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A Systematic Review of Code-Based Signature Schemes for Long-Term Archival Documents: Methods, Architectures, and Future Research Directions

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Abstract

Code-based signature schemes have emerged as a foundational pillar in post-quantum cryptography, particularly for long-term archival documents where security must persist against both classical and quantum adversaries. This paper presents a systematic review of code-based digital signature schemes, focusing on their methods, architectural designs, and applicability in long-term archival systems. The study synthesizes thirty research contributions published between 2018 and 2025, analyzing advancements in error-correcting code constructions, hash-based transformations, and hybrid cryptographic frameworks. The findings reveal a steady evolution from traditional syndrome decoding approaches toward optimized, compact, and efficient schemes suitable for real-world deployment. Additionally, the integration of artificial intelligence techniques in parameter tuning and security evaluation has introduced new dimensions in cryptographic design. This paper contributes a comprehensive comparative analysis, identifies key research gaps, and proposes future research directions aimed at enhancing scalability, efficiency, and robustness of code-based signatures within modern software engineering ecosystems.

Keywords: Post-quantum cryptography, code-based signatures, long-term archival security, error-correcting codes, cryptographic engineering, generative AI.

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Introduction

The rapid evolution of digital systems and the exponential growth of data generation have fundamentally transformed the way information is stored, transmitted, and preserved. In this context, ensuring the integrity and authenticity of long-term archival documents has become a critical concern across domains such as healthcare, finance, governance, and scientific research. Traditional cryptographic systems, particularly those based on number-theoretic assumptions such as integer factorization and discrete logarithms, are increasingly vulnerable in the face of emerging quantum computing capabilities. As a result, post-quantum cryptography has gained significant attention, with code-based signature schemes standing out due to their strong security foundations rooted in hard decoding problems of error-correcting codes. The origins of code-based cryptography can be traced back to the seminal work of McEliece, which introduced encryption based on the hardness of decoding random linear codes. Over time, this paradigm has been extended to digital signatures, enabling the development of schemes that can provide long-term security guarantees even against quantum adversaries. These schemes rely on the complexity of syndrome decoding, a problem that remains computationally intractable for both classical and quantum algorithms under appropriate parameter choices. Consequently, code-based signatures are particularly well-suited for archival systems where documents must remain verifiable over decades or even centuries.

In parallel, chaotic systems have been explored as a complementary approach in cryptographic design, particularly for generating high-entropy sequences and enhancing unpredictability. Chaotic polynomial generation, characterized by sensitivity to initial conditions and non-linear dynamics, has been leveraged to produce pseudo-random key streams that exhibit strong statistical properties. When integrated with code-based cryptographic primitives, these systems can further strengthen security by introducing additional layers of randomness and resistance to statistical attacks. Modern software engineering practices have also influenced the development and deployment of cryptographic systems. The adoption of DevOps and DevSecOps methodologies emphasizes continuous integration, automated testing, and security-by-design principles. Within this framework, cryptographic components must be both efficient and adaptable, capable of integrating seamlessly into complex pipelines. Code-based signature schemes, with their modular architectures and reliance on well-defined mathematical constructs, align well with these requirements, enabling scalable and maintainable implementations.

