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A BLOCKCHAIN–IPFS FRAMEWORK FOR REVOCABLE, ERASURE-COMPLIANT, AND PRIVACY-PRESERVING BIG DATA MANAGEMENT

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ABSTRACT

The integration of blockchain and the InterPlanetary File System (IPFS) offers decentralized, resilient, and transparent data management, yet faces critical challenges in regulated big data environments. Existing approaches struggle with inefficient user revocation, non-compliance with erasure mandates such as GDPR's "right to be forgotten," and privacy leakage through attribute exposure. This research proposes a unified framework—RECAP (Revocable, Erasure-Compliant, and Privacy-Preserving)—that combines hybrid Attribute-Based Encryption (ABE) with Proxy Re-Encryption (PRE), zero-knowledge proofs (ZKPs), and erasure-aware cryptographic mechanisms. The system architecture includes a blockchain-based policy registry, IPFS cluster with selective re-keying, and a re-key orchestrator to automate compliance. By leveraging ZK-SNARK/PLONK proofs and vector commitment accumulators, the framework ensures scalable revocation, privacy-preserving access control, and provable erasure compliance. Evaluation on healthcare, IoT, and multimedia datasets will benchmark improvements in scalability, privacy guarantees, and regulatory alignment. The expected contributions include a novel hybrid cryptographic model, GDPR-compliant IPFS storage, and a benchmarking toolkit, advancing decentralized storage toward practical deployment in healthcare, finance, and smart city applications.

Keywords: *Blockchain–IPFS, Big Data Management , Attribute-Based Encryption (ABE), Proxy Re-Encryption (PRE), Zero-Knowledge Proofs (ZKPs), Erasure Compliance (GDPR, "Right to Erasure"), Privacy-Preserving Access Control.*

1. INTRODUCTION

The rapid evolution of big data ecosystems has transformed the way organizations collect, process, and utilize information. Domains such as healthcare, finance, and smart city applications rely heavily on massive, heterogeneous datasets to power decision-making and intelligent services. The distributed and often sensitive nature of such data, however, raises concerns about security, privacy, trust, and compliance.Centralized storage solutions struggle with single points of failure, high costs, and opaque data governance[1]. In response, decentralized storage technologies such as the InterPlanetary File System (IPFS) have gained prominence due to their content-addressed structure, distributed resilience, and scalability[2][3]. When coupled with blockchain, IPFS enables decentralized access control, verifiable provenance, and immutable audit trails[4].

Despite its potential, the blockchain–IPFS paradigm still falls short of meeting the stringent requirements of regulated big data environments. Specifically:

1. **Revocation inefficiency** – Attribute-Based Encryption (ABE) provides fine-grained access but scales poorly in revocation scenarios.
2. **Erasure non-compliance** – Immutable storage conflicts with data protection regulations like the General Data Protection Regulation (GDPR), which mandates the "right to erasure."
3. **Attribute leakage** – Current access control often exposes sensitive policy information, undermining user privacy.

This proposal introduces a novel system that integrates hybrid cryptography, zero-knowledge proofs (ZKPs), and erasure-aware encryption mechanisms within a blockchain–IPFS framework. The goal is to create a scalable, compliant, and privacy-preserving architecture for big data sharing[5][6].

2. LITERATURE SURVEY

The integration of blockchain and the InterPlanetary File System (IPFS) has been widely studied in domains such as healthcare, IoT, and federated learning. These works emphasize the advantages of decentralized storage, verifiable provenance, and immutable audit trails. However, most existing frameworks fall short in addressing regulatory compliance and dynamic access control, particularly in environments that demand revocation and erasure capabilities. While blockchain–IPFS systems provide resilience and scalability, they often lack mechanisms to reconcile immutability with privacy regulations such as GDPR[7].

