei's team achieved the integrated application of quantum key distribution (QKD) and post-quantum cryptography (PQC), maintaining stable operation for 36 days in a 14-node live network environment with a coding rate error below 2%.

Despite significant progress, three critical challenges remain: First, inadequate technological adaptability—existing encryption schemes struggle to balance multi-scenario demands. Generic privacy frameworks often overprotect or underprotect in healthcare and finance due to neglecting industry-specific data characteristics and business logic, while customized solutions incur prohibitively high cross-scenario reuse costs. Second, a disconnect exists between technical understanding and practical implementation. Explanations of core technical principles lack quantitative support. For instance, homomorphic encryption literature often qualitatively describes "error accumulation due to increased modular operation depth" without specifying concrete data like the plaintext recovery error rate after 10 layers of multiplication in BFV schemes. Similarly, integrated research on "AI + encryption" or " Blockchain + Privacy Protection" often lack logical consistency. For instance, Ethereum's zk-SNARKs deployment fails to account for smart contract gas fees' impact on proof efficiency. Third, the literature system is chaotic, with no unified standards for classifying cryptographic technologies (e.g., homomorphic encryption is categorized under both "privacy computing" and "fundamental cryptographic algorithms"). Terminology diverges across domains ("secure multi-party computation" is termed SMPC in computer science and "privacy computing federation model" in finance). Emerging application scenarios lack systematic linkage with foundational theories, severely hindering cross-research comparisons and technological integration.

Given these challenges, this paper focuses on data encryption computing and protection methods. It aims to clarify the evolution trajectory and application boundaries of these technologies by systematically reviewing domestic and international research. Through literature analysis and comparative case studies, it quantitatively assesses differences in efficiency, security, and scenario adaptability across various encryption techniques. To address issues like insufficient technical adaptability and disconnect between theoretical knowledge and practical implementation, this paper explores innovative pathways integrating quantum cryptography, post-quantum cryptography, and blockchain trust mechanisms. It proposes dynamic encryption strategies and traceable evidence solutions, ultimately providing technical selection references for sectors such as finance, healthcare, and smart cities. This work supports secure compliance and efficient application under market-driven data allocation, contributing to the construction of a trustworthy digital society.

2 Research methodology

Centered on core research objectives in data encryption computing and protection methods, this study adopts a three-tiered framework of "theoretical review-technical comparison-practical validation." It systematically conducts research through literature review, comparative analysis, and case studies, designed as follows:

2.1 Literature review method

By searching core databases including Web of Science, IEEE Xplore, and CNKI using keywords such as "data encrypted computation," "privacy protection methods," and "post-quantum cryptography," relevant literature from 2000 to 2025 was screened. An analytical sample repository comprising approximately 200 core papers was constructed. Based on a three-dimensional framework of "algorithm type-application scenario-technical dimension, " this method systematizes theoretical achievements, evolutionary trajectories, and research gaps in technologies such as symmetric encryption, asymmetric encryption, quantum encryption, and privacy-preserving computation. This forms a technical characteristics database, laying the theoretical foundation for subsequent research.

2.2 Comparative analysis methodology comparisons are conducted across two dimensions

"Algorithm performance" and "scenario adaptability." At the algorithm performance level, compare the performance differences of mainstream encryption technologies based on metrics such as computational efficiency (encryption/decryption latency, resource consumption) and security (resistance to attacks, privacy protection strength). At the scenario adaptability level, analyze the adaptability boundaries of different encryption technologies for core scenarios like cloud computing, IoT, healthcare, and finance, considering scenario characteristics (e.g., low power consumption for IoT, high compliance requirements for healthcare), to clarify the strengths and weaknesses of each technology.

2.3 Case study methodology three categories of representative cases are selected

Technological innovation, industry application, and policy compliance. Examples include technological cases like IBM's commercial QKD and Microsoft Azure's confidential computing; industry cases such as Mayo Clinic's electronic medical record encryption and Tesla's OTA upgrade security; and policy cases like Deutsche Telekom's GDPR compliance transformation. By deconstructing the encryption scheme design, implementation outcomes, and challenges within these cases, we validate theoretical analysis conclusions, distill practical insights, and simultaneously reveal technical implementation bottlenecks to provide reference for optimization directions.

3 Categorized analysis and discussion of literature review

3.1 Foundational cryptographic theory and architecture literature

Foundational encryption technologies form the underlying support for data security protection. Related literature focuses on analyzing the principles, performance optimization, and systematic organization of traditional technologies such as symmetric and asymmetric encryption, laying the theoretical foundation for subsequent technological innovation.

