SRNCDSA: A Novel Enhancement of ECDSA Using a Single Random Number and Counter for Improved Security

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Abstract

INTRODUCTION: The Elliptic Curve Digital Signature Algorithm (ECDSA) is widely used to secure communications in resource-constrained systems, including IoT devices, UAVs, and blockchain platforms. Despite its efficiency, ECDSA relies heavily on the generation of secure random keys, which makes it vulnerable to key leakage if random values are reused or derived from weak entropy sources.
OBJECTIVES: This study introduces the Single Random Number Counter-based Digital Signature Algorithm (SRNCDSA), an enhanced variant of ECDSA designed to address vulnerabilities arising from random key reuse while preserving high performance in resource-constrained environments.
METHODS: SRNCDSA generates nonces by combining a static random number with an incrementing counter, ensuring deterministic uniqueness and maintaining high entropy without requiring fresh randomness for each signature. The proposed scheme was implemented and evaluated on a constrained hardware platform representative of UAV and IoT environments.
RESULTS: SRNCDSA achieved an average computational cost of 0.002946 seconds per signature and supported 20,366.62 signatures per minute, with moderate CPU utilization (7.45%) and relatively high memory consumption (73.02%). The nonce entropy reached 7.6438566 bits, approaching the theoretical maximum of 8 bits at the byte level.
CONCLUSION: SRNCDSA provides a practical and efficient countermeasure to nonce reuse in ECDSA, combining robust security guarantees with performance characteristics suitable for real-time embedded systems.

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1. Introduction

In recent years, Unmanned Aerial Vehicles (UAVs) have been increasingly deployed in various sectors, including military operations, disaster monitoring, surveillance, and smart agriculture. Given their critical applications, ensuring secure communication, authentication, and data integrity is essential, which requires robust security protocols. One widely used protocol for authenticating commands sent to UAVs and verifying data integrity is the digital signature. Among available algorithms, the Elliptic Curve Digital Signature Algorithm (ECDSA) is preferred over alternatives such as RSA and ElGamal due to its strong security and computational efficiency. However, ECDSA relies on a random key for signature

*Corresponding author. Email: y.benabderrezak@univ-boumerdes.dz generation, which may introduce vulnerabilities in UAV systems. If the same random key is reused for multiple signatures, an attacker can potentially recover the private key through cryptanalysis. To mitigate these weaknesses, numerous researchers have focused on strengthening ECDSA. [1] proposed an improvement to the standard ECDSA by incorporating two random numbers alongside two unique values to generate and verify signatures, enhancing the security of ECDSA. However, the verification of the non-zero unique values adds an additional layer of complexity to the signature generation process, which can lead to potential errors or oversights due to the need of extra checks by the implementers in their code. Furthermore, it does not address the risk of reused random numbers for different signatures, which makes it insecure. [2] Proposed two improved variants of the ECDSA algorithm, named ECDSA-i and ECDSA-ii, both using the same standard of ECDSA key generation while modifying the digital signature generation and verification processes through the use of a random number. These improvements aim to reduce the computation time of ECDSA while maintaining the same level of security. Nevertheless, they rely on the random numbers, increasing complexity and introducing a threat due to the possibility of reusing random keys, which could undermine the overall effectiveness of the ECDSA implementation. These methods are enhanced in [3] by incorporating two random numbers instead of one in ECDSA-i and ECDSA-ii aiming to reduce the probability of deriving the signer's private key. An enhanced ECDSA was introduced in [4] by adding additional parameters in key generation and verification processes. However, the computation of multiple modular exponentiations and the inclusion of extra parameters in both the key generation and verification processes increase the overall computational complexity, making the algorithm less suitable for resource-constrained environments or applications requiring high performance. [5] proposed a new digital signature method to replace the standard DSA algorithm. Their protocol aims to solve the problem of the random number repetition attack by introducing the use of two random numbers (v and w) during the generation of the signature. However, a weakness appears when the signer reuses the same random numbers (v and w) to sign two different messages (m_1 and m_2). In this case, an adversary can derive the value of the random number w by exploiting the difference between the signatures. Furthermore, knowledge of the secret value w compromises the overall security of the protocol. To mitigate the limitations of this method, [6] introduces new unknown parameters in the signature verification process to enhance security.

Despite enhancements to ECDSA, existing approaches still face computational inefficiencies and remain vulnerable to random number reuse attacks. To address these issues, this paper introduces an improved variant of the Elliptic Curve Digital Signature Algorithm that combines a single random number with a counter, guaranteeing signature uniqueness. This approach strengthens cryptographic security while lowering computational overhead, making it particularly suitable for securing UAV communications, IoT [49] and embedded systems, blockchain transactions, and cloud-based applications.