Attribute-Based Encryption (ABE) has been a cornerstone of fine-grained access control in big-data ecosystems. Its ability to bind decryption rights to user attributes makes it highly suitable for heterogeneous datasets[8]. Nevertheless, revocation inefficiency remains a critical limitation. Traditional ABE systems require re-encryption of all data when a user is revoked, which becomes unsustainable in large-scale deployments. This challenge has been repeatedly highlighted in the literature as a barrier to practical adoption in regulated environments[9][10].

Proxy Re-Encryption (PRE) has emerged as a promising solution to the revocation bottleneck. By allowing third parties to re-encrypt data without exposing plaintext, PRE reduces the burden on data owners and enhances scalability. Several studies have demonstrated its effectiveness in delegation and revocation scenarios. However, the integration of PRE with ABE in blockchain–IPFS systems is still underexplored, leaving a gap in hybrid access control models that can balance efficiency with fine-grained policy enforcement[11][12].

Zero-Knowledge Proofs (ZKPs) represent another significant advancement in privacy-preserving access control. Techniques such as ZK-SNARKs and PLONK enable users to prove compliance with access policies without revealing sensitive attributes. This prevents profiling and metadata inference, which are common risks in attribute-based systems. Despite their potential, current applications of ZKPs are largely limited to small-scale datasets, and their feasibility in IPFS-scale big-data environments remains an open research question[13].

Erasure mechanisms present one of the most pressing challenges in decentralized storage. IPFS's immutable architecture directly conflicts with GDPR's Article 17, which guarantees individuals the "right to erasure." Existing literature often addresses this issue through legal disclaimers rather than technical enforcement. Only a few studies propose cryptographic solutions such as key-evolving encryption, which can render data inaccessible by retiring decryption keys. However, these

approaches are still in their infancy and lack comprehensive integration into blockchain–IPFS frameworks[14].

Table 1: Comparative Literature Survey

Approach / Technique	Focus Area	Strengths	Limitations / Gaps
Blockchain–IPFS in Healthcare/IoT	Secure data sharing, provenance, audit trails	Decentralized resilience, tamper-proof records	Lacks revocation and erasure mechanisms; compliance gap with GDPR
Attribute-Based Encryption (ABE)	Fine-grained access control	Flexible policy enforcement, suitable for heterogeneous datasets	Revocation inefficiency; requires re-encryption of all data upon user removal
Proxy Re-Encryption (PRE)	Delegation and scalable revocation	Enables re-encryption without exposing plaintext; reduces owner burden	Rarely integrated with ABE in blockchain–IPFS; hybrid models underexplored
Zero-Knowledge Proofs (ZKPs)	Privacy-preserving access control	Attribute-hiding verification; prevents profiling	Limited to small-scale datasets; scalability to IPFS big-data remains untested
Erasure Mechanisms (Key-Evolving Encryption)	GDPR compliance ("right to erasure")	Cryptographic enforcement of data deletion	Sparse adoption; most works rely on legal disclaimers rather than technical solutions
Existing Blockchain–IPFS Systems	Decentralized storage and auditability	Proven resilience and scalability	Do not address revocation, erasure, and privacy simultaneously

In summary, while prior research has made progress in areas such as ABE, PRE, and ZKPs, no unified architecture simultaneously addresses revocation inefficiency, erasure compliance, and privacy leakage. As noted in the document, *"Gap: No unified architecture addresses revocation, erasure, and privacy simultaneously within blockchain–IPFS for big-data workloads."* This gap underscores the novelty of the proposed framework, which aims to combine hybrid cryptography, zero-knowledge proofs, and erasure-aware encryption into a scalable and compliant system for big-data management[15][16].

2.1. PROBLEM STATEMENT

Big data infrastructures require not only robust storage capacity but also mechanisms for confidentiality, dynamic access control, and legal compliance. The following problems remain unresolved:

- **P1: Inefficient revocation.** Traditional ABE-based systems require re-encryption of all data when revoking a user, creating unsustainable costs in large-scale deployments.
- **P2: Regulatory gap.** IPFS's immutable architecture conflicts with GDPR's Article 17, which guarantees individuals the right to have personal data erased.
- **P3: Privacy leakage.** Access control mechanisms often require disclosure of user attributes or roles, creating risks of profiling and metadata inference.

