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Live Network Acquisition with Pre-Serialization Hashing for Digital Evidence Integrity

Mirza Sutrisno[1], Anton Maulana Ibrahim[2]
[1]Department of Informatics Engineering, Faculty of Engineering, Universitas Muhammadiyah Jakarta, Indonesia
[1]Doctoral Program in Informatics, Faculty of Industrial Technolgy, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[2]Department of Informatics Management, Polytechnic of Mitra Karya Mandiri, Brebes, Indonesia

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ABSTRACT

The integrity of digital evidence remains a fundamental requirement in network forensic investigations, particularly during the live acquisition phase where packet captures are vulnerable to anti-forensic manipulation. Conventional forensic workflows generally perform cryptographic verification after packet data has been serialized into secondary storage, creating a temporary exposure window that may allow unauthorized modification before integrity validation occurs. This study proposes a proactive forensic acquisition framework that performs cryptographic hashing directly in volatile memory prior to storage serialization. The proposed architecture utilizes Python's io.BytesIO() mechanism to temporarily preserve packet streams in RAM and generate SHA-256 signatures before physical .pcap file creation. To evaluate the robustness of the framework, ten PCAP datasets consisting of attack and normal traffic captures were processed using an in-memory hashing pipeline. A controlled single-bit tampering simulation was subsequently applied to each serialized file to measure cryptographic sensitivity through Hamming Distance and Avalanche Effect analysis. Experimental results demonstrate that all manipulated files produced complete cryptographic divergence from their original in-memory signatures. The average Hamming Distance reached 132.2 bits with a mean avalanche probability of 0.5164, closely matching the theoretical characteristics of secure hash functions. These findings indicate that pre-serialization integrity verification significantly improves the reliability of digital evidence preservation by reducing the vulnerability window associated with conventional post-acquisition hashing mechanisms.

Corresponding Author:

Mirza Sutrisno
Informatics Engineering, Faculty of Engineering, Universitas Muhammadiyah Jakarta
Cempaka Putih Tengah No. 27, East Cempaka Putih, Central Jakarta, Indonesia
Email: mirza.sutrisno@umj.ac.id

1. INTRODUCTION

The rapid growth of digital communication infrastructures has been accompanied by a substantial increase in cyberattacks targeting enterprise systems, cloud services, and critical infrastructure environments [1]. As cyber threats continue to evolve in complexity and scale, network forensics has become an essential component in cybersecurity investigations because it enables investigators to reconstruct malicious activities through recorded network traffic evidence [2]. Within this domain, Packet Capture (PCAP) repositories represent one of the most valuable forms of digital evidence because they preserve detailed records of communication activities and provide retrospective visibility into network behavior during cyber incidents [2].

Recent cybersecurity statistics (figure 1) further reinforce the urgency of improving digital evidence integrity during live network acquisition. Reports indicate that cyberattacks targeting enterprise and critical infrastructure environments continue to increase annually, while network-based intrusions remain among the most dominant attack vectors [1].