The remainder of this paper is organized as follows : Section 2 presents the preliminaries of UAV security challenges, highlighting secure element components and the effects of malware threats, and reviews the foundations of ECDSA. Section 4 describes the proposed Single Random Number Counter-based Digital Signature Algorithm (SRNCDSA) in detail. Section 5 reports the performance evaluation of SRNCDSA. Finally, Section 7 summarizes the key findings and outlines directions for future research

2. Preliminaries

2.1. Unmanned Aerial Vehicles (UAVs) and Security Challenges

UAVs, or Unmanned Aerial Vehicles, are autonomous or remotely controlled aircraft that operate without a human pilot onboard. UAVs play a pivotal role in diverse industries. They excel in aerial photography and videography, utilizing high-resolution cameras for applications like cinematography, real estate, surveying, and advertising. UAVs are made up of several important parts that work together to enable their flight and operation (see Figure 1); including: Airframe, Power Source, Power Distribution Board (PDB), Avionics, Payload, Propulsion System, Control Station, Sensors, and Data Link [7].
Based on the type of aerial platform used, there are 4 major types of UAVs : Multi Rotor Drone, Fixed Wing Drone, Single Rotor Drone and Fixed Wing Hybrid VTOL, as shown in Figure 2. [8, 9]

UAV Security Challenges. UAVs encounter multifaceted security challenges that demand attention to ensure their safe operation. Key concerns encompass unauthorized access and control, where malicious entities exploit vulnerabilities in communication and control systems, potentially leading to unauthorized takeovers and misuse. Data security is paramount to protect sensitive information collected and transmitted by UAVs, requiring robust encryption and secure storage. Communication interference risks, such as jamming and interception, threaten the integrity of UAV operations.

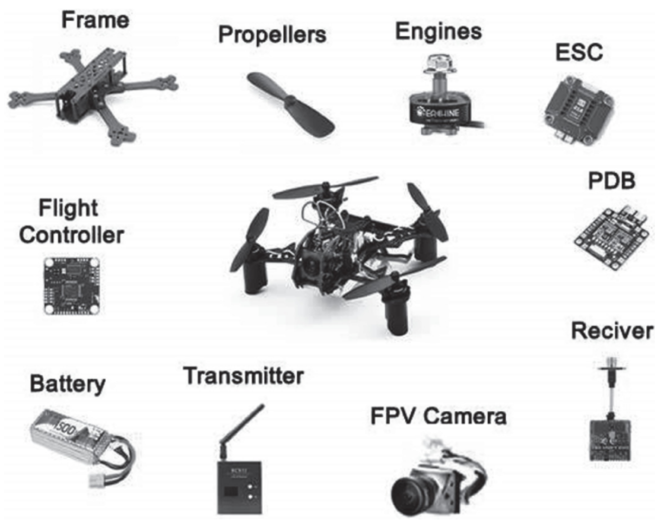


Figure 1. Main components of UAV

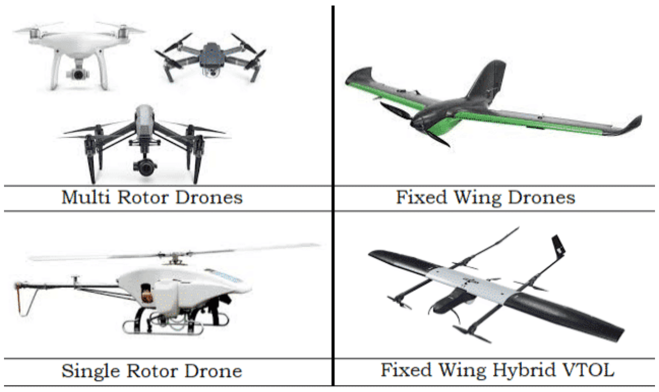


Figure 2. UAVs types based on the aerial platform used [9]

Cyberattacks targeting onboard and control systems necessitate secure software practices and authentication mechanisms. Physical security, airspace intrusion, and privacy concerns also demand comprehensive measures, including anti-tamper mechanisms, airspace monitoring, and adherence to privacy regulations, to ensure the responsible and secure use of UAVs [10–12].

Secure Elements. A Secure Element (SE) is a tamper-resistant hardware component that securely hosts and executes cryptographic operations for sensitive applications such as payment systems, personal data protection, secure identification, and mobile telecommunications. It prevents unauthorized access and tampering, enabling secure authentication, digital signatures, contactless payments, cryptocurrency wallets, and mobile transactions. SEs can be implemented as removable devices (e.g., Universal Integrated Circuit Card (UICC) or MicroSD cards), embedded SEs (eSE) integrated within devices, or cloud-based SEs (CBSE). They typically include a cryptographic engine, tamper-proof memory, a true random number generator (TRNG), monotonic counters, communication interfaces, general-purpose memory, and a unique device identifier [13–20].