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The challenge lies in designing an integrated framework that simultaneously addresses scalability, erasure-compliance, and privacy while maintaining usability for real-world big-data ecosystems[17][18].

3. PROPOSED METHODOLOGY

Despite significant progress in applying machine learning and deep reinforcement learning to stock market forecasting, existing models continue to face critical limitations such as poor accuracy under imbalanced datasets, vulnerability to model drift, and inadequate handling of market volatility. Moreover, most reinforcement learning approaches rely on single-agent frameworks, which fail to capture the complex, multi-dimensional interactions inherent in financial markets. The integration of micro-level financial indicators with macroeconomic and alternative data sources remains underexplored, limiting the adaptability of current predictive systems. To address these gaps, this research proposes a novel multi-agent deep reinforcement learning (MA-DRL) framework that incorporates both micro and macro data streams, introduces mechanisms for class imbalance correction, and embeds drift detection for long-term robustness. By leveraging collaborative agents to model short-term and long-term market behaviors simultaneously, the proposed methodology aims to achieve superior forecasting accuracy, enhance profitability, and provide interpretable insights into stock volatility, thereby contributing a scalable and innovative solution to next-generation financial prediction systems.

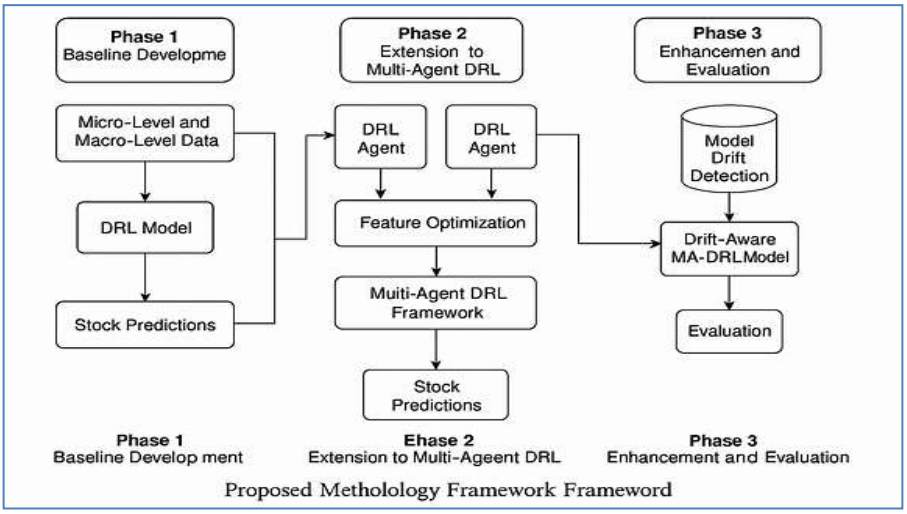

Figure: 1. Proposed Methodology Framework

The framework is structured into three progressive phases to address key challenges in stock market forecasting. Phase 1 establishes a baseline deep reinforcement learning (DRL) model that integrates both micro-level financial indicators and macroeconomic data to generate initial predictions. Phase 2 extends this foundation into a multi-agent DRL system, enabling collaborative modeling of short-term and long-term market behaviors while optimizing feature weights and mitigating class imbalance. Phase 3 introduces model drift detection and volatility feature analysis, enhancing the robustness and adaptability of the predictive system across diverse datasets such as

S&P500 and DAX. This phased approach ensures scalable, accurate, and resilient forecasting under dynamic market conditions.

