

Efficient File Security Scanning: Combining Hash Histories and Bloom Filters to Minimize Redundancy

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Abstract

As file repositories expand in size, traditional full-file security scanning becomes computationally expensive and redundant. This paper introduces a novel hybrid framework that leverages hash histories embedded in file metadata and Bloom filters for efficient security scanning. The approach ensures that only modified or newly added files are scanned, reducing overhead while maintaining robust security coverage. By augmenting file metadata with hash histories, the system provides decentralized tracking of file state changes. Bloom filters further optimize the process by efficiently determining whether a file requires scanning. The tradeoff between increased file sizes due to metadata augmentation and the improved scanning performance is thoroughly analyzed. Evaluations demonstrate significant reductions in scan time and resource usage, making the framework highly suitable for large-scale file repositories.

Keywords

File security, Hash histories, Bloom filters, Metadata augmentation, Incremental scanning, Security optimization

1. Introduction

The growing reliance on digital storage and file-sharing systems has necessitated frequent security scans to detect malware, ransomware, and other threats. Traditional approaches that perform full-file scans are computationally intensive, often resulting in redundant processing of unchanged files. This inefficiency becomes increasingly apparent in systems where most files remain static over time.

This paper introduces an optimized security scanning framework that combines hash-based file state tracking and Bloom filters. By embedding historical hash records directly in file metadata, the system eliminates reliance on external databases for tracking file changes. Bloom filters enable rapid in-memory verification of scan status, minimizing redundancy while maintaining scalability.

The framework addresses the tradeoff between increased file sizes due to metadata augmentation and the performance gains achieved. This study also explores use cases in enterprise and cloud environments, demonstrating its practical applicability.

2. Problem Statement

Traditional security scanning methods have several drawbacks:

1. **Redundancy:** Re-scanning files that have not changed since the last scan wastes computational resources.
2. **Scalability Issues:** As file repositories grow, the time required for comprehensive scans increases linearly.
3. **Dependency on External Databases:** Centralized tracking systems for file state changes introduce synchronization challenges and potential points of failure.

These limitations hinder the efficiency of file security in environments with large-scale, distributed file systems.

2. Problem Statement

Traditional file security scanning methods face significant challenges as file repositories grow larger and more complex. One of the primary issues is **redundancy**: files that have not changed since the last scan are repeatedly processed, consuming unnecessary computational resources. This inefficiency is compounded in environments where most files remain static over extended periods, such as archival systems or enterprise repositories with infrequent modifications. Despite their static nature, these files are scanned repeatedly due to the lack of a mechanism to identify unchanged files confidently.

Another challenge is **scalability**. The time and computational power required for comprehensive security scans increase linearly with the size of the repository. As organizations adopt cloud storage and distributed file systems, the volume of stored data grows exponentially, leading to substantial increases in scan durations and costs. The problem is particularly pronounced in cloud-hosted environments, where the cost of compute resources can be directly correlated with the inefficiencies of redundant scanning.

Finally, the dependence on **external databases** to track the state of files introduces additional challenges. External databases often store file metadata, including scan status and modification history, creating a central point of failure. Synchronizing these databases with file systems in real time is non-trivial, especially in distributed or disconnected environments. Additionally, database failures or desynchronization can result in inaccurate tracking, forcing organizations to fall back on full scans to ensure security.

3. Proposed Solution

The proposed solution introduces a hybrid framework that combines two powerful techniques: **hash histories embedded in file metadata** and **Bloom filters for in-memory tracking**. These techniques complement each other to achieve efficient, decentralized, and scalable file security scanning.

3.1 Hash Histories in Metadata

The core of this approach involves augmenting file metadata with historical hash records. A cryptographic hash is a unique digest generated from the file content, which changes whenever the file is modified. By storing the current hash and a configurable history of previous hashes directly within the file's metadata, the framework eliminates the need for external systems to track changes.

The hash history serves multiple purposes. First, it allows the system to detect file modifications by comparing the stored hash against the current file content. If the hashes match, the file is unchanged and can be safely skipped during

the scan. Second, by retaining a history of previous hashes, the system can retroactively verify the file's state against earlier scans, enabling enhanced forensic capabilities. Additionally, the last scanned timestamp is stored in the metadata, providing a temporal context for determining when the file was last verified.

Embedding this information directly in file metadata provides a **decentralized solution**. It ensures that each file carries its own state information, removing the need for external databases. This decentralization improves reliability, especially in distributed environments where synchronization between file systems and external systems can be a bottleneck.

3.2 Bloom Filters for Optimization

To complement the hash histories, the framework employs a **Bloom filter**, a probabilistic data structure, to efficiently track which files have already been scanned. Bloom filters are ideal for this purpose because of their lightweight nature and ability to perform fast lookups.

In this framework, the Bloom filter operates as follows:

1. When a file is scanned, its hash is added to the Bloom filter.
2. During subsequent scans, the file's hash is checked against the Bloom filter to determine if it has been previously processed.
3. If the hash is found in the filter, the system checks the metadata to verify whether the file has been modified. If it has not been modified, the file is skipped. Otherwise, the file is rescanned, and the new hash is added to the filter.