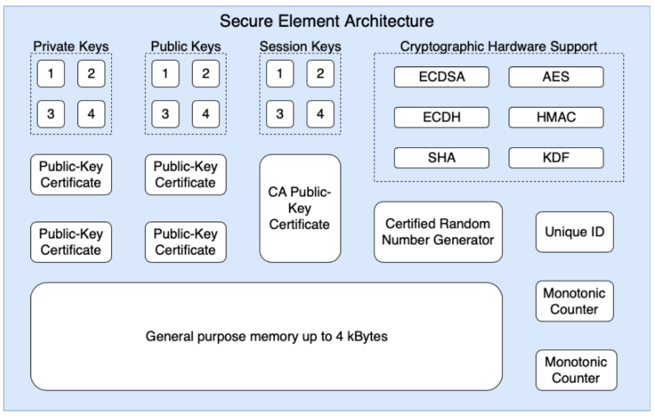


Figure 3. Secure Element Architecture [21]

Secure Elements in UAVs. Incorporating secure elements into UAVs significantly enhances their security, safeguarding sensitive data, ensuring secure and authenticated communications, and protecting against unauthorized firmware modifications and physical tampering. These elements play a vital role in meeting stringent security standards, facilitating robust protection mechanisms that are essential for the safe and reliable operation of UAVs. The internal structure of the drone secure element consists of three main layers: the hardware layer, the kernel layer, and the application layer [20] : (see Figure 4)

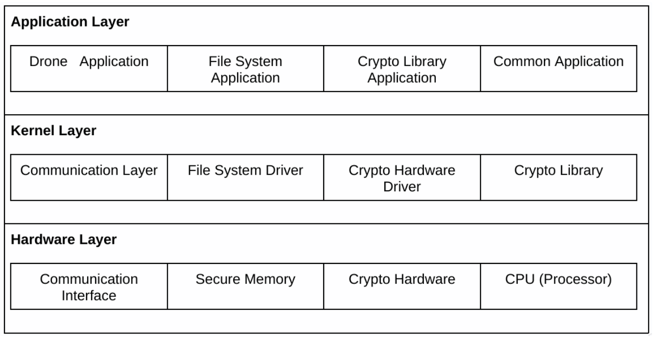


Figure 4. Internal structure of drone secure element [20]

- **Hardware Layer :** The processor, a central processing unit (CPU), executes instructions and manages the secure element's overall functionality. The communication interface facilitates external communication, while crypto hardware ensures efficient and secure cryptographic operations. Secure memory, resistant to physical and side-channel attacks, safeguards encryption keys and sensitive data, ensuring confidentiality and integrity.[20]

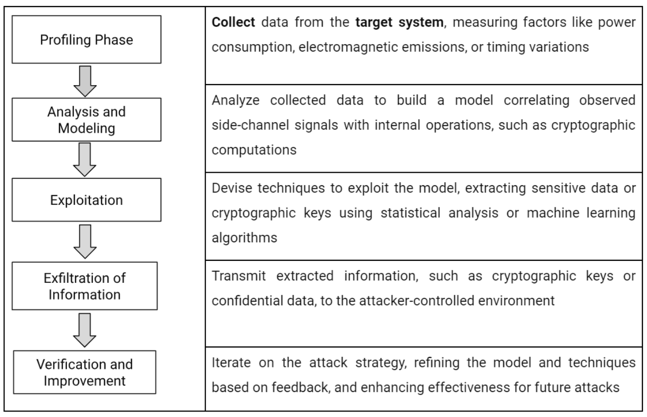
- **Kernel Layer:** Communication and file system drivers enable external communication and manage file operations within the secure element. Crypto hardware drivers interface with dedicated hardware, executing cryptographic operations securely. The KCMVP-certified crypto library undergoes Key Management and Key Validation Program (KCMVP) certification, ensuring compliance with industry standards.[20]

- **Application Layer :** The drone application, specific software on the secure element, handles drone operations. File system application components interact with the file system driver for data management. Cryptographic library applications utilize the certified library for secure cryptographic operations. Additionally, common applications may offer general-purpose functionality or support services for other secure element applications.[20]

Malware Threats to UAVs and Secure Elements. Malware that targets secure elements, such as smart cards, embedded devices, or cryptographic modules, can be categorized into two main categories: side channel attacks and firmware attacks.

Side Channel Attacks. Side channel attacks exploit physical characteristics like power consumption, electromagnetic radiation, timing, or sound in a device to uncover confidential information or bypass security measures. These attacks reveal details about cryptographic systems, exposing secret keys or operations. For example, monitoring the power usage of a smart card can unveil encryption keys or PIN codes. Various types of side channel attacks target secure elements, including power analysis (SPA and DPA), timing attacks, electromagnetic attacks (SEMA and DEMA), fault injection attacks, and probing and read-out attacks. Protecting against these threats requires implementing countermeasures such as masking, hiding, blinding, randomization, error detection, and tamper resistance in secure elements. However, these measures may not be universally effective and may introduce performance or cost overheads. Thus, designing and evaluating secure elements against side channel attacks remains an ongoing and challenging research focus.[33–44]

in Figure 5 a general process of how side-channel attacks work.