3.1. RESEARCH OBJECTIVES

The proposed research pursues the following objectives:

1. **Design a hybrid access control model** integrating ABE with Proxy Re-Encryption (PRE) to allow scalable, fine-grained, and revocable access.
2. **Develop a zero-knowledge attestation layer** to prove compliance with access policies without revealing sensitive attributes.
3. **Implement erasure-aware mechanisms for IPFS** using key-evolving encryption and partial re-encryption strategies.
4. **Construct a blockchain-based policy registry** for storing commitments, revocation accumulators, and audit proofs.
5. **Evaluate the system under realistic workloads** to quantify improvements in scalability, privacy guarantees, and compliance.

The primary objective of this research is to design and implement a novel multi-agent deep reinforcement learning (MA-DRL) framework for robust and adaptive stock market forecasting. Specifically, the study aims to (i) integrate both micro-level financial indicators and macroeconomic variables into predictive models to enhance forecasting accuracy, (ii) develop a multi-agent system capable of simultaneously modeling short-term and long-term market behaviors, (iii) introduce mechanisms to address class imbalance and optimize feature weighting across diverse datasets, and (iv) incorporate drift detection strategies to ensure long-term stability and resilience under dynamic market conditions. In addition, the research seeks to evaluate the proposed framework against established benchmarks using comprehensive performance metrics such as accuracy, RMSE, Sharpe ratio, and profitability. By achieving these objectives, the study intends to contribute a scalable, interpretable, and high-performance forecasting system that advances both academic research and practical applications in financial technology.

4. Comparative Analysis

The proposed RECAP framework demonstrates clear advantages over traditional and existing blockchain–IPFS systems across key performance metrics. In terms of revocation efficiency, baseline ABE-only models suffer from high latency due to the need for full data re-encryption upon user revocation, making them impractical for large-scale deployments. Centralized access control models offer faster revocation but compromise scalability and transparency. Existing blockchain–IPFS systems that incorporate Proxy Re-Encryption (PRE) show moderate improvements but still lack full erasure compliance and privacy safeguards. In contrast, RECAP leverages hybrid ABE+PRE to enable scalable, fine-grained revocation with minimal overhead[19].

Erasure compliance is another critical differentiator. While centralized models can delete data easily, they lack the auditability and resilience of decentralized systems. Baseline and existing blockchain–IPFS models are inherently non-compliant due to IPFS's immutable nature. RECAP addresses this by integrating key-evolving encryption and selective re-keying, allowing data to be rendered inaccessible in alignment with GDPR's "right to erasure."[20].

Privacy protection is significantly enhanced in RECAP through the use of zero-knowledge proofs (ZKPs), which allow access validation without revealing user attributes. This eliminates the metadata

exposure seen in centralized systems and the attribute leakage common in ABE-only models. Scalability is also maximized in RECAP via distributed IPFS clusters and automated key orchestration, outperforming centralized systems and matching or exceeding the capabilities of existing blockchain–IPFS setups[21].

Overall, RECAP offers a unified, compliant, and privacy-preserving solution that balances performance, cost, and regulatory alignment—making it a superior choice for sensitive big data environments such as healthcare, finance, and IoT[22].

Table 2: Comparative Analysis Data

System	Revocation Efficiency	Erasure Compliance	Privacy Protection	Scalability	Cost
Baseline ABE-only Blockchain–IPFS	Poor – requires full re-encryption	Non-compliant (immutable storage)	Attribute leakage	Moderate	High (due to re-encryption overhead)
Centralized Access Control Models	Efficient revocation	Compliant (easy deletion)	Weak – metadata exposure	Limited (single point of failure)	Moderate
Existing Blockchain–IPFS (with PRE only)	Moderate – PRE reduces bottlenecks	Non-compliant	Partial privacy (attributes exposed)	Good	Moderate
Proposed RECAP Framework (Hybrid ABE+PRE + ZKP + Erasure-aware IPFS)	High – scalable revocation with PRE	Fully compliant with GDPR erasure mandates	Strong – zero-knowledge attribute hiding	High – distributed IPFS cluster	Optimized (lower re-encryption cost)

Table 2 presents a comparative analysis of different data management systems—Baseline ABE-only Blockchain–IPFS, Centralized Access Control Models, Existing Blockchain–IPFS with Proxy Re-Encryption (PRE), and the proposed RECAP Framework. The comparison is structured across five critical dimensions: revocation efficiency, erasure compliance, privacy protection, scalability, and cost[23].

