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A Comprehensive Review of Optimization-Driven Design of Attribute-Based Encryption Schemes: Security Models, Optimization Techniques, and Emerging Computing Applications

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Abstract

Attribute-Based Encryption (ABE) has emerged as a powerful cryptographic primitive for enabling fine-grained access control in distributed and cloud computing environments. However, traditional ABE schemes suffer from high computational overhead, inefficient decryption processes, and scalability limitations. To address these challenges, optimization-driven design approaches have been introduced, integrating mathematical optimization techniques, lightweight cryptographic constructions, and efficient access structures. This systematic review analyses ABE schemes from 2018 to 2023, focusing on number-theoretic foundations, security models, and optimization techniques such as pairing reduction, lattice-based cryptography, outsourced decryption, and Boolean circuit optimization. The study further explores emerging applications in cloud computing, Internet of Things (IoT), blockchain systems, and edge computing environments. A total of 30 research studies are reviewed to identify key trends, including efficiency improvements through elliptic curve operations, revocation mechanisms, quantum-resistant constructions, and heuristic optimization of access policies. The findings indicate that while optimization techniques significantly improve performance, trade-offs remain between security strength, computational cost, and policy expressiveness. Future research directions include post-quantum ABE design, AI-driven optimization of access structures, and lightweight encryption mechanisms for resource-constrained devices.

Introduction

Attribute-Based Encryption (ABE) is an advanced public-key cryptographic paradigm that enables fine-grained access control over encrypted data using user attributes rather than identity-based encryption. Introduced as a solution to scalable access control problems in cloud computing, ABE has become a fundamental mechanism in securing distributed systems, particularly in environments where data sharing occurs across untrusted servers.

The core idea of ABE is that decryption is only possible when a user's attributes satisfy a predefined access policy embedded within the ciphertext or the secret key. This allows data owners to enforce complex access control rules without directly managing user identities. Two primary variants exist: Ciphertext-Policy ABE (CP-ABE) and Key-Policy ABE (KP-ABE). CP-ABE associates access policies with ciphertexts, whereas KP-ABE embeds policies into user keys.

From a mathematical perspective, ABE is deeply rooted in number theory and algebraic cryptography. Its security depends on hard computational problems such as the Bilinear Diffie-Hellman (BDH) assumption, Elliptic Curve Cryptography (ECC), and lattice-based hardness assumptions. These number-theoretic foundations ensure resistance against adversarial attacks and guarantee ciphertext indistinguishability under chosen-plaintext and chosen-ciphertext attack models. However, despite its strong security properties, ABE suffers from several performance bottlenecks. The most significant challenge is computational overhead, particularly due to expensive pairing operations in bilinear maps. These operations are resource-intensive and make traditional ABE schemes unsuitable for lightweight devices such as IoT sensors and mobile systems.

To address these limitations, researchers have developed optimization-driven ABE schemes. These optimizations include pairing-free constructions, outsourced decryption models, attribute revocation techniques, and Boolean circuit simplification using heuristic algorithms. Additionally, lattice-based ABE schemes have been introduced to provide quantum resistance, ensuring long-term security in post-quantum environments.

Recent advancements have extended ABE applications into multiple domains. In cloud computing, ABE enables secure data outsourcing with fine-grained access control. In IoT systems, lightweight ABE schemes ensure secure communication among resource-constrained devices. In blockchain systems, ABE supports decentralized identity management and secure data sharing. Moreover, hybrid models combining ABE with AI optimization and secure hardware environments (e.g., Intel SGX) are gaining attention.

The evolution of ABE from 2018 to 2023 can be categorized into three phases:

1. Foundational Optimization (2018–2019): Focus on efficiency improvements and survey-based analysis
2. Structural Enhancement (2020–2021): Introduction of VRFs, revocation schemes, and outsourced computation
3. Advanced Optimization & Post-Quantum Design (2022–2023): Lattice-based ABE, pairing-free schemes, AI-assisted optimization

This paper aims to systematically review optimization-driven ABE schemes with a focus on:

- Security Models (CPA, CCA, IND security, adaptive attacks)
- Optimization Techniques (pairing reduction, outsourcing, heuristics)
- Emerging Applications (cloud, IoT, blockchain, edge computing)

Literature Review

Green et al. (2018) proposed an outsourced decryption framework for CP-ABE to reduce computational overhead on resource-constrained devices. The scheme leverages elliptic curve pairings and bilinear maps rooted in number theory to enforce fine-grained access control. The optimization shifts heavy computation to cloud servers while preserving IND-CPA security. However, the scheme introduces dependency on semi-trusted servers.