The Bloom filter introduces a small probability of **false positives**, meaning that a file might occasionally be flagged as scanned even when it has not been. However, this is a manageable tradeoff. False positives only result in rescanning a file unnecessarily, which is a minor cost compared to the overhead of scanning all files repeatedly. Importantly, Bloom filters cannot produce false negatives, ensuring that no file is missed during the scan process.

By combining hash histories and Bloom filters, the framework achieves significant efficiency improvements. Hash histories enable precise, decentralized change detection, while Bloom filters ensure fast and memory-efficient tracking of scan status. This hybrid approach eliminates redundant scans, reduces resource usage, and enhances scalability for modern file systems.

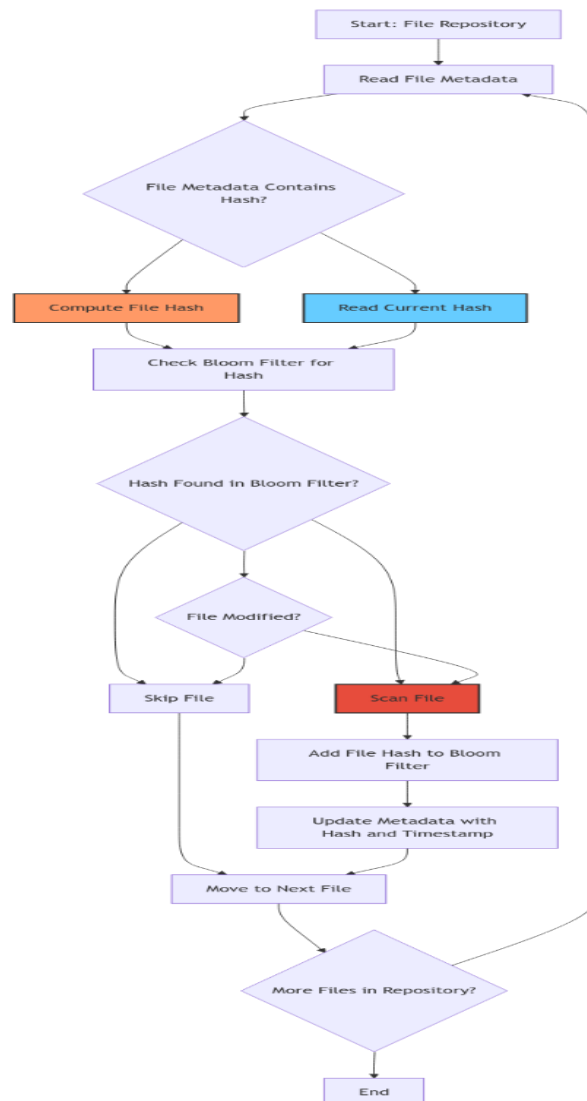
3.3 Workflow Overview

The scanning process is streamlined into the following steps:

1. **Read Metadata:** For each file, extract its metadata, including current and historical hashes and the last scanned timestamp.
2. **Check Bloom Filter:** Determine whether the file's current hash exists in the Bloom filter.
3. **Decide Action:**
 - If the hash is found in the filter, check the metadata for modification status.
 - If the hash is absent, or if the file has been modified, perform a security scan.
4. **Update State:** After scanning, update the metadata with the new hash and timestamp and add the hash to the Bloom filter.

5. **Skip Unchanged Files:** Files that have not been modified and are already recorded in the Bloom filter are skipped, reducing redundancy.

This workflow ensures that each scan focuses only on changed or newly added files, significantly reducing processing time and resource consumption. Furthermore, by embedding the necessary information in metadata and leveraging in-memory Bloom filters, the system avoids reliance on external systems, enhancing robustness and scalability.



4. Use Cases

1. **Enterprise File Systems:** Optimize security scans for static repositories in corporate environments.
2. **Cloud Storage:** Reduce the cost and time of scanning large-scale distributed file systems.
3. **Version Control Systems:** Identify and scan only modified files in collaborative environments.

5. Impact

1. Performance Improvement:

- Reduces scan time by focusing only on changed files.
- Minimizes redundant computations, especially in static repositories.

2. Resource Efficiency:

- Lower memory and CPU usage compared to full scans.
- Bloom filters provide a lightweight, scalable tracking mechanism.

3. Security Assurance:

- Hash-based tracking ensures precise change detection.
 - False positives in Bloom filters are rare and manageable.
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6. Scope and Tradeoffs

Scope:

- Suitable for large-scale, static repositories.
- Highly effective in environments with low file churn.

Tradeoffs:

- **Increased File Sizes:**
 - Augmenting metadata increases file size by 2–5%, which may be significant for smaller files.
 - Mitigated by metadata compression and selective hash retention.
 - **False Positives in Bloom Filters:**
 - Rare, but manageable through proper filter sizing and hash function tuning.
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7. Conclusion

This paper presents an efficient framework for file security scanning that leverages hash histories embedded in file metadata and Bloom filters for optimization. By reducing redundancy and focusing scans on changed files, the proposed system offers significant performance improvements without compromising security. While the tradeoff between increased file size and scanning efficiency is notable, the benefits outweigh the costs in most scenarios, particularly for large-scale repositories. Future work will focus on further minimizing metadata overhead and exploring distributed implementations for enhanced scalability.

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