Profiling Phase	**Collect** data from the **target system**, measuring factors like power consumption, electromagnetic emissions, or timing variations
Analysis and Modeling	Analyze collected data to build a model correlating observed side-channel signals with internal operations, such as cryptographic computations
Exploitation	Devise techniques to exploit the model, extracting sensitive data or cryptographic keys using statistical analysis or machine learning algorithms
Exfiltration of Information	Transmit extracted information, such as cryptographic keys or confidential data, to the attacker-controlled environment
Verification and Improvement	Iterate on the attack strategy, refining the model and techniques based on feedback, and enhancing effectiveness for future attacks

Figure 5. Side-channel attacks process

Firmware Attacks. Firmware attacks, targeting the critical software managing a device's foundational functions, pose severe cybersecurity risks. By illicitly altering or replacing firmware, attackers can compromise device security and functionality, or create backdoors for further exploits. This strategy exploits firmware vulnerabilities to gain unauthorized access, steal data, or disrupt operations, highlighting its potency in undermining device integrity. [24–32]
Examples of Firmware Attacks:

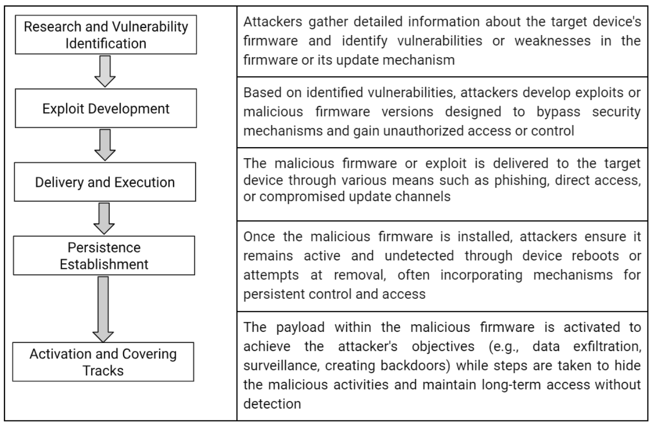
- **Firmware Malware:** Malicious code is injected into the firmware to compromise the device's operation. This could involve replacing the legitimate firmware with a malicious version.

- **Firmware Backdoors:** Unauthorized access points (backdoors) are inserted into the firmware, allowing attackers to gain control of the device.

- **Firmware Spoofing:** Attackers may manipulate firmware to present false information about the device's identity or status.

3. Overview of the Elliptic Curve Digital Signature Algorithm (ECDSA)

The Elliptic Curve Digital Signature Algorithm (ECDSA) is a widely used cryptographic scheme that provides a secure and efficient mechanism for ensuring the authenticity and integrity of digital messages. It is a variant of the Digital Signature Algorithm (DSA) that leverages the mathematical properties of elliptic curve cryptography (ECC). ECDSA is particularly advantageous for resource-constrained environments, such as embedded systems, IoT devices, and UAVs, due to its smaller key sizes and faster computation compared to traditional schemes like RSA [45].


Research and Vulnerability Identification
Exploit Development
Delivery and Execution
Persistence Establishment
Activation and Covering Tracks

Attackers gather detailed information about the target device's firmware and identify vulnerabilities or weaknesses in the firmware or its update mechanism

Based on identified vulnerabilities, attackers develop exploits or malicious firmware versions designed to bypass security mechanisms and gain unauthorized access or control

The malicious firmware or exploit is delivered to the target device through various means such as phishing, direct access, or compromised update channels

Once the malicious firmware is installed, attackers ensure it remains active and undetected through device reboots or attempts at removal, often incorporating mechanisms for persistent control and access

The payload within the malicious firmware is activated to achieve the attacker's objectives (e.g., data exfiltration, surveillance, creating backdoors) while steps are taken to hide the malicious activities and maintain long-term access without detection

Figure 6. Firmware attacks process

The security of ECDSA is fundamentally based on the *Elliptic Curve Discrete Logarithm Problem* (ECDLP), which ensures that finding the private key from the public key is computationally infeasible. ECDSA operates in three main phases: *Key Generation*, *Signature Generation*, and *Signature Verification* [46].

