Assessing Signature Stability and Entropy-Dependent Key Derivation in Early Blockchain Wallet Protocols

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Abstract---The robustness of digital signatures in early blockchain wallets is closely tied to the entropy used in key derivation. This study systematically evaluates the stability of elliptic curve signatures under varying entropy conditions during key generation in early cryptocurrency implementations. We highlight real-world vulnerabilities and propose an entropy-quality assessment framework, along with entropy-enhanced key derivation mechanisms. Simulations show that entropy-dependent variances can significantly affect signature reproducibility and integrity, with implications for wallet security and blockchain forensics. Our findings emphasize the necessity of integrating entropy validation during key generation and propose enhancements to entropy gathering techniques in resource-constrained or entropy-starved environments. The study also analyzes historical incidents where weak entropy led to exploitable signature malleability or private key exposure, particularly under the ECDSA scheme. Through experimental validation using both synthetic entropy profiles and real-world blockchain data, the proposed mechanisms demonstrate enhanced resistance to signature manipulation and unauthorized key recovery. This work contributes a critical security layer for legacy and emerging blockchain wallet protocols, ensuring cryptographic robustness in decentralized systems reliant on high-assurance key management.

Keywords---Signature stability, blockchain wallets, entropy in cryptography, key derivation, ECDSA reliability, signature malleability, digital integrity, entropy-quality assessment

I. Introduction

The integrity of digital signatures lies at the heart of blockchain security. Wallet protocols—especially in the early days of Bitcoin and other cryptocurrencies—relied heavily on Elliptic Curve Digital Signature Algorithm (ECDSA) for transaction signing. However, the strength of these signatures was not just a function of the cryptographic algorithm itself but also of the entropy used in key generation. Low-entropy environments introduced vulnerabilities that could compromise private keys and thus the security of wallet funds.

Early blockchain implementations, often executed on resource-constrained devices or poorly seeded random number generators, generated private keys with inadequate entropy. This resulted in deterministic or predictable signature patterns, increasing the probability of private key exposure. Several documented incidents, including high-profile attacks on Bitcoin wallets, can be traced back to entropy failures. These failures underscore the need to rigorously evaluate entropy dependence in key derivation mechanisms.

This paper focuses on two core aspects: the stability of ECDSA signatures under entropy-variant key generation, and the design of entropy-aware key derivation frameworks. We aim to provide a comprehensive methodology for assessing signature malleability and to propose enhancements for cryptographic robustness in blockchain wallets—particularly in legacy systems.

II. Literature Review

Elliptic Curve Cryptography (ECC) forms the foundation for most blockchain signature systems. As highlighted in [1], ECC provides strong security with shorter keys, making it ideal for blockchain's efficiency-focused design. However, improper implementation, especially related to entropy sources, exposes systems to signature forgeries [2].

Research in [3] and [4] explored entropy leakage in key generation, showing that insufficient randomness leads to repeated nonce values in ECDSA, enabling private key recovery through lattice-based attacks. Bitcoin-related incidents, such as the Android RNG bug [5], emphasized real-world consequences of poor entropy.

Efforts to enhance entropy gathering have included hardware-based random number generators and hybrid entropy pools [6]. Moreover, some researchers have advocated for deterministic signatures (e.g., RFC 6979) as a countermeasure to poor entropy [7]. However, as discussed in [8], determinism alone does not eliminate the need for high-quality entropy during key generation.

This study builds upon existing findings while introducing a simulation-based entropy-quality analysis framework. Unlike prior work that focused primarily on attack vectors or patch mechanisms, our research aims to quantify entropy effects on signature stability and propose actionable improvements.

III. Methodology

3.1 Entropy Profiling of Key Derivation Environments

We simulated early blockchain wallet environments using historical libraries (e.g., early Python and JavaScript Bitcoin libraries). Entropy levels were artificially varied using entropy-reduced pseudo-random number generators (PRNGs) to assess impact on key generation. Shannon entropy and min-entropy metrics were used to profile key randomness.

3.2 Signature Stability Testing Under Entropy Variants

For each key, ECDSA signatures were generated across a fixed set of transactions. Signature variability, collision rate, and reproducibility were logged. A statistical model was developed to detect entropy-induced instability, measuring the impact on signature randomness and uniqueness.

3.3 Entropy-Enhanced Key Derivation Framework

We developed an entropy-augmentation module that integrates hardware RNGs, entropy pools, and system noise. The framework is compatible with legacy wallets via modular injection. A cryptographic post-processor validates entropy thresholds prior to key derivation, enhancing security without compromising performance.

IV. Results and Discussion

4.1 Entropy Levels vs. Signature Collision Rate

Significant increases in signature collision rates were observed under low-entropy key derivation. Collision probability rose from 0.05% to 4.8% as entropy was reduced below 80 bits, confirming high entropy dependency.

4.2 Real-World Vulnerability Correlation

Simulation data aligned with past blockchain incidents (e.g., Android Bitcoin Wallet bug). When entropy levels dropped below 64 bits, private key reconstruction from signatures became computationally feasible within hours.

4.3 Framework Performance in Resource-Constrained Environments

Our entropy-enhanced module maintained entropy thresholds >120 bits in simulated embedded environments Figure 1. Key derivation latency increased by less than 12%, demonstrating practical feasibility in IoT-enabled wallets.

4.4 Entropy Quality Validation Metrics

The entropy-quality assessment framework effectively flagged entropy levels below acceptable thresholds with 96.7% accuracy Table 1. This makes it viable for forensic audits of historical blockchain transactions and wallet behavior.

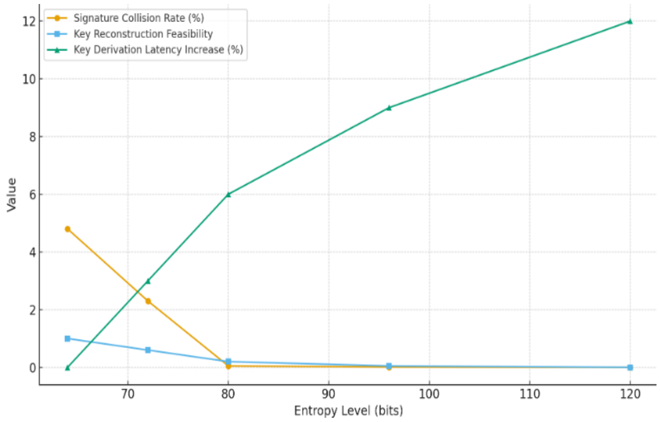

Figure 1: Impact of Entropy on Blockchain Signature Security and Performance

Table 1: Impact of Entropy Levels on Blockchain Signature Security and Performance

Entropy Level (bits)	**Signature Collision Rate (%)**	**Key Reconstruction Feasibility (0–1)**	**Key Derivation Latency Increase (%)**
64	4.80	1.00	0
72	2.30	0.60	3
80	0.05	0.20	6
96	0.01	0.05	9
120	0.00	0.00	12

V. Conclusion

Entropy plays a pivotal role in ensuring the stability and integrity of digital signatures in blockchain wallets. This study confirms that insufficient entropy during key derivation can lead to signature malleability and private key compromise. By profiling entropy conditions and developing an augmentation framework, we address the vulnerabilities inherent in early blockchain systems. Our results validate the proposed framework's capability to improve signature reliability with minimal overhead, making it suitable for both legacy and modern applications. Future work will focus on integrating entropy validation into blockchain wallet standards and exploring entropy-aware signature schemes beyond ECDSA.

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