In his study Research on Data Encryption Technologies, Zhou Rong systematically reviews the core algorithmic logic of symmetric encryption (e. g., DES, AES) and asymmetric encryption (e. g., RSA, ECC) from cryptographic mathematical foundations. By comparing different algorithms' encryption/decryption latency, key length, and resistance to attacks, he reveals the inherent balance between "security, efficiency, and resource consumption" in data encryption technologies. The core value of this literature lies not only in integrating the theoretical framework of traditional encryption technologies but also in addressing practical needs across financial and governmental scenarios. It proposes that "algorithm selection must align with the sensitivity of business data" —for instance, recommending the AES-GCM algorithm for high-concurrency transaction data (balancing efficiency and security) and the ECC algorithm for digital signature scenarios (featuring short keys and fast signing speeds). Furthermore, addressing key management challenges, the paper proposes an optimized approach of "dynamic key updates + hierarchical key systems." This provides actionable theoretical guidance for enterprises building foundational encryption protection systems while offering technical foundations for policymakers refining data security standards.

"Research on Data Encryption Technologies and Privacy Protection in Cyberspace Security" adopts a technology application perspective to review the industrial implementation status of mainstream encryption technologies. The paper details the iterative optimization journey of the AES algorithm in symmetric encryption (security upgrades from AES-128 to AES-256), highlighting its dominant role in cloud storage encryption and database encryption; It also analyzes the limitations of the RSA algorithm in asymmetric encryption (where 2048-bit keys face quantum computing threats) and the advantages of the ECC algorithm (where 160-bit keys offer security equivalent to RSA-1024 while reducing computational overhead by 60%). In the privacy protection section, the literature emphasizes the synergistic application of data anonymization, access control, and encryption technologies. For instance, medical data achieves compliant storage through "anonymization processing + AES encryption," while government data ensures transmission integrity via "role-based access control (RBAC) + ECC signatures. " The paper's innovation lies in its pioneering assertion that "fundamental cryptographic technologies must be deeply integrated with privacy protection mechanisms." This breaks from the previous singular focus on "encryption solely for data security" and identifies current technical challenges—such as traditional cryptography's inability to meet the "compute-while-encrypting" demands of big data scenarios—thereby providing research impetus for the subsequent rise of privacy-preserving computation technologies.

"Research on Data Encryption Technologies and Their Effectiveness in Cyberspace Security" further expands the boundaries of foundational cryptography research. By tracing the evolution of data encryption from "ancient simple substitution ciphers" to "modern public-key cryptosystems," the paper constructs a three-dimensional evaluation model: "technological maturity - scenario adaptability - compliance satisfaction." In the technical effectiveness validation section, the literature analyzes real-world cases: for instance, in financial transaction scenarios, transaction data encrypted with AES-256 reduces leakage risk by 92% compared to unencrypted data, but increases key management costs by 35%. In IoT device scenarios, traditional RSA algorithms struggle to meet low-power device requirements due to high computational complexity (e. g., 500ms latency for 1024-bit key encryption/decryption). Consequently, the literature proposes an "algorithm optimization + hardware acceleration" improvement path—such as reducing computational overhead by simplifying RSA modulus operations or enhancing AES efficiency through integrated specialized encryption chips (e. g., Intel AES-NI instruction set) (encryption speed increased from 1Gbps to 10Gbps). The paper's value lies in quantifying the actual protective effectiveness of foundational encryption technologies while revealing the core issue of "disconnect between theoretical technical advantages and engineering practice demands, " providing direction for subsequent research on lightweight encryption technologies and hardware acceleration solutions.

"Analysis and Comparison of Encryption Algorithms for Big Data Privacy Protection" focuses on technical adaptation challenges in big data scenarios. The paper highlights that big data possesses characteristics of "massiveness, real-time processing, and diversity," presenting three major challenges for traditional encryption technologies: First, efficiency bottlenecks in encrypting massive datasets (e.g., encrypting 10TB of data with AES-256 takes 12 hours, failing to meet real-time processing demands); Second, compatibility issues during multi-source data fusion (e. g., RSA encryption for structured data and AES for unstructured data necessitate frequent algorithm switching during cross-type processing). Third, the conflict between data computation and encryption (traditional encryption requires decryption before computation, introducing data leakage risks). To address these issues, the literature compares the performance of 12 mainstream encryption algorithms in big data scenarios and proposes a "scenario-specific algorithm combination" approach. For instance: It also recommends integrating homomorphic encryption and differential privacy with traditional encryption to achieve dual objectives of "encrypted computation + privacy protection." The core contribution lies in providing quantitative criteria for selecting encryption technologies in big data scenarios, advancing foundational

cryptography toward "scenario-specific and combinatorial" approaches.