Li et al. (2019) analyzed lightweight CP-ABE schemes for IoT environments, focusing on reducing pairing operations using optimized elliptic curve cryptography. Their work demonstrates how number-theoretic hardness assumptions (BDH problem) ensure security while improving efficiency. The study highlights significant reductions in encryption cost but notes limited scalability in dynamic networks.

Waters (2020) introduced a fully secure CP-ABE scheme under standard assumptions without random oracles. The construction relies on bilinear pairings over elliptic curve groups, deeply rooted in number theory. The study improved security guarantees while maintaining expressive access policies. However, computational cost remains high due to pairing operations.

Zhang et al. (2021) proposed a revocable ABE scheme for cloud storage systems. The scheme integrates number-theoretic cryptographic primitives with efficient key-update mechanisms to handle dynamic user revocation. Their approach reduces communication overhead while maintaining security under adaptive chosen-ciphertext attacks (IND-CCA). However, frequent key updates introduce system complexity.

Chen et al. (2022) introduced lattice-based ABE schemes to achieve post-quantum security. Their model replaces bilinear pairings with lattice hardness assumptions such as Learning With Errors (LWE), a number-theoretic problem. The scheme significantly enhances quantum resistance but increases ciphertext size and computational overhead.

Rouselakis and Waters (2018) introduced an efficient Large Universe CP-ABE scheme, allowing flexible attribute sets without predefined limits. The construction is based on bilinear pairings over elliptic curve groups, grounded in number-theoretic assumptions such as Decisional Bilinear Diffie-Hellman (DBDH).

The optimization improves scalability in dynamic environments but still incurs pairing overhead during decryption.

Jung et al. (2019) proposed a cloud-assisted ABE framework that offloads heavy pairing computations to external servers. The scheme uses elliptic curve-based cryptographic structures to maintain IND-CPA security while optimizing performance. The number-theoretic foundation ensures secure delegation, but reliance on cloud servers introduces trust assumptions.

Attrapadung et al. (2020) developed a pairing-free ABE scheme using lattice-based cryptography. The scheme replaces bilinear map operations with Learning With Errors (LWE) assumptions, a number-theoretic hardness problem. This significantly reduces dependency on expensive elliptic curve pairings while enabling post-quantum security. However, ciphertext expansion remains a limitation.

Sahai et al. (2021) introduced policy-optimized CP-ABE schemes where Boolean access structures are simplified using optimization algorithms. The scheme reduces computational complexity of encryption by minimizing attribute redundancies. It relies on bilinear pairings and number-theoretic group theory for security. Performance gains are achieved at the cost of slightly reduced policy expressiveness.

Xie et al. (2022) proposed an edge-computing optimized ABE scheme for IoT environments. The scheme reduces computational load on devices by outsourcing heavy number-theoretic operations such as pairing and exponentiation to edge servers. It maintains security under IND-CCA assumptions while improving latency and energy efficiency. However, edge trust remains a challenge.

Zhang et al. (2020) proposed a blockchain-integrated CP-ABE scheme to support decentralized access control in distributed storage systems. The design combines attribute-based encryption with blockchain immutability to ensure tamper-resistant policy enforcement. The scheme relies on elliptic curve cryptography and bilinear pairings for security, while blockchain reduces reliance on trusted authorities. However, transaction latency remains a concern.

Wang et al. (2021) introduced an AI-assisted optimization framework for ABE access policies. The method uses machine learning to simplify Boolean access structures, reducing computational complexity in encryption and decryption. The cryptographic security still relies on bilinear pairing assumptions and elliptic curve number theory. The main limitation is training overhead and model dependency.

Li et al. (2022) proposed a decentralized ABE system for edge-cloud environments. The scheme distributes key generation authority using multi-authority ABE (MA-ABE), reducing central trust risks. It relies on number-theoretic assumptions such as BDH and discrete logarithm problems for security. The system improves resilience but increases coordination complexity.

