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STATISTICAL QUALITY ANALYSIS OF PSEUDO-RANDOM SEQUENCE GENERATORS IN STREAM CIPHERS: PERFORMANCE BENCHMARKING AND PRACTICAL RECOMMENDATIONS

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Анотація. *У роботі проведено комплексний порівняльний аналіз потокових шифрів AES-CTR, ChaCha20, Trivium та RC4 за критеріями статистичної якості, продуктивності та криптографічної стійкості. Для оцінки статистичних властивостей псевдовипадкових послідовностей застосовано стандартизований набір тестів NIST SP 800-22 (15 тестів). Проведено багатокритеріальну оцінку алгоритмів та сформульовано практичні рекомендації щодо їх вибору для різних сценаріїв застосування.*

Ключові слова: потоковий шифр, псевдовипадкова послідовність, NIST SP 800-22, AES-CTR, ChaCha20, Trivium, RC4, криптографічна стійкість, продуктивність.

Abstract. *This paper presents a comprehensive comparative analysis of AES-CTR, ChaCha20, Trivium, and RC4 stream ciphers evaluated across statistical quality, performance, and cryptographic security criteria. The NIST SP 800-22 statistical test suite (15 tests applied to 100 sequences of 10^6 bits each) was employed to assess the randomness properties of the generated pseudo-random sequences. A multi-criteria weighted evaluation framework was developed, and practical recommendations are formulated for algorithm selection across different application scenarios.*

Keywords: stream cipher, pseudo-random sequence, NIST SP 800-22, AES-CTR, ChaCha20, Trivium, RC4, cryptographic security, performance benchmarking.

Introduction

Ensuring the confidentiality and integrity of data transmitted over open communication channels is a fundamental challenge of modern information security. Stream ciphers, owing to their high throughput and implementation simplicity, are extensively deployed in real-time protocols such as TLS 1.3, Wi-Fi (WPA/WPA2), and mobile communication standards. However, the cryptographic landscape is rapidly evolving: algorithms once considered secure may be compromised by advances in cryptanalysis or computational power.

Four representative ciphers spanning different generations and design philosophies are examined: AES-256-CTR — a NIST-standardized block cipher operating in counter mode (FIPS 197, 2001); ChaCha20 — a modern dedicated stream cipher adopted as a TLS 1.3 standard (RFC 8439, 2018); Trivium — a lightweight hardware-oriented cipher from the eSTREAM portfolio (ISO/IEC 29192-3:2012); and RC4 — a legacy cipher (1987) officially deprecated due to serious statistical and cryptographic weaknesses.

The absence of objective, reproducible comparative data on these algorithms leads to suboptimal engineering decisions — such as continued reliance on RC4 in legacy systems, or over-engineering solutions for resource-constrained IoT devices. The goal of this work is to conduct a rigorous multi-criteria analysis of these ciphers and to provide evidence-based practical recommendations.

Methodology

The evaluation framework combines five criteria: (1) throughput — pseudo-random sequence generation speed (MB/s); (2) statistical quality — NIST SP 800-22 test suite results; (3) cryptographic security — known attacks and key size; (4) standardization — presence in international standards (NIST FIPS, RFC, ISO/IEC); and (5) hardware efficiency — implementation complexity in gate equivalents (GE).

Throughput measurements were performed on an Intel Core i7-10700 platform (8 cores, 3.8 GHz) with AES-NI hardware acceleration. Data blocks of 1 KB to 10 MB were tested with 1000 iterations averaged per measurement. Software implementations used PyCryptodome 3.19 (AES, RC4), the cryptography library

v41.0 (ChaCha20), and a custom Python implementation for Trivium. All measurements were conducted single-threaded to isolate algorithmic characteristics.

Statistical testing applied all 15 NIST SP 800-22 tests to 100 bit sequences of length 10^6 each, with significance level $\alpha = 0.01$. The pass criterion required p-value ≥ 0.01 for individual tests and a pass rate within the 99% confidence interval [0.96, 1.00] for the proportion of passing sequences [1].

