Entropy-Aware Cryptographic Primitives for Secure Key Management in Legacy Cryptocurrency Wallets

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***Abstract*---**Legacy cryptocurrency wallets, particularly those developed during the early phases of blockchain adoption, often operate in environments with limited entropy availability, compromising the security of private key generation and digital signature schemes. In such systems, inadequate randomness can lead to predictable keys and repeated nonce reuse, making them susceptible to key recovery and signature forgery attacks. This paper presents an in-depth study of entropy-aware cryptographic primitives that are designed to mitigate such vulnerabilities. We examine historical entropy generation mechanisms across various early software and hardware wallets, identify entropy deficiencies, and evaluate real-world exploits that stem from such weaknesses. Furthermore, we propose enhancements involving hybrid entropy models and hash-based key derivation functions (HKDF) to strengthen the randomness quality while maintaining compatibility with legacy systems. Experimental validation using emulated environments of early wallets shows that our proposed approach significantly improves key unpredictability and digital signature reliability, without introducing prohibitive computational overhead. These findings underscore the critical need for entropy resilience in legacy systems to uphold cryptographic integrity in blockchain applications.

Keywords---Entropy analysis, Key generation, Cryptocurrency wallets, Digital signatures, Legacy systems, Hash-based cryptography, Wallet security, Entropy-aware primitives.

I. INTRODUCTION

The widespread adoption of cryptocurrency has led to significant advancements in cryptographic security, yet many early wallets still in use today suffer from foundational weaknesses. These legacy wallets were often implemented with minimal entropy safeguards, rendering key generation and signature algorithms vulnerable to cryptographic attacks. Since cryptographic strength fundamentally relies on high-quality randomness, entropy insufficiencies can directly undermine the security guarantees of these systems.

In environments such as air-gapped hardware wallets or early mobile devices, entropy sources like mouse movement or thermal noise were either weak or improperly seeded. As a result, key material and digital signatures derived from these systems may lack the required unpredictability, increasing the risk of brute-force attacks and nonce reuse in elliptic curve signatures.

Addressing this problem, our work focuses on entropy-aware cryptographic primitives capable of integrating with legacy systems. We aim to enhance the unpredictability of key material and protect against digital signature attacks without requiring significant modifications to the original wallet implementations. Our solution leverages hybrid entropy models and modern hash-based cryptographic techniques to reinforce key security while maintaining backward compatibility.

II. LITERATURE REVIEW

Recent studies have highlighted the importance of high-entropy sources in cryptographic applications, especially in blockchain-based systems. Bonneau et al. [1] emphasized how weak entropy during wallet initialization leads to widespread vulnerabilities in Bitcoin key management. Similarly, Giechaskiel et al. [2] detailed hardware entropy failures, especially in constrained IoT and embedded systems used in early cold storage wallets.

Elliptic Curve Digital Signature Algorithm (ECDSA) weaknesses due to poor nonce generation were exploited in real-world attacks, such as the PlayStation 3 incident and Bitcoin address leaks [3], [4]. This has prompted researchers to explore deterministic alternatives like RFC 6979 [5], which reduces the reliance on random nonces. However, these

approaches still assume a minimum entropy threshold that legacy systems often fail to meet.

Other works such as by Yilek et al. [6] demonstrated how virtual machine snapshots and entropy reuse lead to predictable SSL keys. Tools like Fortuna and HAVEGE were proposed to mitigate entropy bottlenecks [7], yet their integration into legacy wallets has been minimal. Additionally, studies like those by Lenstra et al. [8] have shown the need for cross-platform entropy hardening and hybrid approaches combining environmental and deterministic entropy models.

III. METHODOLOGY

3.1 Entropy Source Profiling in Legacy Wallets

We first profiled entropy collection mechanisms across a variety of legacy wallets, including early versions of Bitcoin Core and Electrum. Using reverse engineering and dynamic tracing, we identified points of entropy injection, such as system clock, file access patterns, and device identifiers. These were then evaluated for entropy contribution using NIST SP 800-90B statistical entropy tests.

Figure 1: Entropy Source Profiling in Legacy Cryptocurrency Wallets Using Reverse Engineering and Statistical Testing

3.2 Hybrid Entropy Augmentation Model

To compensate for low-entropy environments, we designed a hybrid model that combines environmental noise (e.g., clock jitter, ambient light sensors) with cryptographic hash-based entropy pooling. A SHA-512-based entropy harvester aggregates weak sources and feeds them into an HKDF (HMAC-based Key Derivation Function) to derive secure private keys. This model ensures robustness against partial entropy failures.

3.3 Emulation and Security Validation

Legacy wallet behavior was emulated in QEMU-based virtual environments replicating early Linux and mobile OS platforms. Simulated attacks—including entropy reuse, nonce prediction, and collision-based signature forgeries—were applied. Our hybrid entropy module was integrated and tested across 50 wallet instances, and entropy quality was re-evaluated post-modification.

IV. RESULTS AND DISCUSSION

4.1 Entropy Weakness Characterization

The entropy profile of unmodified legacy wallets revealed an average Shannon entropy score of just 0.45 bits/byte. Time-of-day and system PID were frequently used alone, making key generation deterministic under certain conditions.

4.2 Hybrid Model Performance

Our augmented model raised entropy levels to over 7.8 bits/byte, as validated using Diehard and ENT randomness tests. Key unpredictability improved significantly without requiring modifications to the original wallet source code.

4.3 Signature Security Enhancement

With HKDF integration, ECDSA signatures exhibited no nonce reuse or leakage vulnerabilities under simulated conditions. Attackers were unable to derive private keys even under constrained entropy scenarios.

4.4 Overhead and Compatibility

Our entropy enhancement approach increased execution time by only 2–3 ms during key generation, which is negligible for practical use. Legacy wallet emulation confirmed that the hybrid module remains backward-compatible and does not interfere with wallet integrity.

V. CONCLUSION

Entropy deficiencies in legacy cryptocurrency wallets pose a significant threat to secure key management and digital signature integrity. Our analysis identified systemic weaknesses in early entropy sources and demonstrated how entropy-aware cryptographic primitives—particularly those based on hybrid entropy harvesting and hash-based derivation functions—can effectively mitigate these vulnerabilities. By enhancing randomness quality through lightweight cryptographic modules, we show that it is possible to improve the resilience of legacy wallets without incurring significant computational overhead or compromising backward compatibility. This work underscores the importance of entropy audits in cryptographic software and opens a path toward post-facto hardening of historical wallet implementations still in use today.

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