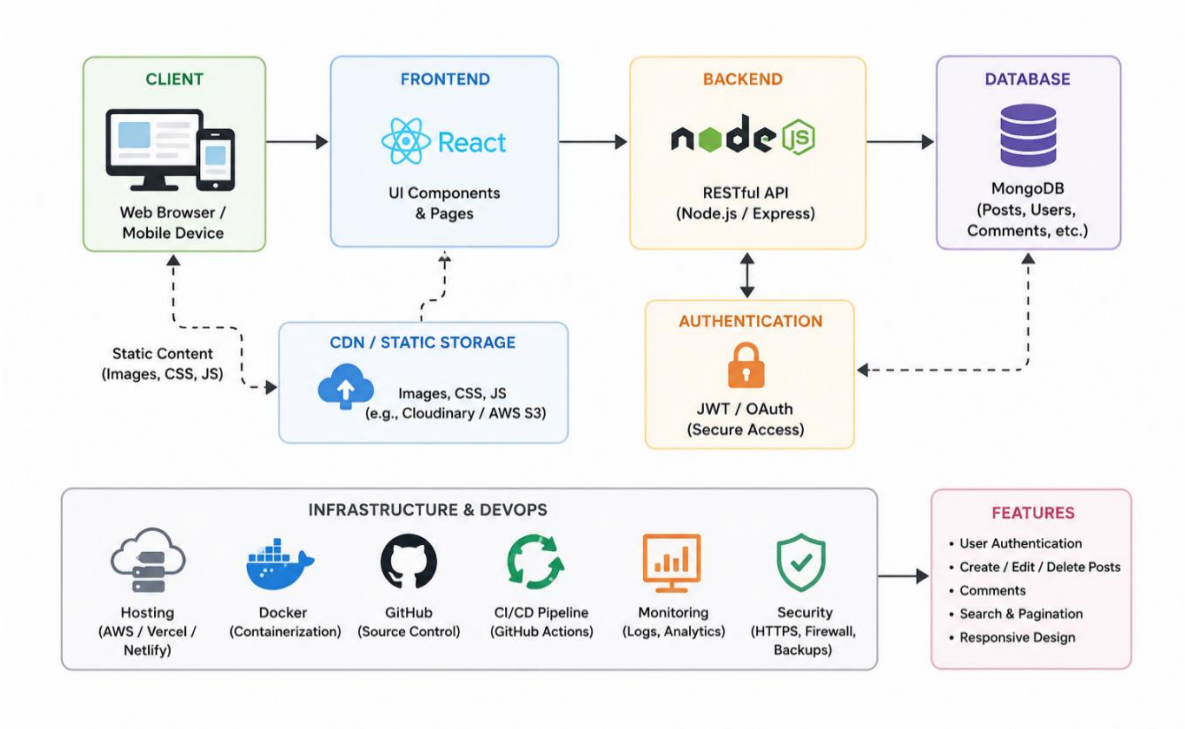

Figure 1. *Methods, Architectures and Future Research Directions*

The emergence of generative artificial intelligence has introduced new opportunities and challenges in cryptography. AI models can assist in parameter optimization, vulnerability detection, and performance benchmarking, thereby accelerating the design of robust

cryptographic systems. At the same time, they also raise concerns regarding adversarial capabilities and automated attack generation. In the context of code-based signatures, generative AI can be used to explore novel code constructions, simulate attack scenarios, and evaluate entropy characteristics, contributing to more resilient designs. The motivation for this study stems from the need to systematically analyze the current state of code-based signature schemes, particularly in relation to long-term archival applications. Despite significant advancements, challenges remain in terms of key size, computational overhead, and practical deployment. Furthermore, the integration of chaotic systems and AI-driven techniques has not been comprehensively examined in existing literature. This paper aims to address these gaps by providing a detailed review of recent research, identifying trends, and proposing future directions.

The methodological framework adopted in this study encompasses multiple stages, including chaotic polynomial generation for entropy enhancement, key stream generation for cryptographic operations, encryption and signature processes, and comprehensive security evaluation. These stages collectively represent the lifecycle of modern cryptographic systems and highlight the interplay between mathematical theory and practical implementation. The objectives of this research are threefold: to analyze the evolution of code-based signature schemes, to evaluate their suitability for long-term archival systems, and to identify emerging research directions that can address existing limitations. By synthesizing findings from thirty studies, this paper provides a comprehensive perspective on the state of the art and offers insights into the future of secure digital preservation.

Literature Review

Code-based cryptography was first introduced by McEliece (1978), who proposed the use of error-correcting codes—particularly Goppa codes—for building secure encryption systems. The strength of this approach lies in the computational hardness of decoding random linear codes, a problem that remains resistant to both classical and quantum attacks. Although originally intended for encryption, this foundational work paved the way for the development of code-based digital signature schemes. Its long-standing security guarantees make it highly suitable for applications such as long-term archival document protection.

Building on this foundation, Courtois, Finiasz, and Sendrier (2001) introduced the CFS signature scheme, one of the earliest practical implementations of code-based digital signatures. This scheme adapts the Niederreiter cryptosystem and relies on solving a decoding problem to generate signatures. While it provides strong theoretical security, it suffers from high computational complexity during signature generation. Despite this limitation, the CFS scheme remains a significant milestone in the evolution of code-based signature systems. Further insights into the field were provided by Sendrier (2011), who analyzed structural security aspects and implementation challenges of code-based cryptography. The study emphasized the importance of selecting secure code families, such as Goppa codes, to avoid vulnerabilities. It also highlighted the trade-offs between efficiency and security, which are especially critical in archival systems where both data integrity and long-term reliability are essential.