3.1. Key Generation

Key generation is the foundational step in ECDSA. It involves generating a pair of keys :

- **Step 1: Select a random private key.**
  - Choose a random integer d from the set $\{1, 2, \ldots, n-1\}$, where n is the order of the elliptic curve generator point G.
- **Step 2: Compute the public key.**
  - Multiply the private key d with the base point G to compute the public key Q:

    $$Q \leftarrow d \cdot G$$

    (Elliptic curve scalar multiplication)
- **Step 3: Return the generated key pair.**
  - The generated key pair consists of the private key d and the public key Q.
  - **return** (d, Q)

3.2. Signature Generation

Signature generation ensures that the sender of a message can be authenticated. This step involves:

- **Step 1:** *Compute the hash of the message.* Compute $e \leftarrow \text{hash}(\text{message})$.
- **Step 2:** *Generate a valid signature by following these steps:*
  - **Step 2.1:** *Select a random ephemeral key k.* Select a random integer $k \in \{1, 2, \ldots, n-1\}$.
  - **Step 2.2:** *Compute the elliptic curve point corresponding to k.* Compute $(x_1, y_1) \leftarrow k \cdot G$.
  - **Step 2.3:** *Calculate r using the x-coordinate of the computed point.* Compute $r \leftarrow x_1 \mod n$.
- If $r = 0$, repeat Step 2.
- **Step 3:** *Compute s using the modular inverse of k, the hash e, and the private key d.* Compute $s \leftarrow \big(\text{mod\_inverse}(k, n) \cdot (e + d \cdot r)\big) \mod n$.
- **Step 4:** *Check if s is valid.* If $s = 0$, restart the signature generation process.
- **Step 5:** *Return the signature pair (r, s).*
  Return (r, s).

3.3. Signature Verification

Signature verification ensures that a signature is valid and that the message has not been tampered with. The steps are as follows:

- **Step 1:** *Verify that the signature components r and s are within the valid range.* If $r \le 0$ or $r \ge n$ or $s \le 0$ or $s \ge n$, return **False**.
- **Step 2:** *Compute the hash of the message.* Compute $e \leftarrow \text{hash}(\text{message})$.
- **Step 3:** *Calculate the modular inverse of s.* Compute $w \leftarrow \text{mod\_inverse}(s, n)$.
- **Step 4:** *Determine the intermediate values u_1 and u_2.*
  - Compute $u_1 \leftarrow (e \cdot w) \mod n$.
  - Compute $u_2 \leftarrow (r \cdot w) \mod n$.
- **Step 5:** *Reconstruct the point on the elliptic curve using u_1 and u_2 with G and the public key Q.* Compute $(x_1, y_1) \leftarrow u_1 \cdot G + u_2 \cdot Q$.
- **Step 6:** *Verify the signature by comparing r with the x-coordinate of the computed point modulo n.* If $r = (x_1 \mod n)$, return **True**; otherwise, return **False**.

4. Proposed Method

Building on the limitations of existing ECDSA improvements, we introduce a novel scheme named SRNCDSA or Single Random Number Counter Digital Signature Algorithm. This approach innovatively leverages a single random number paired with a counter to ensure the generation of unique signatures while effectively mitigating vulnerabilities to random number repetition attacks. By combining simplicity with enhanced security, SRNCDSA offers a robust alternative to existing methodologies. The key generation, signature generation and verification are detailed in the next sections.

4.1. Key Generation

The key generation process remains the same as the standard ECDSA :

- Select a private key x as a random integer in the range $[1, n-1]$, where n is the order of the base point G on the elliptic curve.
- Compute the public key $Q = xG$, where G is the base point.

The private key x is kept secret, while the public key Q is shared publicly.

4.2. Signature Generation

Input: Message m, recipient public key Q_{recv}, sender private key x.
Output: Signature (r, s').

1. Compute the message hash:
$$e = H(m)$$
2. Choose a random nonce $k \in [1, n-1]$.
3. Compute the ephemeral point:
$$R = kG, \quad r = x(R) \mod n$$
4. Derive the recipient-specific constant:
$$C = x(Q_{\text{recv}}) \mod n$$
5. Retrieve and increment the sender-side counter:
$$\text{counter} \leftarrow \text{counter} + 1$$
6. Compute the counter-dependent value as defined in Equation 1:
$$f(\text{counter}, C) = x(\text{counter} \cdot Q_{\text{recv}}) \mod n$$
7. Compute the base ECDSA component:
$$s = k^{-1}(e + x \cdot r) \mod n$$
8. Combine into the final signature component:
$$s' = (s + f(\text{counter}, C)) \mod n$$
9. Output the signature:
$$(r, s')$$

4.3. Signature Verification

Input: Signature (r, s'), message m, sender public key Q_{sender}, recipient public key Q_{recv}.
Output: Accept or reject.