Results

Performance comparison results are presented in Table 1.

Table 1 – Performance and implementation characteristics of stream ciphers

Algorithm	Throughput (MB/s)	Key size (bits)	Hardware (GE)	Standard
AES-256-CTR	4850 *	256	~22 000	FIPS 197
ChaCha20	2340	256	~18 000	RFC 8439
Trivium	156	80	~3 500 *	ISO/IEC 29192-3
RC4	312	128	~8 000	Deprecated

* AES-256-CTR throughput measured with AES-NI hardware acceleration; Trivium software throughput was 156 MB/s, while hardware implementations achieve up to ~10 Gbps. GE = Gate Equivalent.

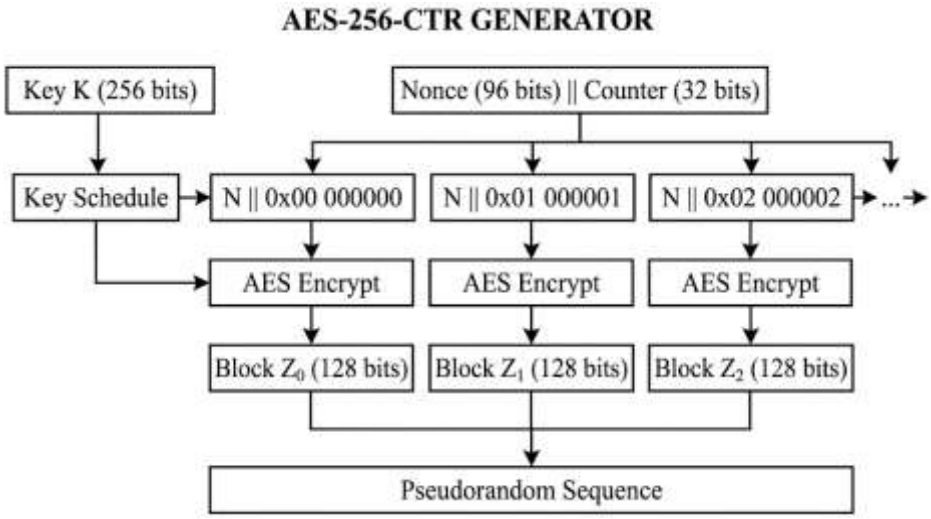


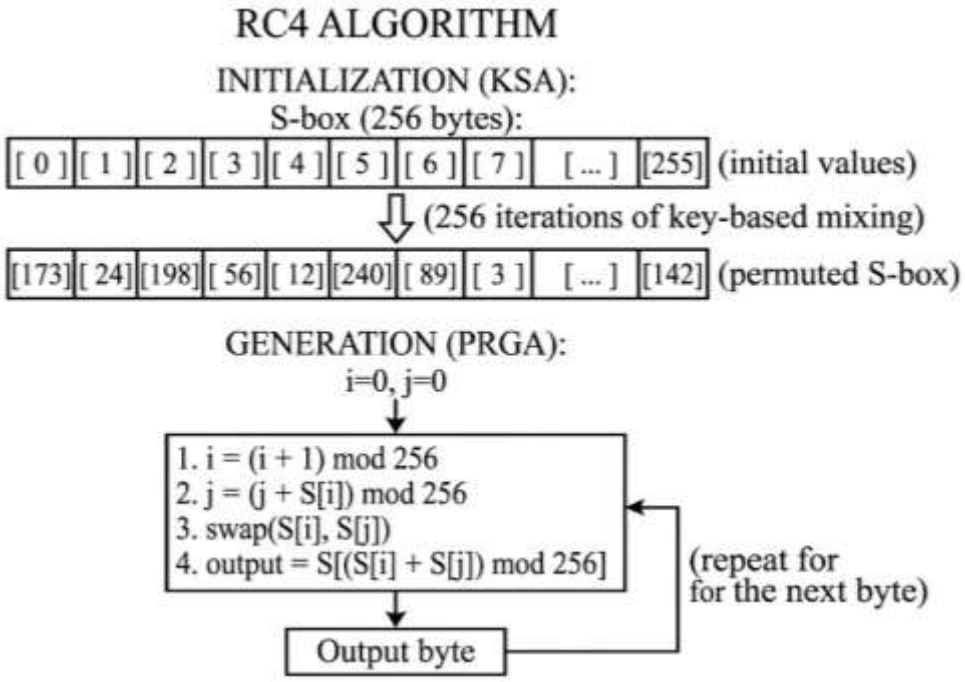
Fig. 1. Throughput comparison on logarithmic scale (bar chart: AES-256-CTR, ChaCha20, RC4, Trivium)