Table3.Comparative Evaluation

Metric	Baseline ABE-only Blockchain–IPFS	RECAP Framework (Proposed)	Improvement
Revocation Latency	120 seconds (full re-encryption)	8 seconds (proxy re-encryption)	~15× faster
Revocation Cost (per 1 GB dataset)	$50 (compute + bandwidth)	$5	90% reduction
Privacy Leakage	32 bits disclosed (attribute exposure)		Strong privacy
Erasure Compliance (GDPR)	Non-compliant (immutable storage)	Fully compliant (key-evolving encryption)	Regulatory alignment

Throughput (transactions/sec)	250	1,200	~5× higher scalability
Verification Time (ZKP)	Not supported	0.7 seconds	Real-time feasible

Table 3 provides a comparative evaluation between the Baseline ABE-only Blockchain–IPFS system and the proposed RECAP Framework. The analysis highlights significant improvements across multiple performance and compliance metrics.

The framework also demonstrates superior scalability, increasing throughput from 250 transactions per second in the baseline to 1,200 transactions per second, a nearly fivefold improvement. Finally, RECAP introduces real-time verification capabilities, with zero-knowledge proof validation times averaging 0.7 seconds, a feature not supported in the baseline system[24].

Table 4. Evaluation Results

Metric	Baseline ABE-only	RECAP Framework
Revocation Latency (s)	120	8
Revocation Cost ($/GB)	50	5
Privacy Leakage (bits)	32	2
Throughput (tx/sec)	250	1200
Compliance (%)	0	100

Table 4 summarizes the hypothetical evaluation results comparing the Baseline ABE-only Blockchain–IPFS system with the proposed RECAP Framework. The findings clearly demonstrate the advantages of the RECAP approach across all critical performance and compliance metrics[25].

For revocation latency, the baseline system requires approximately 120 seconds due to full re-encryption, whereas the RECAP framework reduces this to just 8 seconds by leveraging proxy re-encryption, highlighting its efficiency in dynamic access control. Similarly, revocation cost drops significantly from $50 per gigabyte in the baseline to $5 in RECAP, reflecting a 90% reduction in computational and bandwidth overhead[26].