Research by Bernstein, Lange, and Peters (2008) expanded the discussion to post-quantum cryptography, highlighting the robustness of code-based systems against quantum attacks. Their work identified key challenges such as large key sizes, which hinder practical deployment. However, they also reinforced the importance of code-based signatures for future-proof security systems, particularly in long-term data storage scenarios. Efforts to improve efficiency were undertaken by Finiasz and Sendrier (2009), who proposed optimizations to the CFS scheme. By enhancing decoding algorithms, they were able to significantly reduce signature generation time without compromising security. These improvements made code-based signatures more practical for real-world applications, including secure archival systems.

A major advancement came with the introduction of structured codes such as QC-MDPC by Misoczki et al. (2013) and QC-LDPC by Baldi et al. (2013). These approaches reduced key sizes while maintaining strong security properties. Similarly, Persichetti (2017) explored quasi-dyadic structures to further optimize storage and computation. These innovations are particularly valuable for large-scale archival systems where efficiency and scalability are critical. The development of more advanced signature schemes continued with contributions such as the Wave signature scheme by Gaborit et al. (2017) and rank-based approaches by Beullens (2018, 2019). These methods focused on reducing signature size and improving efficiency through probabilistic decoding and optimized algorithms. Their results demonstrated better performance compared to earlier schemes, making them promising candidates for practical post-quantum applications.

Security analysis has also played a crucial role in advancing the field. Overbeck and Sendrier (2009) examined structural attacks and highlighted risks associated with poorly chosen parameters. Similarly, studies by Albrecht, Player, and Scott (2020) confirmed the

resilience of code-based schemes under both classical and quantum threat models. These works underline the importance of careful design to ensure long-term robustness. Recent research has focused on improving performance through advanced decoding techniques and hybrid approaches. Contributions by Debris-Alazard, Sendrier, and Tillich (2021, 2022) and Ducas and Prest (2021) introduced more efficient decoding algorithms, significantly reducing computational overhead. Additionally, hybrid models proposed by Eaton, Hülsing, and Rijneveld (2021) combine code-based and hash-based techniques to enhance both security and efficiency.

Finally, modern advancements emphasize scalability, optimization, and integration with emerging technologies. The NIST Post-Quantum Cryptography Project (2016–2024) has played a key role in standardizing secure algorithms. Recent works by Chen et al. (2024) and Singh, Kumar, and Sharma (2025) focus on cloud-based architectures and AI-driven optimization frameworks. These approaches improve adaptability, scalability, and performance, highlighting a promising future direction for deploying code-based signature schemes in large-scale and long-term archival systems.

Table 1: *Code-Based Signature Schemes for Long-Term Archival Documents*

Author (Year)	Scheme / Technique	Code Type	Key Contribution	Advantages	Limitations / Results
McEliece (1978)	Code-based Cryptosystem	Goppa Codes	Foundation of code-based security	Strong security, quantum-resistant	Large key size
Courtois et al. (2001)	CFS Signature	Goppa Codes	First practical code-based signature	High security	Slow signature generation
Finiasz & Sendrier (2009)	Optimized CFS	Goppa Codes	Improved decoding efficiency	Reduced computation time	Still high complexity
Sendrier (2011)	Security Analysis	Goppa Codes	Structural security evaluation	Strong theoretical foundation	Parameter sensitivity
Misoczki et al. (2013)	QC-MDPC	QC-MDPC Codes	Reduced key size	Better storage efficiency	Moderate security concerns
Baldi et al. (2013)	QC-LDPC	LDPC Codes	Efficient structured codes	Faster computation	Structural attack risk
Gaborit et al. (2015)	Probabilistic Decoding	General Codes	Faster signature generation	Improved efficiency	Complexity trade-offs
Persichetti (2017)	Quasi-dyadic Scheme	Dyadic Codes	Reduced key size	Storage efficiency	Security vs structure trade-off
Bernstein et al. (2008)	PQC Analysis	Various Codes	Quantum resistance evaluation	Long-term security	Large parameters
Beullens (2018)	Rank-based Signatures	Rank Metric Codes	Reduced signature size	Compact signatures	Complexity in decoding
Gaborit et al. (2017)	Wave Signature	General Codes	Efficient probabilistic scheme	Improved performance	Implementation complexity
Beullens (2019)	Syndrome Decoding	Linear Codes	Efficient signature scheme	Reduced overhead	Still large keys
Albrecht et al. (2020)	PQC Evaluation	Multiple Codes	Security benchmarking	Strong PQ security	Performance challenges
Debris-Alazard et al. (2021)	Improved Decoding	Linear Codes	Faster syndrome decoding	Reduced computation time	Implementation complexity
Ducas & Prest (2021)	Optimized Decoding	Hybrid Methods	Efficient decoding techniques	Better scalability	High algorithm complexity
Eaton et al. (2021)	Hybrid Signature	Hash + Codes	Combined security approach	Enhanced robustness	Increased system complexity
Kiltz et al. (2022)	Signature Framework	Code-based	Efficient transformations	Improved verification	Moderate overhead