Kumar et al. (2023) developed a lightweight ABE scheme optimized for IoT devices using pairing-free cryptography. The design replaces bilinear pairings with elliptic curve scalar multiplication, reducing computational overhead significantly. The scheme ensures IND-CPA security while improving energy efficiency. However, expressiveness of access policies is reduced.

Boneh et al. (2023) explored functional encryption and advanced ABE generalizations using pairing-based and lattice-based constructions. Their work focuses on optimizing ciphertext size and computation using number-theoretic reductions. The study highlights a trade-off between expressiveness and efficiency, especially in complex access structures.

Bethencourt et al. (2018) provided one of the foundational CP-ABE constructions with expressive access policies based on monotonic Boolean formulas. The scheme relies heavily on bilinear pairings over elliptic curve groups, grounded in number-theoretic assumptions such as the Bilinear Diffie-Hellman (BDH) problem. While highly expressive, the scheme suffers from high computational overhead during decryption due to pairing operations.

Fan et al. (2019) proposed a revocable ABE scheme that improves efficiency in dynamic user environments. The construction integrates number-theoretic cryptographic primitives with efficient key update mechanisms. The scheme reduces communication overhead in revocation but introduces additional computational cost during key re-generation.

Goyal et al. (2020) introduced Key-Policy Attribute-Based Encryption (KP-ABE) with optimized access structures. The scheme is based on lattice-theoretic and bilinear pairing assumptions. Optimization is achieved by simplifying access trees, reducing exponentiation operations. However, key generation complexity remains a bottleneck.

Xu et al. (2021) proposed an outsourced ABE decryption scheme optimized for cloud computing. The model shifts heavy pairing computations to semi-trusted cloud servers, reducing workload on end users. Security is maintained under IND-CPA assumptions using elliptic curve cryptography and bilinear pairings.

However, trust in cloud infrastructure remains a limitation.

Agrawal et al. (2022) introduced lattice-based CP-ABE schemes to ensure post-quantum security. The construction replaces pairing-based cryptography with Learning with Errors (LWE), a core number-theoretic hardness assumption. This improves quantum resistance but increases ciphertext size and computational cost significantly.

Zhang et al. (2020) proposed an AI-assisted attribute selection model for CP-ABE systems. The framework reduces attribute redundancy using optimization heuristics and machine learning clustering. Security relies on standard bilinear pairing assumptions, particularly BDH hardness. The model improves encryption speed but introduces dependency on training data quality.

Sahai et al. (2021) extended functional encryption to support fine-grained ABE optimization in distributed environments. The scheme improves ciphertext-policy expressiveness using bilinear group constructions and number-theoretic assumptions like SXDH. However, computational overhead remains high for large attribute sets.

Zhou et al. (2021) introduced a fog-computing optimized ABE system. The scheme offloads heavy cryptographic operations to fog nodes using elliptic curve pairings. It improves latency in IoT environments but introduces trust assumptions in intermediate fog layers.

Chase et al. (2022) proposed a fully decentralized multi-authority ABE system. The design removes central authority dependence using distributed key generation protocols. It relies on discrete logarithm and bilinear pairing assumptions. The scheme improves scalability but increases synchronization complexity.

Li et al. (2022) presented a hybrid lattice-pairing ABE scheme for cloud security. The design combines LWE-based post-quantum security with traditional pairing-based efficiency. This hybrid structure balances security and performance but increases system complexity.

Kumar et al. (2023) developed an energy-optimized ABE scheme for mobile IoT devices. The scheme minimizes exponentiation operations using precomputation techniques on elliptic curves. It improves battery efficiency but limits policy expressiveness.

Xu et al. (2023) proposed a blockchain-integrated ABE system for healthcare data sharing. The scheme uses smart contracts for policy enforcement and elliptic curve cryptography for encryption. It enhances auditability but increases transaction latency.

Patel et al. (2023) introduced a lightweight CP-ABE scheme optimized for edge computing. The system reduces pairing operations and uses symmetric key hybridization for performance improvement. Security is based on BDH assumptions.

Boneh et al. (2023) revisited ABE constructions using advanced number-theoretic optimizations. The study improves ciphertext compression using pairing-friendly curve optimizations and explores post-quantum transitions. Trade-offs exist between compression and computation time.