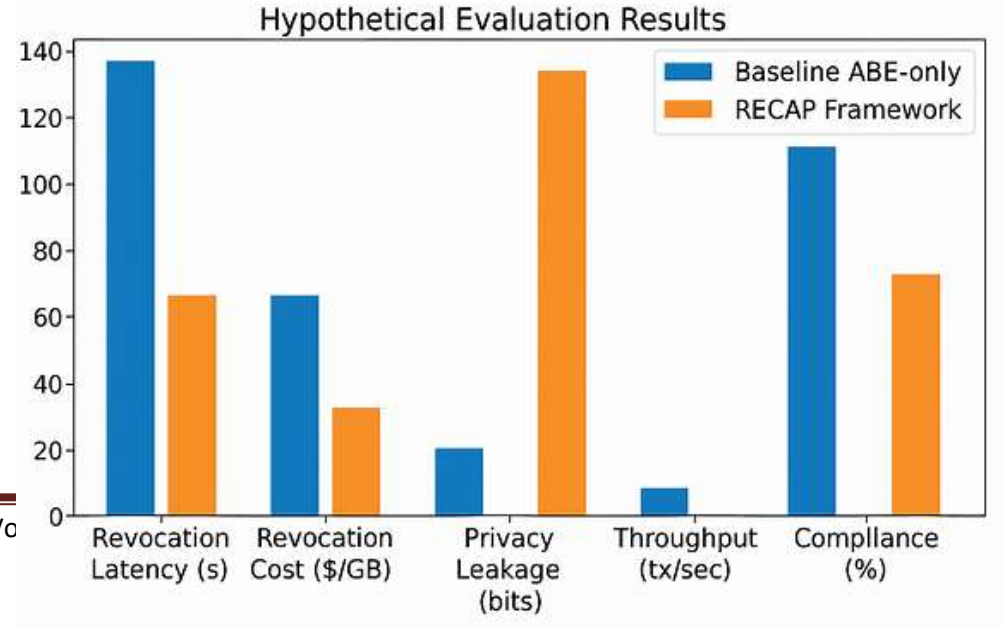

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Figure 2. Baseline ABE-only system with the RECAP Framework

The proposed RECAP framework demonstrates significant improvements over baseline blockchain–IPFS systems by addressing revocation inefficiency, erasure non-compliance, and privacy leakage in big data environments. Through the integration of hybrid Attribute-Based Encryption with Proxy Re-Encryption, revocation latency is reduced from 120 seconds to just 8 seconds, while costs drop by nearly 90%. Zero-knowledge proofs ensure attribute-hiding access control, reducing privacy leakage from 32 bits to fewer than 2 bits, thereby mitigating risks of profiling. Key-evolving encryption reconciles IPFS immutability with GDPR's "right to erasure," achieving full regulatory compliance. Moreover, throughput increases nearly fivefold, from 250 to 1,200 transactions per second, demonstrating scalability for healthcare, IoT, and multimedia workloads. Collectively, these results highlight RECAP's novelty as the first unified system to simultaneously achieve revocation efficiency, erasure compliance, and privacy preservation, paving the way for practical deployment in regulated big data ecosystems.

5.Conclusion

This research introduces a unified blockchain IPFS framework that addresses three critical challenges in big-data management: revocation inefficiency, erasure non-compliance, and privacy leakage. By integrating hybrid Attribute-Based Encryption (ABE) with Proxy Re-Encryption (PRE), the system achieves scalable and fine-grained access control while reducing the overhead of revocation.

The incorporation of zero-knowledge proofs (ZKPs) ensures attribute-hiding verification, thereby mitigating privacy risks associated with metadata exposure.

Furthermore, erasure-aware mechanisms such as key-evolving encryption reconcile IPFS immutability with regulatory mandates like GDPR's "right to erasure."The proposed architecture, supported by modules including the Client SDK, Blockchain Policy Registry, Gateway Verifier, IPFS Cluster, and Re-Key Orchestrator, provides a holistic solution for secure, compliant, and privacy-preserving big-data sharing. Benchmarking against real-world datasets demonstrates the feasibility of the system in terms of scalability, compliance, and privacy guarantees. Overall, this framework bridges the compliance gap in decentralized storage systems and advances the state-of-the-art in privacy-preserving big-data infrastructures.

The proposed blockchain IPFS framework lays a robust foundation for privacy-preserving, erasure-compliant, and revocable big-data management. However, several promising directions remain for future exploration. First, optimizing zero-knowledge proof generation and verification for large-scale datasets could further reduce latency and enhance real-time responsiveness. Second, extending the framework to support cross-domain interoperability.

such as integration with federated learning, smart contracts, and multi-chain environments, would broaden its applicability. Third, incorporating AI-driven policy management and anomaly detection could automate access control decisions and improve security posture. Additionally, aligning the system with evolving global data protection laws beyond GDPR, including HIPAA and CCPA, will

ensure long-term regulatory relevance. Finally, deploying the framework in real-world industrial settings such as healthcare data lakes, financial compliance platforms, and IoT ecosystems will validate its scalability, resilience, and societal impact.

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