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CRYPTOGRAPHIC APPROACHES TO FILE METADATA SECURITY IN MODERN INFORMATION SYSTEMS

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ABSTRACT

In modern information systems, file metadata has become an essential component for data management, interoperability, and automated processing. However, metadata often contains sensitive information such as authorship, timestamps, device identifiers, and contextual attributes, which can be exploited to compromise confidentiality and user privacy. While traditional security mechanisms primarily focus on protecting data content, metadata security remains insufficiently addressed.

This paper investigates cryptographic approaches to file metadata security in modern information systems. The proposed approach is based on selective cryptographic protection of metadata using symmetric, asymmetric, and hybrid encryption schemes. By treating metadata as a first-class security object, the approach ensures confidentiality, integrity, and controlled access while preserving system functionality and interoperability. Comparative analysis demonstrates that cryptographic protection provides stronger security guarantees than conventional metadata removal or obfuscation techniques, with minimal computational and storage overhead. The results indicate that cryptography-based metadata protection is a practical and effective solution for secure data exchange in enterprise systems, cloud environments, and electronic government platforms.

KEYWORDS

File metadata, Cryptographic protection, Information security, Metadata privacy, Information systems.

INTRODUCTION

Modern information systems rely heavily on metadata to support data organization, interoperability, and automated processing across heterogeneous platforms [1–4]. Metadata provides descriptive, structural, and administrative information about digital objects, but it also introduces significant security and privacy risks. Sensitive attributes such as user identity, timestamps, location, and device information may be exploited for inference, traffic analysis, and unauthorized profiling even when content data is encrypted [5–8].

Most existing security mechanisms focus on content protection, while metadata is often left unprotected or mitigated through removal and anonymization techniques. Although such approaches reduce direct exposure, they frequently disrupt interoperability, auditability, and automated workflows, particularly in enterprise and cloud environments [9–11].

Therefore, cryptographic approaches are increasingly required to protect metadata without eliminating its operational value. Cryptographic methods provide confidentiality, integrity, and controlled access while preserving essential metadata functionality. This paper analyzes metadata-related security threats, systematizes cryptographic techniques for metadata protection, and evaluates their effectiveness compared to traditional sanitization methods [12], [13].

Metadata Security Challenges in Modern Information Systems

File metadata is generated and processed throughout the data lifecycle, often automatically and without direct user control, which significantly increases its exposure to unauthorized analysis [5]. Unlike content data, metadata attributes such as timestamps, file size, identifiers, and communication frequency can be correlated to infer sensitive contextual information, even in encrypted environments [6–8].

In addition to confidentiality risks, unauthorized modification of metadata may compromise integrity and authenticity by falsifying authorship, provenance, or automated processing workflows, leading to regulatory and operational risks in electronic government and enterprise systems [9–11]. At the same time, metadata protection mechanisms must preserve interoperability and essential system functions such as indexing, access control, and auditing.

Therefore, effective metadata protection requires a balanced approach that combines strong security guarantees with operational usability. Cryptographic solutions address these requirements by enabling controlled access, protecting against inference-based attacks, and preserving metadata functionality across modern information systems [12], [13].

Cryptographic Approaches to Metadata Protection

Cryptographic approaches provide an effective solution for protecting file metadata by ensuring confidentiality, integrity, and controlled access while preserving metadata functionality [12]. Unlike metadata removal or obfuscation, cryptography enables secure handling of sensitive metadata attributes without disrupting interoperability or automated processing.

Symmetric encryption algorithms such as AES are widely applied

to protect sensitive metadata fields due to their efficiency and low computational overhead, especially in cloud and enterprise environments [14]. Selective encryption of attributes such as authorship identifiers, timestamps, and device-related information minimizes performance impact while reducing information leakage [5]. Asymmetric cryptographic techniques, including RSA and elliptic curve cryptography (ECC), address secure key distribution and access control by protecting symmetric metadata keys rather than the metadata itself, which is particularly relevant in multi-user and inter-organizational systems [15], [16], [10]. Hybrid cryptographic models combine symmetric encryption for metadata protection with public-key techniques for key management, providing scalability, efficiency, and flexible access control in heterogeneous information systems [13], [12]. In addition to confidentiality, metadata integrity and authenticity are ensured through cryptographic hash functions, HMAC, and digital signatures, enabling detection of unauthorized modifications and verification of provenance [18], [19].

Overall, cryptographic approaches offer stronger security guarantees and higher resistance to inference-based attacks than traditional sanitization methods. However, their effectiveness depends on proper key management and policy enforcement, which remain critical challenges in large-scale deployments [20]. Despite these limitations, cryptography-based metadata protection represents a practical and robust foundation for securing metadata in modern information systems.

Performance and Security Analysis

This section evaluates the performance and security of cryptographic approaches for metadata protection, focusing on computational overhead, storage impact, and resistance to metadata-based attacks [12], [13]. Selective encryption of sensitive metadata introduces minimal overhead, as symmetric algorithms such as AES efficiently process small metadata sizes, even in high-throughput environments [14]. Asymmetric cryptographic operations are mainly limited to key exchange and access control, resulting in negligible performance impact [15].

Cryptographic protection causes a modest increase in file size due to encrypted metadata and integrity-related information; however, this overhead remains proportional to metadata size and does not affect interoperability or usability [11]. From a security perspective, encrypted metadata prevents unauthorized extraction and significantly reduces inference and profiling attacks, while integrity mechanisms such as HMAC and digital signatures reliably detect unauthorized modifications [5], [6], [18], [19].

Compared to metadata removal and obfuscation, cryptographic approaches provide stronger and more reliable protection without disrupting system functionality, offering a favorable balance between security and performance for modern information systems [9], [10], [20].

CONCLUSION

This paper examined cryptographic approaches to file metadata security in modern information systems, highlighting metadata as a significant yet often overlooked source of security and privacy risks. Unlike traditional content-focused protection mechanisms, metadata can enable inference attacks and unauthorized profiling even in encrypted environments.

The study systematized symmetric, asymmetric, and hybrid cryptographic techniques for selective metadata protection, ensuring confidentiality, integrity, and controlled access while preserving interoperability. Compared to metadata removal and obfuscation, cryptographic protection provides stronger security guarantees with minimal performance and storage overhead.

The results confirm the practical applicability of cryptography-based metadata protection in enterprise, cloud, and electronic government systems. Future research should address key management and access control challenges through intelligent metadata classification and adaptive policy enforcement to further improve scalability and robustness.

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