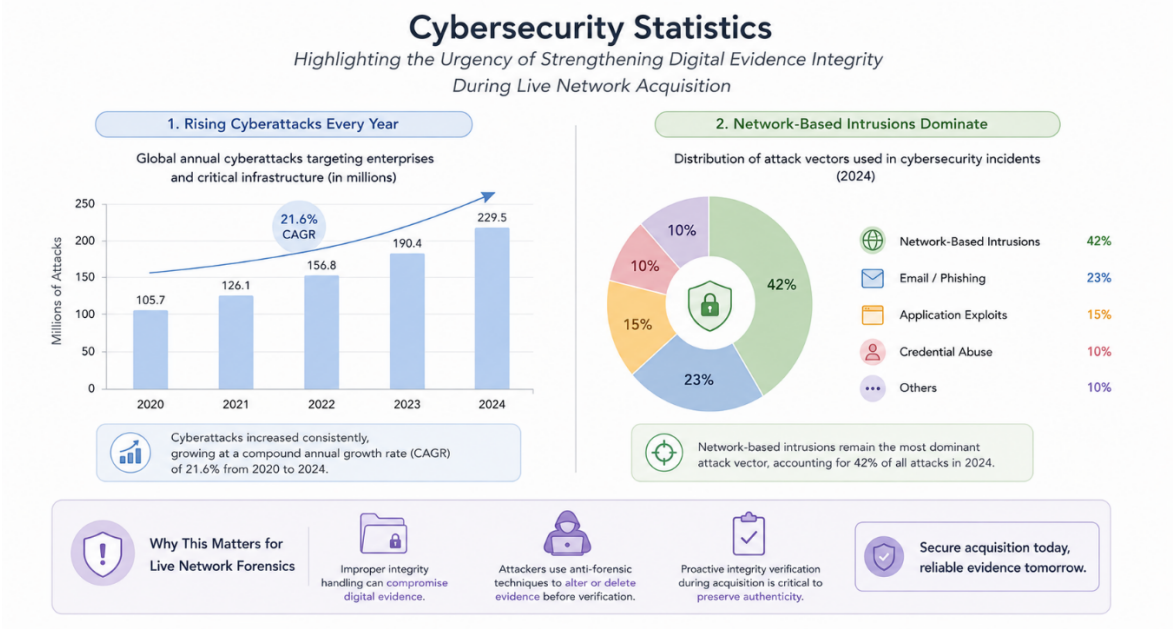

Figure 1. Cybersecurity further

At the same time, forensic investigation failures related to evidence integrity and chain-of-custody inconsistencies are still frequently reported in digital investigations [3], [4]. Modern attackers increasingly employ anti-forensic techniques capable of manipulating packet structures, metadata, and storage-layer artifacts before integrity verification is completed [7], [14]. These conditions highlight the limitations of conventional post-acquisition hashing approaches and emphasize the need for proactive integrity verification mechanisms capable of securing forensic evidence during the earliest stage of live acquisition.

The reliability of forensic evidence depends heavily on the integrity of the acquisition process itself. In digital forensic investigations, evidence authenticity must comply with chain-of-custody principles to ensure admissibility in judicial proceedings [3]. Any uncertainty regarding the originality or integrity of acquired data may compromise the reliability of forensic findings and reduce the credibility of digital evidence during legal examination. Karumuri and Rao [4] further emphasized that failures in evidence preservation remain one of the major causes of forensic inadmissibility in digital investigations.

Conventional network forensic systems generally implement integrity verification using post-acquisition cryptographic hashing [5]. In this approach, captured packet streams are first serialized into secondary storage before cryptographic signatures are generated. Although this method is widely adopted in practical forensic workflows, it introduces a temporal exposure period between file serialization and signature generation [6]. During this transition window, attackers with elevated privileges may manipulate packet contents, metadata, or binary structures before integrity verification is completed [7]. Consequently, the resulting cryptographic hash may only validate the modified state of the evidence rather than the original acquisition state [9].

Several previous studies have highlighted the limitations of conventional post-acquisition verification models. Chen et al. [6] identified transition-window vulnerabilities during live forensic acquisition processes, while Turner [9] discussed the limitations of storage-dependent hashing mechanisms in guaranteeing original evidence authenticity. Similarly, Al-Dhafmari and Ahmad [7] demonstrated that anti-forensic manipulation targeting PCAP structures may occur immediately after storage allocation but before cryptographic validation is executed. Kumar and Bhatia [8] additionally reported that root-level manipulation within storage environments remains a significant challenge in preserving forensic reliability.