3.2 Cutting-edge dryptographic technologies and scenario Innovation literature

With the rise of quantum computing, IoT, and AI, cutting-edge cryptographic technologies have become research hotspots. Related literature focuses on algorithmic innovations, scenario adaptation, and practical validation for techniques like homomorphic encryption, quantum key distribution (QKD), and differential privacy, pushing beyond the application boundaries of traditional cryptography. 3.2.1 Research on Homomorphic Encryption

In "Homomorphic Encryption for Secure Outsourcing of Machine Learning Computations" (IEEE Transactions on Computers, 2023), Song Y et al. address privacy leakage issues in cloud-based machine learning computations by proposing a homomorphic encryption algorithm based on an improved BFV (Brakerski/Fan-Vercauteren) scheme. Traditional homomorphic encryption faces two major bottlenecks: high ciphertext expansion (e. g., 1KB plaintext encrypted to 100MB) and excessive computational latency for complex operations (e.g., neural network inference, which is 1000 times slower than plaintext computation). This paper reduces ciphertext expansion by 40% through optimized polynomial ring parameter selection (increasing ring dimension from 2^13 to 2^15 while controlling noise growth). simultaneously designing a "layered computation + partial decryption" mechanism that reduces neural network inference latency to within 500 times that of plaintext computation. This addresses cloud service providers' demand for "secure outsourced computation" —for instance, medical AI companies can upload encrypted patient imaging data to cloud platforms, which can directly perform lesion identification on encrypted data and return results without decryption. This safeguards patient privacy while enabling AI model reuse. The innovation of this paper lies in its pioneering integration of homomorphic encryption with machine learning scenarios, validating the feasibility of "cryptographic computation" in addressing "data silos" and providing a new pathway for collaborative computing in sensitive data domains like healthcare and finance. The CSDN blog post "New Advances in Data Encryption Technology: Innovative Methods for Protecting Sensitive Information" tracks the industrial standardization progress of homomorphic encryption. The blog mentions that Intel has boosted computational efficiency by threefold through its Intel HE Libraries. Microsoft, meanwhile, has integrated homomorphic encryption services into its Azure cloud platform, enabling users to perform basic arithmetic operations like addition, subtraction, multiplication, and division on encrypted data in the cloud. Additionally, the blog introduces the technical approach proposed by the MIT team for "transitioning from semi-homomorphic to fully homomorphic encryption"—combining multiple semi-homomorphic encryption schemes (e.g., the Paillier scheme for addition and the Goldwasser-Micali scheme for multiplication) to achieve "limited-time fully homomorphic computation." This approach has enabled "credit score calculations on encrypted data" in financial risk control scenarios, with a computational accuracy error rate of only 2.1% compared to plaintext calculations. The value of this literature lies in supplementing the practical implementation progress of homomorphic encryption technology from an industrial perspective. It reveals that "technology standardization + hardware acceleration" is key to advancing the industrialization of cutting-edge technologies. It also highlights ongoing challenges—such as the computational efficiency of fully homomorphic encryption still struggling to meet the demands of complex AI models (e. g., deep learning), necessitating further optimization of algorithmic structures.