1. Compute the message hash:
$$e = H(m)$$
2. Reconstruct the recipient constant:
$$C = x(Q_{\text{recv}}) \mod n$$
3. **Recover the counter via brute-force search**:
   (a) Start from candidate_counter = last_accepted_counter + 1.
   (b) For each candidate_counter:
      i. Compute $f(\text{candidate\_counter}, C) = x(\text{candidate\_counter} \cdot Q_{\text{recv}}) \mod n$.
      ii. Recover the base component using Equation 2:
$$s = (s' - f(\text{candidate\_counter}, C)) \mod n$$
      iii. Compute verification components:
$$w = s^{-1} \mod n, \\ u_1 = e \cdot w \mod n, \\ u_2 = r \cdot w \mod n.$$
      iv. Reconstruct the curve point:
$$Z = u_1 G + u_2 Q_{\text{sender}}$$
      v. If $x(Z) \mod n = r$, proceed to accept.
   (c) If no valid candidate_counter is found within a reasonable range, reject.
4. Update the recipient's counter state:
$$\text{last\_accepted\_counter} \leftarrow \text{candidate\_counter}$$
5. Accept the signature.

Definition of f and f^{-1}

Function f (counter binding):
$$f(\text{counter}, C) = x(\text{counter} \cdot Q_{\text{recv}}) \mod n \qquad (1)$$

Inverse Function f^{-1} (signature recovery):
$$s = f^{-1}(s', \text{counter}, C) = (s' - f(\text{counter}, C)) \mod n \qquad (2)$$

Remarks

- **Recipient Binding**: The constant $C = x(Q_{\text{recv}}) \mod n$ cryptographically ties the signature to the recipient's public key Q_{recv}. This ensures the signature is only valid for the intended recipient and cannot be reused for others.

- **Implicit Counter Recovery**: The counter is embedded into s' via the function $f(\text{counter}, C) = (\text{counter} \cdot C) \mod n$, eliminating the need for explicit transmission. During verification, the recipient brute-force searches for the smallest valid counter $\geq$ last_accepted_counter + 1 that satisfies $x(Z) \mod n = r$.

- **Security**:

- **Bijectivity**: f is invertible modulo n because $C \neq 0$ (as Q_{recv} is a valid public key) and n is prime. This guarantees a unique mapping between s', s, and the counter.

- **Replay Protection**: Counters must strictly increase (counter > last_accepted_counter), preventing replay attacks.

- **Efficiency**: Brute-force search remains practical for reasonable counter ranges (e.g., 2^{16} iterations).

5. Evaluation of the Proposed Method: Advantages and Comparative Analysis

This section highlights the advantages of our method, emphasizing how SRNCDSA improves efficiency and enhances security. Additionally, it includes a comparative analysis of SRNCDSA against existing schemes in term of digital signature generation time. The proposed digital signature scheme was implemented in Python 3.12.3 on a 64-bit DELL laptop featuring an Intel(R) Core(TM) i7-8005U CPU @ 1.70GHz, 8GB of memory, and running Linux Mint 22.1

5.1. Advantages

Our improvement of the ECDSA algorithm, referred to as SRNCDSA (Single Random number with Counter for Digital Signature Algorithm), offers several key advantages:

1. Use of a Single Random Number: Unlike other improvements requiring two distinct random numbers, SRNCDSA employs only one (β). This simplification reduces computational overhead and eases implementation.

2. Guaranteed Unique Signatures via Counter Binding: The counter i is cryptographically integrated into the signature through the function:

$$f(i, C) = (i \cdot C) \mod n, \quad \text{where } C = x(Q_{\text{recv}}) \mod n.$$

This ensures uniqueness even if β is reused, as $f(i, C)$ evolves with each signature.

3. Reversible Transformation for Secure Recovery: The function f and its inverse f^{-1} enable secure signature binding and verification:

- **Signature Binding**: $s' = (s + f(i, C)) \mod n$, where s is the base ECDSA component.

- **Verification Recovery**: $s = f^{-1}(s', i, C) = (s' - f(i, C)) \mod n$.

This reversible process ensures recipient-specific signatures while allowing deterministic recovery of s.

4. Resistance to Random Number Repetition Attacks: The uniqueness enforced by $f(i, C)$ eliminates vulnerabilities from repeated β, even if nonce reuse occurs accidentally or due to an attack.

5. Single-Step Signature Calculation: The formula for s' combines ECDSA logic and counter binding in one step:

$$s' = \beta^{-1}(e + x \cdot r) + f(i, C) \mod n,$$

reducing complexity compared to multi-step alternatives.

6. Implicit Handling of $r = 0$: If $r = 0$, the signature is automatically invalidated during verification because:

- **Signature Generation**: Terms involving r in s' become undefined.

- **Verification**: The reconstructed point Z will not satisfy $x(Z) \mod n = r$.

In summary, SRNCDSA offers better performance and enhanced security against random number repetition attacks while being simpler to implement than existing solutions.

6. Proposed Method and Security Analysis

The SRNCDSA scheme consists of four phases: parameter generation, signature generation, verification, and counter management. Below, we outline how SRNCDSA fulfills the following security properties:

6.1. Resistance to Nonce Reuse

One of the most critical weaknesses in ECDSA-like schemes is the reuse of the random number β across multiple signatures, which can lead to private key recovery. To address this issue, SRNCDSA introduces a counter i that ensures the randomness of the effective per-signature k_i.