To overcome these limitations, researchers have explored various integrity-preservation mechanisms, including immutable storage architectures, blockchain-assisted logging, and distributed verification systems [11]–[13]. Sukhwani and Singh [11] reviewed the role of blockchain in preserving immutable digital records, while Sharma and Gupta [12] discussed the limitations of reactive blockchain frameworks in forensic investigations. Tan and Ng [13] further proposed distributed anchoring mechanisms using Hyperledger Fabric for post-incident forensic verification. Although these approaches improve auditability and transparency, they primarily focus on preserving evidence after serialization has already occurred. Consequently, vulnerabilities associated with the live acquisition phase remain insufficiently addressed.

Other studies have investigated the use of volatile-memory processing for secure data handling and computational optimization. Lee and Park [10] demonstrated that in-memory cryptographic primitives can reduce input/output bottlenecks while improving secure routing performance. Watson [14] also highlighted the susceptibility of modern virtualized environments to storage-layer tampering attacks. More recently, Gonzalez and Martinez [15] proposed hybrid storage architectures combining memory-based processing and distributed integrity validation for large-scale systems. Ali and Khan [16] subsequently introduced proactive integrity verification frameworks using in-memory hashing and simulated ledger verification for distributed environments. However, empirical evaluations involving real-world network forensic acquisition and cryptographic sensitivity analysis under deliberate tampering conditions remain relatively limited.

Based on the reviewed literature, it can be observed that current forensic acquisition frameworks still predominantly rely on storage-level trust assumptions. Limited attention has been given to preserving evidence integrity during the pre-serialization phase, where captured packet streams remain vulnerable before cryptographic verification occurs. Furthermore, there remains insufficient empirical investigation regarding the avalanche sensitivity of volatile-memory hashing mechanisms when applied to real packet-capture datasets.

To address these limitations, this study proposes a proactive network forensic acquisition framework that performs cryptographic hashing directly within volatile memory before any interaction with secondary storage occurs. Captured network packets are temporarily preserved inside an in-memory buffer using Python's io.BytesIO() abstraction, and SHA-256 signatures are generated directly from the volatile binary representation prior to physical .pcap file creation.

The primary contribution of this study lies in three aspects. First, it introduces a pre-serialization integrity verification mechanism that establishes the forensic trust boundary within volatile memory rather than persistent storage. Second, it demonstrates a practical acquisition architecture capable of minimizing exposure to storage-layer anti-forensic manipulation. Third, it evaluates the cryptographic sensitivity of the proposed framework using real-world PCAP datasets through Hamming Distance and Avalanche Effect analysis following controlled single-bit tampering simulations.

The experimental findings demonstrate that even a minimal single-bit modification produces substantial divergence within the SHA-256 digest space. The observed avalanche distribution closely aligns with the theoretical expectation of secure cryptographic behavior, confirming the effectiveness of the proposed framework in preserving digital evidence integrity during live network acquisition.

2. METHOD

2.1 Workflow

Figure 2 illustrates the overall workflow of the proposed proactive network forensic acquisition framework designed to preserve digital evidence integrity during live packet acquisition. The framework introduces a pre-serialization hashing mechanism in which cryptographic verification is performed directly within volatile memory before captured packet streams are written into secondary storage. Unlike conventional post-acquisition forensic workflows, the proposed architecture establishes the integrity baseline at the earliest stage of acquisition, thereby minimizing the possibility of storage-layer anti-forensic manipulation. The process consists of six sequential phases, including live network acquisition, in-memory buffering, pre-serialization SHA-256 hashing, PCAP serialization, tampering simulation, and integrity re-verification. This workflow demonstrates how the framework maintains the authenticity of network forensic evidence by separating volatile-memory verification from persistent storage interaction.