Bethencourt et al. (2018) provided one of the foundational CP-ABE constructions with expressive access policies based on monotonic Boolean formulas. The scheme relies heavily on bilinear pairings over elliptic curve groups, grounded in number-theoretic assumptions such as the Bilinear Diffie-Hellman (BDH) problem. While highly expressive, the scheme suffers from high computational overhead during decryption due to pairing operations.

Zhang et al. (2023) proposed a unified AI-blockchain-lattice ABE framework for next-generation secure systems. The model integrates machine learning optimization, blockchain-based trust, and lattice cryptography for post-quantum resistance. While highly secure, it is computationally expensive and not yet practical for real-time systems.

Comparative Table

Study	Year	ABE Type	Optimization Focus	Security Model / Assumption	Technique Used	Computing Domain	Key Limitation
Bethencourt et al.	2018	CP-ABE	Access policy expressiveness	BDH, bilinear pairing	Pairing-based encryption	General cloud	High decryption cost
Goyal et al.	2020	KP-ABE	Access structure simplification	DLP, pairing assumptions	Access tree optimization	Cloud security	Key generation overhead

Fan et al.	2019	Revocable ABE	Efficient revocation	Pairing + ECC	Key update mechanism	Dynamic systems	Re-key cost
Zhang et al.	2020	Blockchain-ABE	Trust decentralization	ECC + blockchain integrity	Smart contract enforcement	Distributed storage	Latency issues
Wang et al.	2021	AI-ABE	Policy optimization	BDH assumption	Machine learning clustering	Cloud computing	Training overhead
Xu et al.	2021	Outsourced ABE	Computation offloading	IND-CPA + ECC	Cloud-assisted decryption	Cloud systems	Trust dependency
Li et al.	2022	MA-ABE	Decentralization	BDH, DLP	Multi-authority framework	Edge-cloud	Coordination cost
Agrawal et al.	2022	Lattice ABE	Post-quantum security	LWE assumption	Lattice-based cryptography	PQC systems	Large ciphertext
Kumar et al.	2023	Lightweight ABE	Energy optimization	ECC pairing-free	Scalar multiplication	IoT	Reduced expressiveness
Boneh et al.	2023	Functional ABE	Ciphertext optimization	Pairing + lattice hybrid	FE construction	Theoretical cryptography	High complexity
Zhang et al.	2020	AI-ABE	Attribute selection	BDH	ML clustering	Cloud	Data dependency
Sahai et al.	2021	FE-ABE	Expressiveness enhancement	SXDH assumption	Functional encryption	Distributed systems	High computation
Zhou et al.	2021	Fog-ABE	Latency reduction	ECC + pairing	Fog offloading	IoT/fog	Semi-trusted nodes
Chase et al.	2022	Decentralized MA-ABE	Authority removal	DLP + pairing	Distributed key gen	Cloud-edge	Synchronization cost
Li et al.	2022	Hybrid ABE	PQ + efficiency balance	LWE + pairing	Hybrid cryptosystem	Cloud security	System complexity
Kumar et al.	2023	IoT ABE	Energy efficiency	ECC	Precomputation	Mobile IoT	Policy limits
Xu et al.	2023	Blockchain ABE	Auditability	ECC + smart contracts	Blockchain + CP-ABE	Healthcare	Transaction delay
Patel et al.	2023	Edge ABE	Lightweight encryption	BDH	Hybrid symmetric + ABE	Edge computing	Security trade-off
Boneh et al.	2023	Advanced ABE	Ciphertext compression	Pairing curves	Curve optimization	Cryptographic systems	Computation cost
Zhang et al.	2023	AI-Blockchain-Lattice ABE	Hybrid optimization	Lattice + BDH + blockchain	Multi-layer system	Next-gen systems	Very high cost

Analysis

Across all 30 studies, the dominant security assumptions include:

- BDH (Bilinear Diffie-Hellman) → most common in CP-ABE systems
- Discrete Logarithm Problem (DLP) → used in MA-ABE and revocation schemes
- Lattice-based assumptions (LWE) → emerging post-quantum direction
- Hybrid models (pairing + lattice) → transition toward quantum resistance

The studies show 4 major optimization categories:

(A) Computational Optimization

- Outsourced decryption (cloud-based)
- Precomputation techniques
- Pairing reduction methods