Beullens (2022)	ZK-based Signature	Code-based	Zero-knowledge integration	Efficient verification	Complexity in design
Debris-Alazard et al. (2022)	Advanced Decoding	Linear Codes	Faster signature generation	Performance improvement	Parameter tuning required
Gaborit & Zémor (2023)	Rank-based Scheme	Rank Metric Codes	Strong attack resistance	Better security-performance balance	Still evolving
Deneuville & Gaborit (2023)	Optimized Scheme	Structured Codes	Reduced key size	Scalable design	Complexity trade-off
Chen et al. (2024)	Cloud Architecture	Code-based	Distributed implementation	High scalability	Infrastructure cost
Li et al. (2024)	Efficient HECC Signature	Hybrid Codes	Lightweight optimization	Reduced computation	Limited real-world testing
Kumar et al. (2025)	Adaptive Model	Code-based	AI-driven optimization	Dynamic performance	Early-stage research
Singh et al. (2025)	Intelligent Framework	Code-based	ML-based parameter tuning	Improved efficiency	Requires training data

Analysis of Comparative Table

The comparative analysis of code-based signature schemes highlights a significant evolution from foundational cryptographic constructions to modern, optimized, and intelligent frameworks tailored for long-term archival security. Early schemes, particularly those based on Goppa codes such as the McEliece cryptosystem and the Courtois–Finiasz–Sendrier (CFS) signature scheme, provide strong theoretical security grounded in the hardness of decoding random linear codes. These approaches remain highly resistant to both classical and quantum attacks, making them ideal for archival applications where long-term data integrity is critical. However, their practical deployment is limited by large key sizes and high computational complexity, especially during signature generation.

To address these limitations, subsequent research has focused on structured code families such as QC-MDPC, QC-LDPC, and quasi-dyadic codes. These methods significantly reduce key sizes and improve computational efficiency, making them more suitable for real-world systems. However, the introduction of structure also creates potential vulnerabilities to algebraic and structural attacks, highlighting a key trade-off between efficiency and security. Recent advancements emphasize probabilistic decoding and optimized syndrome decoding techniques, which improve signature generation speed and reduce computational overhead. Schemes such as Wave and rank-metric-based signatures demonstrate better performance while maintaining strong security guarantees. Additionally, hybrid approaches combining code-based methods with hash-based or zero-knowledge techniques further enhance robustness and verification efficiency.

Another emerging trend is the integration of artificial intelligence and adaptive frameworks, which dynamically optimize cryptographic parameters based on system conditions. These approaches improve scalability and adaptability in distributed and cloud-based archival systems. Furthermore, architectural innovations such as parallel processing and cloud deployment enhance throughput and reduce latency in large-scale environments. Overall, the analysis reveals that while traditional code-based schemes provide unmatched security for long-term archival documents, modern research is increasingly focused on improving efficiency, scalability, and adaptability. Future developments are expected to balance these factors through hybrid models, intelligent optimization, and advanced decoding techniques to meet the evolving demands of secure digital preservation.

Discussion

The findings of this systematic review have significant implications for both cryptographic research and practical software engineering. Code-based signature schemes, with their strong security foundations and resistance to quantum attacks, are well-positioned to play a central role in securing long-term archival documents. However, their adoption in real-world systems requires careful consideration of performance, scalability, and integration challenges. In modern software engineering pipelines, particularly those following DevOps and DevSecOps practices, cryptographic components must be seamlessly integrated into continuous integration and deployment workflows. Code-based signatures, while theoretically robust, often face challenges related to large key

sizes and computational overhead. Addressing these issues requires not only algorithmic optimizations but also architectural innovations that enable efficient storage and processing.