3.2.1 Research on quantum key distribution (QKD) technology

Wang X et al. in "Quantum Key Distribution for Secure Internet of Things Communications: A Survey" (IEEE Internet of Things Journal, 2024) systematically analyzed the adaptability of QKD technology to address security pain points in IoT scenarios (resource-constrained devices, complex transmission links, diverse attack methods). The literature indicates that QKD, grounded in quantum mechanics' "Uncertainty Principle" and "Quantum Non-Cloning Theorem," theoretically enables "unconditionally secure" key distribution, addressing the quantum computing threats faced by traditional encryption techniques (e.g., RSA, ECC). By comparing QKD with traditional key distribution technologies, the study found that between IoT endpoints (e.g., smart home sensors, industrial IoT gateways), QKD achieves key generation rates up to 1 Mbps (meeting real-time encryption demands) and demonstrates significantly superior resistance to man-in-the-middle attacks compared to TLS protocols. However, QKD also has limitations—restricted transmission distance (traditional fiber-based QKD spans approximately 100 kilometers, requiring repeaters for extension), high equipment costs (quantum detectors cost over 100, 000 yuan each), and susceptibility to environmental interference (temperature fluctuations increase key generation error rates to 15%). To address these challenges, the literature reviews recent technical improvements: First, adopting "measurement-device-independent QKD (MDI-QKD)" technology (e.g., Pan Jianwei's team achieved 400 km transmission) to mitigate environmental interference's impact on key security; Second, developing "lightweight QKD terminals" that reduce device power consumption from 10W to 1W (suiting IoT devices' low-power requirements); Third, proposing a "QKD-post-quantum cryptography (PQC) integration" approach—transmitting keys via QKD while authenticating them using the NIST-standardized Kyber algorithm, ensuring long-term security while reducing short-term deployment costs. The core contribution of this paper lies in establishing the first adaptation evaluation framework for "QKD technology in IoT scenarios." It provides a hybrid "quantum + traditional" encryption approach for secure IoT communications while offering practical guidance for industry-wide scaling of QKD applications (e. g.,

prioritizing QKD deployment between core gateways in industrial IoT networks, with lightweight PQC algorithms for end devices).

3.2.2 Research on differential privacy and secure multi-party computation technologies

Differential privacy technology focuses on balancing "data usability and privacy protection," while secure multi-party computation addresses the trust challenges in "cross-organizational collaborative data processing." Both technologies find extensive applications in healthcare, finance, and other fields, with relevant literature emphasizing scenario adaptation and performance optimization.

Li Z et al. in "Differential Privacy in Healthcare Data Analytics: A Review" (Journal of Medical Systems, 2025) systematically reviewed the application progress of differential privacy technology, addressing the unique characteristics of healthcare data (high privacy sensitivity, stringent compliance requirements). The paper notes that healthcare data must comply with regulations like HIPAA (U.S.) and Grade 2.0 (China). Traditional encryption techniques (e.g., AES) only secure data storage but fail to prevent privacy leaks during analysis—such as identifying patients through medical record linkage. Differential privacy achieves a balance between "individual privacy protection and aggregate data utility" by introducing "noise" (e.g., Laplace noise, Gaussian noise) into datasets. For instance, in medical image analysis, applying Gaussian noise to image features (privacy parameter $\varepsilon = 0.5$) protects patient privacy while reducing lesion detection accuracy by only 2.1% (Li Z et al. experimental data). However, when $\varepsilon = 1$, accuracy declines by 8-12%, revealing the trade-off between privacy strength and data utility.

The literature further explores synergistic applications of differential privacy with other technologies: First, combining it with homomorphic encryption enables encrypted storage of medical data followed by encrypted analysis via differential privacy, eliminating leakage risks during decryption. Second, integrating it with federated learning allows multiple hospitals to jointly train AI models through federated learning, where locally processed data under differential privacy only uploads model parameters—achieving "data stays put while models move." The paper's value lies in quantifying differential privacy's effectiveness through empirical healthcare data while identifying current challenges—such as noise addition strategies lacking adaptive adjustment capabilities (requiring manual ε optimization for different medical data types) and insufficient compatibility with existing Healthcare Information Systems (HIS) —providing direction for future technical refinements.

Zhang H et al. in "Secure Multi-Party Computation for Cross-Institutional Credit Risk Assessment" (Information Sciences, 2023) propose a cross-institutional collaboration solution based on secure multi-party computation (SMPC) to address the "data silo" problem in finance. Using a joint bank risk control scenario as an example, the paper highlights two major risks in traditional cross-institutional data sharing: first, leakage risks from plaintext data transmission (e.g., a bank fined $230 million for sharing customer credit data); second, disputes over data ownership. SMPC technology addresses this challenge through its capability for "multi-party collaborative computation without data exposure." For instance, three banks can jointly train a risk control model using the GMW/SPDZ framework (a mainstream SMPC protocol). Each bank uploads encrypted shards of its local data, performs model parameter computations in encrypted form, and ultimately outputs only the joint model results—achieving "zero data leakage." Experiments validated this approach's performance: with 1 million customer credit data samples, cross-institutional modeling accuracy improved by 15% compared to single-institution models (due to more comprehensive data samples), while encryption/decryption latency remained under 500ms (meeting real-time risk control requirements). Furthermore, addressing SMPC's limitations (high communication complexity and computational overhead), the paper proposes an optimization strategy combining "offline computation during preprocessing + lightweight interaction during online processing," reducing communication volume by 40%. The innovation of this paper lies in its pioneering integration of SMPC technology with financial risk control scenarios. It provides a complete evidence chain encompassing "technical solutions, performance data, and implementation pathways," offering a practical paradigm for financial institutions to break down data silos and conduct collaborative risk control in compliance with regulations.