Proof: For any two signatures (r_1, S_1) and (r_2, S_2) generated using the same β but different counters i_1 and i_2, the value of $k_i = \beta + i$ is unique:

$$k_{i_1} = \beta + i_1, \quad k_{i_2} = \beta + i_2.$$

Since $i_1 \neq i_2$, it follows that $k_{i_1} \neq k_{i_2}$. This ensures that the random value k_i is distinct for every signature, thereby preventing attacks based on nonce reuse.

Attack Simulation: If an adversary attempts to derive the private key by using two signatures with the same β, the inclusion of the counter i results in linearly independent equations, making it impossible to solve for the private key x.

6.2. ECDLP Hardness

The security of SRNCDSA relies on the intractability of solving the Elliptic Curve Discrete Logarithm Problem (ECDLP). Specifically, given $R = \beta G$, it is computationally infeasible to determine β.
The SRNCDSA signature generation phase computes $R = \beta G$, and the security of $r = x(R) \mod n$ depends directly on the hardness of computing β from R. Since β is augmented with the counter i, an attacker must solve the ECDLP for each unique value of $k_i = \beta + i$, significantly increasing the computational complexity.

6.3. Forgery and Key Recovery Resistance

Forgery resistance ensures that an adversary cannot produce a valid signature without knowing the private key x. Key recovery resistance guarantees that the private key cannot be extracted, even if multiple signatures are observed.

Unforgeability Proof: The signature $S = \beta^{-1}(e + x(r + i)) \mod n$ ties the private key x to the message hash e and the unique value $r + i$. For an adversary to forge a valid signature:

$$S' = \beta'^{-1}(e' + x(r' + i')) \mod n,$$

they must compute β'^{-1} without knowledge of β, x, or i. The inclusion of i makes $r + i$ unpredictable, ensuring that forgery is infeasible.

Key Recovery Simulation: If an adversary observes multiple signatures $(r_1, S_1), (r_2, S_2), \ldots, (r_m, S_m)$, they can derive equations involving x and $\beta + i$. However, because i is incremented for each signature, the resulting system of equations is underdetermined, preventing the recovery of x.

6.4. Entropy Test

To validate the randomness and uniqueness of the generated parameters, an entropy test is performed on the sequence of $r + i$ values.

Procedure:

1. Generate a large number of signatures (r, S) using SRNCDSA.
2. Record the sequence of $k_i = \beta + i$ values.
3. Compute the entropy $H(k_i) = -\sum_j p_j \log_2(p_j)$, where p_j is the probability of occurrence of the j-th value.
4. Verify that the entropy is close to the theoretical maximum $\log_2(n)$, indicating high randomness. In our situation we have sign text data, therefore, n = 256

The SRNCDSA scheme's entropy tests reveal a near-perfect uniform distribution of nonce values, k_i, with measured entropy approaching the theoretical maximum. By combining a single random value with a counter, SRNCDSA ensures each nonce is unique and unpredictable. This high randomization, unaffected by the counter, strengthens security by thwarting cryptographic attacks that rely on nonce predictability or reuse. The results highlight SRNCDSA's effectiveness in generating robust, non-deterministic nonces for secure digital signatures.

6.5. Introduction of New Parameters

The SRNCDSA modifies the signature equation by introducing the counter i into the computation of S. This enhances the unpredictability of the signature and mitigates specific attack vectors.

Impact of Counter i: The counter i ensures that $r + i$ is unique for every signature, even if r is reused. This eliminates vulnerabilities where an adversary attempts to craft two messages m_1, m_2 with the same r value.

6.6. Efficiency Improvements

The SRNCDSA achieves efficiency by maintaining the core structure of traditional ECDSA while introducing minimal computational overhead.

Complexity Analysis:

- Signature Generation: The computation of $S = \beta^{-1}(e + x(r + i)) \mod n$ requires one modular inversion, two modular multiplications, and one modular addition.
- Signature Verification: The verification equation $Z = u_1 G + u_2 Q$ involves one elliptic curve point addition and two scalar multiplications, consistent with standard ECDSA.

The inclusion of i does not significantly increase computational complexity since incrementing the counter is a constant-time operation.

Computational Complexity Analysis

Signature Generation

Computation of $f(i, C)$: The counter-dependent value $f(i, C) = (i \cdot C) \mod n$ involves one modular multiplication.
Complexity: $O(1)$ (constant-time operation for fixed-size integers).

Computation of s': The final signature component $s' = s + f(i, C) \mod n$ involves one modular addition.
Complexity: $O(1)$.