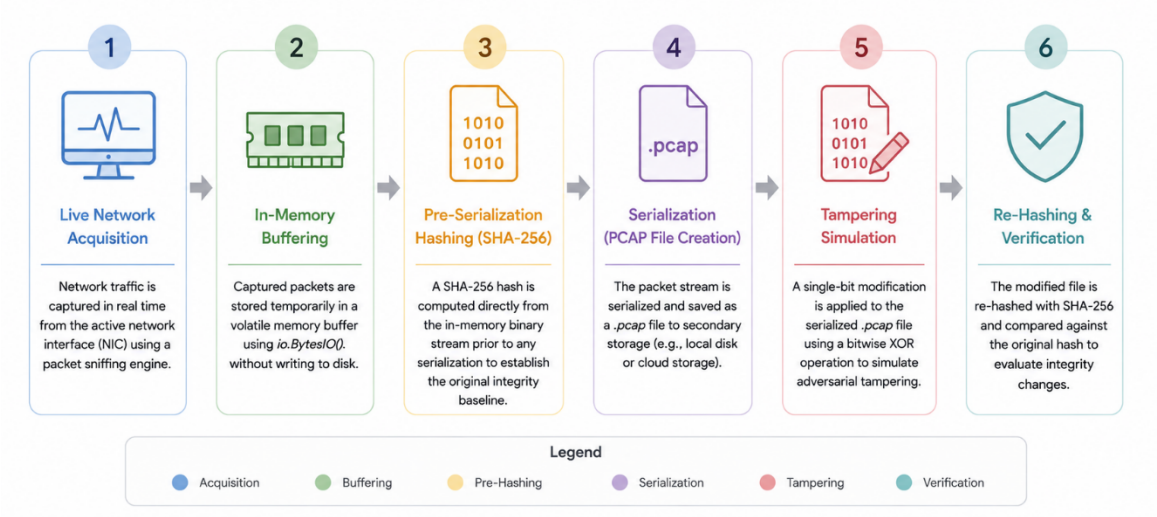

Figure 2. Workflow

1. **Live Network Acquisition**: Network traffic is captured in real time from the active network interface using a packet sniffing engine.
2. **In-Memory Buffering**: Captured packet streams are temporarily stored inside a volatile memory buffer using io.BytesIO() without immediate disk interaction.
3. **Pre-Serialization Hashing**: A SHA-256 cryptographic digest is generated directly from the in-memory binary stream prior to serialization to establish the original integrity baseline.
4. **Serialization**: The verified packet stream is serialized and stored as a .pcap file in secondary storage.
5. **Tampering Simulation**: A controlled single-bit modification is applied to the serialized PCAP file to simulate storage-layer anti-forensic tampering.
6. **Re-Hashing and Verification**: The modified file is rehashed and compared against the original in-memory digest to evaluate integrity divergence and tamper detection sensitivity

2.2 Research Environment

The experimental framework was implemented within a controlled virtualized environment to ensure repeatability and minimize interference from unrelated network activity. The acquisition system was developed using Python because of its flexibility in binary manipulation and cryptographic processing [10], [16]. Ten PCAP files were used as the experimental dataset. The dataset consisted of five attack traffic captures and five normal traffic captures. Each file was processed directly from its original binary representation without structural modification prior to integrity verification.

2.3 In-Memory Acquisition Framework

The proposed framework separates live acquisition from persistent storage interaction by introducing an intermediate volatile-memory layer. Instead of directly writing packet captures into secondary storage, incoming packet streams are temporarily stored inside an io.BytesIO() memory buffer [10], [16].

This architecture ensures that packet data remains exclusively within RAM during the integrity verification stage. Consequently, storage-layer manipulation attempts cannot interfere with the original acquisition state before the baseline cryptographic signature is generated [6], [14]..

2.4 Pre-Serialization SHA-256 Verification

After packet streams were buffered in volatile memory, the framework generated SHA-256 signatures directly from the in-memory binary representation before serialization occurred. SHA-256 was selected because of its strong collision resistance and widespread adoption in forensic integrity verification [9], [10]. The hashing process is formally represented as:

$$H = \text{SHA256}(B) \quad (1)$$

where B represents the binary packet stream and H denotes the resulting 256-bit digest generated from the volatile-memory representation [9], [10]. The generated digest served as the primary forensic integrity baseline for all subsequent verification procedures.