3.3 Literature on technology convergence and Industry applications

Technology convergence represents a key development trend in encrypted computing and data protection. Related literature focuses on synergistic applications of blockchain, AI, and other technologies with cryptography, as well as scenario-specific solutions across industries, driving the transition from theory to practice.

Chen Y et al. in "Blockchain-Enabled Data Encryption and Sharing in Financial Industry" (Future Generation Computer Systems, 2024) leverage blockchain's "decentralization, immutability, and traceability" to design a financial data encryption sharing scheme. The paper identifies two core challenges in financial data sharing: lack of trust (institutions fearing data leaks or misuse) and lack of traceability in the sharing process (making it difficult to pinpoint responsible parties in case of leaks). The solution's core logic is as follows: Financial institutions encrypt data using AES-256 and store it in a private cloud, simultaneously uploading the hash value of the encryption key and data access records to the blockchain. When sharing data across institutions, a smart contract triggers the "key authorization-access audit" process. For example, when Bank A shares corporate credit data with Bank B, it initiates an authorization request on the

blockchain. Bank B verifies its identity via ECC signature to obtain a temporary key, with access records recorded on-chain in real-time and immutably.

The literature experimentally validated the solution's effectiveness: in supply chain finance scenarios, it increased data sharing efficiency by 50% (eliminating offline authorization agreements), reduced data leakage risks by 90% (blockchain-traceable access), and simultaneously met GDPR's "right to data portability" and China's Grade 2.0 cybersecurity standards' "audit log retention" requirements. Furthermore, the paper compares cost differences between "blockchain + encryption" and traditional data sharing models. It finds that while blockchain deployment incurs a 30% increase in initial costs, long-term operational expenses (e. g., key management, auditing) decrease by 60%, validating the solution's economic viability. The paper's significance lies in pioneering the application paradigm of "blockchain + encryption technology" in finance, offering novel approaches to address challenges in financial data sharing and regulation.

The CSDN blog post "New Advances in Data Encryption Technology: Innovative Methods for Protecting Sensitive Information" also highlights the fusion of AI and cryptography, such as the "neurocryptography framework" proposed by the DeepMind team in 2024. This framework uses Generative Adversarial Networks (GANs) to automatically optimize encryption parameters. In image encryption scenarios, GANs dynamically adjust the S-box parameters of the AES algorithm based on image complexity (e.g., texture density, color dimension), expanding the key space to 2^256. This achieves three times the resistance to differential attacks compared to fixed-parameter schemes. Simultaneously, by training an "encryption strategy selection model" through reinforcement learning, the model can automatically match optimal encryption algorithms based on data types (e.g., text, images, video). For instance, it recommends RSA for text data and AES-GCM for image data. This technology has been implemented in NVIDIA's encrypted GPU drivers, ensuring GPU data security while eliminating subjective errors from manual encryption strategy selection. The blog notes that while the integration of AI and cryptography is still in its infancy, it has already demonstrated "adaptive and intelligent" advantages, holding promise for resolving the challenge of "difficulties in matching encryption strategies in complex scenarios" in the future.

4 Conclusion

Through reviewing core literature across three categories—fundamental cryptographic techniques, cutting-edge cryptographic technologies, and technology convergence with industry applications—this paper concludes that:

Data encryption computing and protection technologies have formed a framework characterized by "traditional encryption as the foundation, cutting-edge technologies as breakthroughs, and technological convergence as the trend." Symmetric and asymmetric encryption remain mainstream in current industrial applications, while frontier technologies like homomorphic encryption, QKD, and differential privacy have demonstrated unique advantages in specific scenarios (e.g., medical data analysis, quantum-secure communications).

Scenario requirements across different industries dictate encryption technology selection: the financial sector requires both security and traceability (recommended approach: "secure multi-party computation + blockchain"), the healthcare sector must balance privacy protection and data usability (recommended approach: "differential privacy + homomorphic encryption"), and the IoT sector prioritizes low power consumption and lightweight solutions (recommended approach: "lightweight ECC + QKD relay").

Existing research has achieved an initial transition "from theory to practice," but still faces engineering bottlenecks, insufficient cross-scenario compatibility, and lagging responses to quantum threats, requiring further breakthroughs in subsequent studies.

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