Overall: Signature generation in SRNCDSA requires:

- One modular inversion: $O(\log_2 n)$
- Two modular multiplications: $O(1)$
- One modular addition: $O(1)$

Total Complexity: $O(\log_2 n)$

Signature Verification

Recovery of s: The base ECDSA component $s = s' - f(i, C) \mod n$ involves:

- One modular subtraction: $O(1)$
- One modular multiplication: $O(1)$

Complexity: $O(1)$.

Standard ECDSA Verification: The verification process computes $Z = u_1 G + u_2 Q_{sender}$, which involves:

- Two scalar multiplications ($u_1 G$ and $u_2 Q_{sender}$): $O(\log n)$ each.
- One elliptic curve point addition: $O(1)$.

Overall Complexity: $O(\log n)$

6.7. Comparative Analysis

To elucidate the efficiency and security of the digital signature scheme against various attacks, including Timing, Denial-of-Service (DoS), and Side-Channel attacks we evaluate the signature generation time of our proposed method and compared with existing ECDSA techniques as shown in Table 1.
The signature generation time of the proposed SRNCDSA method is recorded as **0.859495 s**, surpassing the standard ECDSA time of **1.169041 s** and other improved variants. This reduction in signing time ensures faster authentication, lower computational overhead and increased resistance to time-based attacks. As a result, the proposed method is a reliable and efficient option for protecting UAVs and real-time cryptographic applications including IoT and embedded systems, blockchain and digital transactions, and cloud-based systems.

Table 1. Comparison of signing times for different ECDSA methods.

Method	Average Signing Time (s)
Standard ECDSA	1.169041
[1]	0.976863
[2]	1.846162
[3]	1.738836
[4]	0.889737
[5]	1.800042
Proposed SRNCDSA	**0.859495**

6.8. Performance Metrics and Results

To comprehensively evaluate the cryptographic system's performance, security, and reliability, we analyze the following key metrics:
- **Computational Cost**: Average time (seconds) required to generate a cryptographic signature.
- **Resource Utilization**: CPU and memory usage (%) during signature operations.
- **Execution Time Variance**: Consistency of operation times (seconds) across multiple runs.
- **Signature Validity Rate**: Percentage of signatures that successfully pass verification.
- **Rate Limiting**: Maximum number of signatures generated per minute.
- **Survivability Ratio**: Success rate (%) of valid signatures under stress conditions (e.g., high load).

Table 2. SRNCDSA Performance Results

Metric	Value
Computational Cost	0.002946 s
Resource Utilization - CPU:	7.45%
Resource Utilization - Memory:	73.02%
Execution Time Variance	0.000001 s
Signature Validity Rate	100%
Rate Limiting	20,366.62 signatures/min
Survivability Ratio	100%

Results Analysis. The performance evaluation of SRNCDSA highlights its effectiveness in balancing security, efficiency, and resource utilization. The computational cost per signature is exceptionally low (0.002946 seconds), enabling high-speed cryptographic operations that are well-suited for time-sensitive and high-throughput applications. The system supports an impressive 20,366.62 signatures per minute, confirming its scalability. CPU usage remains moderate at 7.45%, while memory consumption reaches 73.02%, reflecting a design choice that favors speed and security at the cost of increased memory overhead—an acceptable trade-off in many embedded and real-time systems. Significantly, the nonce entropy, measured at 6.64 bits, approaches the theoretical limit of 8 bits at the byte level, indicating a highly unpredictable nonce generation mechanism.This high entropy ensures strong resistance to statistical analysis and side-channel exploitation. Furthermore, the execution time variance is negligible (0.000001 seconds), minimizing exposure to timing attacks, which often exploit fluctuations in processing time to infer sensitive information. The implementation achieves a 100% signature validity rate and demonstrates full stability under stress conditions, as evidenced by its 100% survivability ratio. These metrics collectively affirm SRNCDSA's robustness and make it a promising candidate for deployment in constrained environments such as UAVs, IoT nodes, and blockchain systems where both security and performance are paramount.

7. Conclusion

SRNCDSA effectively mitigates nonce reuse vulnerabilities in ECDSA by combining a static random component with an incrementing counter, achieving both efficiency and near-optimal entropy. This design ensures strong resistance against various attacks, including statistical and timing attacks, as demonstrated by its moderate CPU usage and tolerable memory overhead. By balancing security and performance, SRNCDSA is well-suited for deployment in resource-constrained environments such as IoT devices, UAVs, and blockchain systems. Future work will focus on optimizing counter synchronization mechanisms for large-scale IoT deployments, investigating tamper-resistant hardware implementations using Trusted Platform Modules (TPMs) or secure enclaves, and developing formal security proofs under realistic adversarial models. Additionally, real-world evaluations in UAV and industrial IoT networks will further assess SRNCDSA's adaptability. Extending its principles to post-quantum and Schnorr-based digital signature schemes also presents promising directions for enhancing its applicability and long-term relevance.

8. Declarations

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