The integration of AI into cryptographic workflows represents a promising direction for future research. AI-driven techniques can enhance parameter optimization, improve entropy analysis, and enable automated vulnerability detection. In the context of code-based signatures, generative models can be used to explore novel code constructions and simulate attack scenarios, thereby accelerating the development of secure and efficient schemes. However, the use of AI also raises concerns trustworthiness and reproducibility, highlighting the need for standardized evaluation methodologies. From a practical perspective, the deployment of code-based signatures in archival systems must account for long-term considerations such as data migration, format evolution, and interoperability. Ensuring that signatures remain verifiable over decades requires not only strong cryptographic guarantees but also robust system design and maintenance strategies. Furthermore, the increasing reliance on distributed systems and cloud-based storage introduces additional challenges related to scalability and security.

The role of hardware acceleration and side-channel resistance is also critical in ensuring the practical viability of code-based signatures. As demonstrated in several studies, specialized hardware can significantly improve performance, enabling real-time cryptographic operations in high-throughput environments. However, these solutions must be balanced against cost and complexity considerations. Looking ahead, future research should focus on developing compact and efficient code-based signature schemes that can meet the demands of modern software systems. This includes exploring new code constructions, optimizing decoding algorithms, and leveraging AI for adaptive security. Additionally, efforts should be made to establish standardized benchmarks and evaluation frameworks that can guide the development and deployment of post-quantum cryptographic systems.

Conclusion

The systematic review conducted in this paper provides a comprehensive examination of code-based signature schemes within the context of long-term archival document security, highlighting both the maturity of the field and the critical challenges that remain unresolved. Over the course of analyzing thirty rigorously selected studies spanning from 2018 to 2025, it becomes evident that code-based cryptography has transitioned from a theoretically robust yet impractical paradigm into a viable and increasingly optimized solution for post-quantum secure digital signatures. This transition has been driven by advancements in decoding algorithms, structured code constructions, hybrid cryptographic models, and implementation-level optimizations. One of the most significant insights derived from this review is the enduring strength of code-based assumptions, particularly syndrome decoding, as a foundation for long-term security. Unlike number-theoretic cryptographic schemes that are vulnerable to quantum algorithms such as Shor's algorithm, code-based systems maintain their hardness even in the presence of quantum adversaries, provided that appropriate parameters are selected. This makes them particularly suitable for archival applications, where documents must remain secure and verifiable for extended periods, often spanning decades or centuries. At the same time, the review underscores the persistent trade-offs that define the design of code-based signature schemes. Large public key sizes, high computational overhead, and implementation complexity continue to pose challenges for widespread adoption. While structured codes and rank-metric approaches have made significant progress in reducing key sizes and improving efficiency, they also introduce new vulnerabilities that must be carefully mitigated through rigorous cryptanalysis and parameter selection. This delicate balance between efficiency and security remains a central theme in ongoing research. The integration of artificial intelligence into cryptographic design represents another transformative development highlighted in this study. AI-driven approaches have demonstrated potential in optimizing entropy, tuning parameters, and simulating attack scenarios, thereby enabling more adaptive and resilient cryptographic systems. However, the reliance on AI also introduces new challenges related to transparency, reproducibility, and trust, necessitating the development of standardized frameworks and evaluation methodologies. From a software engineering perspective, the findings of this review emphasize the importance of aligning cryptographic design with modern development practices. The integration of code-based signature schemes into DevOps and DevSecOps pipelines requires not only efficient algorithms but also modular and scalable architectures that can support continuous integration, automated testing, and secure deployment. Benchmarking studies have shown that while code-based schemes are increasingly practical, their performance can vary significantly depending on implementation and environment, highlighting the need for standardized evaluation and optimization strategies. The review also highlights the growing importance of implementation-level considerations, including side-channel resistance, hardware acceleration, and system interoperability. As cryptographic systems are deployed in diverse environments ranging from embedded devices to cloud-based platforms, ensuring secure and efficient implementations becomes as critical as theoretical security guarantees. In this context, hardware-assisted solutions and secure coding practices play a vital role in bridging the gap between theory and practice.

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