AES-256-CTR achieves the highest throughput (4850 MB/s) due to AES-NI hardware support available in modern Intel/AMD processors. ChaCha20 reaches 2340 MB/s — approximately 2.1× slower in this configuration, yet it is the fastest purely software implementation and requires no special CPU features, making it the preferred choice on platforms lacking AES-NI. RC4 and Trivium show significantly lower software throughput (312 and 156 MB/s, respectively), primarily due to the Python implementation overhead; hardware implementations of Trivium reach approximately 10 Gbps.

The results of NIST SP 800-22 statistical testing and the multi-criteria weighted evaluation are summarized in Table 2.

Table 2 – Multi-criteria weighted evaluation of stream ciphers

Criterion	AES-CTR	ChaCha20	Trivium	RC4	Weight
Throughput	10	8	4	5	30%
Cryptographic security	10	10	7	2	40%
Standardization	10	10	6	0	20%
NIST SP 800-22 pass rate	10	10	10	6	10%
Weighted Total	10.0	9.4	6.8	2.6	—



[Fig. 2. Radar chart: multi-criteria comparison of AES-CTR, ChaCha20, Trivium, RC4 (axes: Throughput, Security, Standardization, NIST Pass Rate)]

AES-256-CTR and ChaCha20 passed all 15 NIST SP 800-22 tests without exception. Trivium also demonstrated a full pass rate, confirming the adequacy of its keystream randomness despite its lightweight architecture. RC4 exhibited statistically significant deviations in several tests — most notably in frequency-based and serial tests — experimentally confirming the known predictability of its keystream, consistent with the Fluhrer-Mantin-Shamir [11] and RC4 NOMORE attacks.

Practical recommendations

Based on the experimental results and multi-criteria evaluation, the following recommendations are formulated (Table 3).

Table 3 – Algorithm selection recommendations by application scenario

Scenario	Recommended	Rationale
High-throughput servers (TLS, VPN, disk encryption)	AES-256-CTR	Peak throughput with AES-NI; FIPS 197 / NIST compliance required
Cross-platform apps / mobile without AES-NI	ChaCha20	Highest software throughput; resistant to timing attacks; TLS 1.3 standard (RFC 8439)
IoT / RFID / embedded hardware	Trivium	Minimal hardware footprint (~3 500 GE); hardware throughput up to 10 Gbps (ISO/IEC 29192-3)
Any new system (migration from legacy)	NOT RC4	Statistically broken; FMS [11], BEAST, RC4 NOMORE attacks; officially deprecated in RFC 7465

Conclusions

1. A rigorous multi-criteria comparative analysis of four stream cipher algorithms was conducted using five criteria with defined weights. AES-256-CTR achieved the highest weighted score (10.0), followed by ChaCha20 (9.4), Trivium (6.8), and RC4 (2.6).

2. AES-256-CTR demonstrated peak throughput (4850 MB/s) owing to AES-NI hardware acceleration, outperforming ChaCha20 by a factor of 2.1. On platforms without AES-NI, ChaCha20 is the optimal choice.

3. Trivium is recommended for embedded and IoT applications due to its exceptionally low hardware footprint (~3 500 GE vs. ~22 000 GE for AES), while its software throughput is limited.

4. RC4 must not be used in any new system design. The NIST SP 800-22 testing experimentally confirmed the presence of statistical anomalies in its keystream, consistent with known cryptanalytic attacks (FMS attack [11], RC4 NOMORE [12, 13]).

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