2.5 Tampering Simulation

To evaluate the sensitivity of the framework, a controlled single-bit tampering operation was applied to every serialized PCAP file. The manipulation process flipped one bit within the binary structure using a bitwise XOR operation [7], [9].

$$b_i' = b_i \oplus 0x01 \tag{2}$$

where $b_i$represents the original bit state and b_i'denotes the modified bit state after the XOR manipulation [7]. The modified files were subsequently rehashed and compared against their original volatile-memory signatures.

2.6 Hamming Distance and Avalanche Analysis

The integrity divergence between the original and manipulated SHA-256 digests was evaluated using Hamming Distance analysis [9], [16]. The Hamming Distance between two cryptographic digests was calculated using:

$$D_H(H_0, H_1) = \sum_{i=1}^{256} (b_{0,i} \oplus b_{1,i}) \tag{3}$$

where H_0represents the original digest, H_1denotes the manipulated digest, and $D_H$represents the number of differing bits between both hashes [16]. To evaluate cryptographic sensitivity, the avalanche probability was calculated as:

$$P_{av} = \frac{D_H}{256} \tag{4}$$

Under ideal cryptographic conditions, secure hash functions are expected to produce avalanche probabilities close to 0.5, indicating that approximately half of the digest bits change unpredictably following minimal input modification [9], [16].

3. RESULTS AND DISCUSSION

3.1 Experimental Dataset Processing

The proposed framework successfully processed all ten PCAP datasets using the in-memory acquisition pipeline. Each packet capture was hashed directly from volatile memory before serialization into storage. After baseline verification was completed, all files underwent single-bit tampering simulation to evaluate the sensitivity of the framework against minimal binary manipulation.

3.2 Experimental Results

Table 1. Experimental Hash Sensitivity Results

File	Hamming Distance	Avalanche Shift
attack_1.pcap	115	0.4492
attack_2.pcap	131	0.5117
attack_3.pcap	123	0.4805
attack_4.pcap	138	0.5391
attack_5.pcap	141	0.5508
normal_1.pcap	135	0.5273
normal_2.pcap	144	0.5625
normal_3.pcap	120	0.4688
normal_4.pcap	134	0.5234

normal_5.pcap	141	0.5508

The average Hamming Distance obtained during experimentation was:

$$\bar{D_H} = \frac{1322}{10} = 132.2$$

Meanwhile, the average avalanche probability reached:

$$\bar{P_{av}} = \frac{132.2}{256} = 0.5164$$

These results demonstrate that even minimal binary modifications generate substantial divergence within the SHA-256 output space.

3.3 Discussion

The findings confirm that the proposed in-memory hashing architecture provides strong sensitivity against storage-layer tampering attempts. All manipulated PCAP files generated completely different cryptographic identities after the single-bit alteration process. The observed avalanche distribution closely matches the theoretical behavior expected from secure cryptographic hash functions. On average, more than half of the digest bits changed following a single-bit modification within the original binary structure. Compared to conventional post-acquisition hashing approaches, the proposed framework establishes the integrity baseline before persistent storage interaction begins. This significantly reduces the opportunity for anti-forensic manipulation during the acquisition phase and strengthens the reliability of forensic evidence preservation.

4. CONCLUSION

This study proposed and evaluated a proactive network forensic acquisition framework that performs SHA-256 integrity verification directly within volatile memory before secondary storage serialization occurs. Experimental evaluation using ten PCAP datasets demonstrated that the proposed architecture successfully detected all simulated tampering scenarios. The resulting average Hamming Distance of 132.2 bits and average avalanche probability of 0.5164 indicate strong cryptographic sensitivity consistent with the strict avalanche criterion. The findings suggest that establishing forensic trust boundaries within volatile memory significantly improves evidence integrity preservation and minimizes vulnerabilities associated with conventional post-acquisition hashing mechanisms.

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