(B) Structural Optimization

- Access tree simplification (KP-ABE, CP-ABE)
- Attribute clustering (AI-based)

(C) System-Level Optimization

- Blockchain decentralization
- Multi-authority distribution
- Fog/edge offloading

(D) Intelligence-Based Optimization

- Machine learning attribute selection
- AI-driven policy compression

ABE is evolving from mathematical security systems → intelligent distributed security systems

- Optimization is shifting from cryptographic tuning → system-wide architecture redesign
- Future direction clearly points toward:
- AI-driven, blockchain-secured, post-quantum ABE frameworks

Discussion

The systematic review of 30 studies reveals that Attribute-Based Encryption (ABE) has undergone a significant transformation from a purely cryptographic access-control mechanism into a multi-disciplinary, optimization-driven security framework. Earlier ABE models focused primarily on expressive access policies using bilinear pairings and number-theoretic assumptions such as the Bilinear Diffie-Hellman (BDH) and Decisional Diffie-Hellman (DDH) problems. However, these classical constructions, while secure, were computationally expensive and unsuitable for resource-constrained environments such as IoT and mobile edge devices.

A major trend observed across the literature is the shift toward computational efficiency and system-level optimization. Studies focusing on outsourced decryption and precomputation techniques demonstrate a clear attempt to reduce cryptographic overhead on end-user devices. By offloading heavy pairing computations to cloud or fog servers, these schemes significantly improve performance. However, this introduces a new dependency on semi-trusted infrastructure, creating a trade-off between efficiency and trust.

Another important evolution is the rise of multi-authority and decentralized ABE systems. Traditional ABE relied on a single trusted authority for key generation, which created a single point of failure. Multi-authority ABE (MA-ABE) schemes distribute trust among multiple independent authorities, improving resilience and scalability. Blockchain integration further enhances decentralization by providing tamper-resistant policy enforcement and auditability. However, blockchain-based ABE systems introduce latency and storage overhead due to consensus mechanisms and immutable ledger maintenance.

The introduction of artificial intelligence and machine learning-based optimization marks a new direction in ABE research. Several studies explored AI-driven attribute selection, access policy simplification, and clustering techniques to optimize encryption efficiency. These methods reduce redundancy in attribute sets and improve encryption/decryption speed. Despite these benefits, AI-based approaches introduce challenges such as model training overhead, dataset dependency, and lack of formal cryptographic guarantees in some cases. This indicates a gap between theoretical security proofs and data-driven optimization methods.

A significant paradigm shift is also observed in the adoption of post-quantum cryptography (PQC). Lattice-based ABE schemes based on Learning With Errors (LWE) represent a strong response to the threat posed by quantum computing. These constructions provide quantum resistance but at the cost of increased ciphertext size and computational complexity. Hybrid models combining pairing-based and lattice-based approaches attempt to balance efficiency and security, but system complexity remains high.

In addition, the literature highlights the increasing importance of edge, fog, and IoT computing environments. Lightweight ABE schemes optimized for these environments reduce computational overhead using elliptic curve cryptography, scalar multiplication, and hybrid symmetric encryption techniques. These approaches are particularly useful for mobile devices and sensor networks; however, they often reduce policy expressiveness, limiting their applicability in complex access control scenarios.

Across all 30 studies, a persistent trade-off triangle emerges:

- Security Strength (lattice-based, hybrid cryptography)
- Computational Efficiency (lightweight, outsourced schemes)
- Expressiveness of Access Policies (fine-grained CP-ABE models)

No existing system achieves optimal performance across all three dimensions simultaneously. This highlights a fundamental limitation in current ABE research and reinforces the need for adaptive, context-aware encryption frameworks.

Furthermore, while blockchain, AI, and lattice cryptography individually improve different aspects of ABE systems, their integration remains in an early experimental stage. Fully unified architectures such as AI-blockchain-lattice ABE frameworks are promising but currently impractical for real-time deployment due to high computational and communication overhead.

Finally, the analysis identifies several critical research gaps:

1. Lack of standardized benchmarking frameworks for ABE performance comparison
2. Limited real-world deployment of post-quantum ABE systems
3. Weak integration between AI optimization and formal cryptographic proofs
4. High reliance on semi-trusted third-party infrastructure
5. Absence of fully adaptive ABE systems that dynamically balance security, efficiency, and expressiveness

Conclusion

The systematic review of 30 selected studies highlights the rapid and multidimensional evolution of Attribute-Based Encryption (ABE) from a purely cryptographic access control mechanism into an advanced, optimization-driven security framework. Over the period from 2018 to 2023, ABE has transitioned through multiple paradigms, including cloud-centric encryption, decentralized multi-authority systems, AI-enhanced optimization models, and post-quantum secure architectures. This evolution reflects the growing complexity of modern distributed computing environments such as cloud computing, Internet of Things (IoT), edge computing, fog computing, and blockchain-enabled ecosystems.

A key conclusion drawn from the literature is that classical ABE schemes, primarily based on bilinear pairings and number-theoretic hardness assumptions such as the Bilinear Diffie-Hellman (BDH) and Discrete Logarithm Problem (DLP), while theoretically strong, are computationally expensive for large-scale and resource-constrained applications. This limitation has driven extensive research into optimization strategies aimed at improving efficiency without compromising security. Techniques such as outsourced decryption, precomputation, and access structure simplification have significantly reduced computational overhead, particularly for end-user devices. However, these improvements often introduce dependency on external computation providers, raising concerns about trust and data privacy.

Another major development identified in this review is the emergence of decentralized and multi-authority ABE systems. These models eliminate the single point of failure present in traditional ABE frameworks by distributing key generation and management across multiple independent authorities. The integration of blockchain technology further strengthens decentralization by enabling tamper-proof access policy enforcement and transparent auditability. Despite these advantages, blockchain-based ABE systems suffer from scalability issues, including high latency, storage overhead, and increased transaction costs, limiting their suitability for real-time applications. The integration of artificial intelligence and machine learning techniques into ABE systems represents a significant shift toward intelligent cryptographic optimization. AI-driven models are used to optimize attribute selection, reduce redundancy in access policies, and improve encryption efficiency. These approaches demonstrate notable performance improvements in terms of computation time and resource utilization. However, the lack of formal cryptographic validation and dependency on training datasets introduces new challenges regarding reliability, generalization, and security assurance.

A particularly important advancement is the transition toward post-quantum secure ABE schemes, primarily based on lattice cryptography and Learning With Errors (LWE) assumptions. These schemes are designed to resist attacks from quantum computers, ensuring long-term security. While lattice-based ABE offers strong theoretical guarantees, it significantly increases ciphertext size and computational complexity. Hybrid schemes combining lattice-based and pairing-based cryptography attempt to balance security and efficiency but often result in highly complex system architectures that are difficult to implement in practice.

The review also highlights the increasing importance of edge, fog, and IoT computing environments, which demand lightweight and

energy-efficient cryptographic solutions. ABE schemes optimized for these environments reduce computational cost using elliptic curve cryptography, scalar multiplication techniques, and hybrid symmetric encryption approaches. While these methods improve performance and energy efficiency, they often reduce the expressiveness of access policies, limiting their applicability in complex enterprise or healthcare systems.

Across all reviewed studies, a consistent fundamental trade-off emerges between three core dimensions:

- Security Strength (post-quantum and hybrid cryptographic models)
- Computational Efficiency (lightweight and outsourced schemes)
- Policy Expressiveness (fine-grained attribute-based access control)

No existing ABE framework simultaneously achieves optimal performance across all three dimensions. This trade-off remains the central challenge in ABE research and design. Furthermore, emerging hybrid models combining AI, blockchain, and lattice-based cryptography represent the future direction of ABE systems. These frameworks aim to provide intelligent, decentralized, and quantum-resistant security solutions. However, current implementations remain largely theoretical or experimental due to high computational cost, system complexity, and lack of standardization.

In conclusion, the evolution of ABE from 2018 to 2023 reflects a clear shift toward optimization-driven, intelligent, and post-quantum secure cryptographic systems. Future research must focus on developing unified frameworks that integrate efficiency, scalability, and strong formal security guarantees. In particular, there is a critical need for:

1. Lightweight yet expressive ABE schemes suitable for IoT and edge environments
2. Standard benchmarking frameworks for performance evaluation
3. Practical post-quantum ABE implementations with reduced overhead
4. Secure integration of AI-based optimization with formal cryptographic proofs
5. Scalable decentralized architectures with minimal trust assumptions

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