

Experimental Evaluation of the Performance and Security of the ChaCha20 Stream Cipher Using Python

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Abstract: In this new digital age, security and integrity of data have become crucial especially in real-time applications and environments where resources are limited. This study introduces a performance and security analysis of the ChaCha20 stream cipher using a Python-based implementation of the algorithm. Encryption and decryption time, avalanche effect, key sensitivity, decryption success rate, ciphertext byte distribution are the evaluation metrics. Experiments were done with plaintext sizes from 64 to 2048 bytes. The results show that ChaCha20 has very low encryption and decryption times which verified the high efficiency and scalability. The avalanche effect although does decrease slightly with the size of plaintext, maintains enough diffusion to fight against differential cryptanalysis. Key sensitivity is consistently close to 50%, and decryption success is 100% for all tested inputs indicating strong key dependence and a reliable operation. Additionally, the ciphertext shows that there is no skewed distribution of bytes and the text follows a uniform distribution, which verifies that there is a high randomness and a strong resistance against statistical attacks. Overall, the results confirm the validity of ChaCha20 as a fast, secure and reliable cryptographic solution that can be implemented in the modern software-based security applications such as real-time communications and high throughput data systems.

Keywords: ChaCha20, Stream Cipher, Encryption, Avalanche Effect, Key Sensitivity, Cryptographic

1. Introduction

In the ever-changing digital world, information security has become a critical issue. Modern applications such as cloud, real-time communications, embedded systems, or online financial services demand cryptographic mechanisms that have non-intrusive performance and offer confidentiality, integrity, and authenticity. The increasing dependence on software-based systems is another reason to have a lightweight, efficient, and secure encryption algorithm that can operate efficiently under various computational constraints.

A stream cipher called ChaCha20, the creation of Daniel J. Bernstein, has become a promising replacement for more traditional ciphers, such as AES because it is simple, fast, and has strong security properties. Unlike block ciphers, stream ciphers encrypt data on a continuous basis, and can therefore be useful for applications that require low-latency encryption. ChaCha20 uses a 256-bit key and a 64-bit nonce, and it uses a series of arithmetic and logical operations to produce a pseudorandom keystream which is XORed with plaintext to produce ciphertext. Its design guarantees resistance to popular cryptanalysis such as differential and linear cryptanalysis, with minimal computational overhead.

Despite the theoretical merits of ChaCha20, it is important to assess how well it performs and how secure it is under realistic scenarios. Stuff like encryption and decryption time, avalanche effect, key sensitivity, decryption accuracy and ciphertext randomness give valuable insights into how efficient or reliable the algorithm is. These parameters are especially important for software based applications and real-time systems for which both speed and security are important.



This research work attempts to give an overall experimental evaluation of ChaCha20 using a Python-based implementation. The research tests the algorithm with varying plaintext sizes, and results are determined including performance, diffusion, key sensitivity and ciphertext randomness. By bringing these results in an ordered way, the current work adds to a better insight into the practical capabilities of ChaCha20 and its applicability to contemporary cryptographic applications.

2. Related Work

Cryptography is an essential component in the secure communication and data protection in modern information systems. Over the years, many symmetric and asymmetric encryption techniques have been invented to keep up with the intense demand for these high security solutions in a variety of applications which are cloud computing, internet-of-things (IoT), and embedded systems. Symmetric ciphers in particular, are widely used because of their efficiency and simplicity, which make them suitable for resource impaired environments.

Among symmetric algorithms, it is worth mentioning stream ciphers for their ability to encrypt the data in a continuous data stream, and thus offer low-latency and high throughput encryption. A variant of the original Salsa20 algorithm proposed by Bernstein [1], ChaCha20 has become quite popular because of its simplicity, speed and good security properties. Unlike block ciphers, ChaCha20 produces a pseudorandom keystream that is XORed with the plaintext so that it will encrypt it efficiently without requiring any padding. Its design is resistant to most popular cryptanalytic attacks, including differential and linear cryptanalysis, and it has high key sensitivity and diffusion properties.

A number of studies have been dedicated to the evaluation of the performance and security of ChaCha20, in different environments. For example, Bernstein [1] introduced the design principles of the algorithm and security analysis of the algorithm, which is resistant to cryptanalytic attacks and suitable for hardware and software implementation. Biryukov et al. [2] performed a comparative study between ChaCha20 and AES from the software and hardware platform showing that they perform similarly or even better in high-speed software applications. More recent work [3-5] has studied the avalanche effect, key sensitivity and ciphertext randomness of ChaCha20, and verified its robustness and good application effect in practicable scenarios of real-time encryption.

Furthermore, ChaCha20 has been incorporated into the latest protocols such as TLS 1.3 [6] and OpenSSH [7], either to replace traditional ciphers or in compliment of them towards achieving better performance as well as security. The combination of high speed, low computational overhead requirements, and high security make ChaCha20 a prime candidate for cryptographic systems used in software now and in the future, especially in those where energy efficiency and low-latency encryption are paramount.

In this context, the present work is aimed to give a systematic experimental evaluation of the encryption problems in terms of encryption/decryption performance, avalanche effect, key sensitivity and decryption success rate, and distribution of ciphertext bytes of ChaCha20. By comparing results for different plaintext size, this study is also a contribution to a general understanding of the practical capabilities and limitation of the algorithm, and a supplement in the literature.

3. Materials and Methods

This paper implements and measures the performance and security characteristics of the ChaCha20 stream cipher, using a Python-based method to assess the security characteristics of the ChaCha20 stream cipher against multiple plaintext sizes. The methodology is aimed at offering a methodical and repeatable evaluation, including the algorithm implementation, experimental setup and measurement of several assessment metrics.

3.1. Algorithm Implementation

ChaCha20 is a 256-bit key stream cipher algorithm, which is implemented in Python by using standard cryptographic libraries so that it is accurate and reliable. The implementation complies with the original specification

suggested by Bernstein [8], including: Key setup: 256 bit key encryption key and 64 bit nonce initialization Keystream generation: a sequence of a series of 20 rounds of quarter-round operations on the internal state matrix Encryption and decryption: XOR operation of keystream and plaintext and ciphertext respectively. The Python implementation has been optimized for efficiency considering strict adherence to the security specifications of the algorithm. The correctness of encryption and decryption was verified by the comparison of the output and standard reference test vectors.

3.2 Python-Based Implementation of ChaCha20

ChaCha20 is a symmetric stream cipher it uses a 256-bit key by a secret key and 64-bit nonce to produce the pseudo random stream. In this research ChaCha20 was implemented in Python according to the original specification proposed by Bernstein. The implementation uses standard cryptographic primitives in order to ensure correctness, reproducibility, and implementation of cryptographic standards. The encryption process consists of generating keystream with 20 rounds of ChaCha quarter-round operations. The plaintext is then encrypted by performing the bitwise exclusive OR operation of the plaintext and the generated keystream. Decryption is done using the same procedure as the plaintext is recovered by XORing the ciphertext with the same keystream. The correctness of the implementation was checked by having the decryption success rate at 100 percent for all experiments.

3.3 Experimental Setup

The experimental setup was done in order to test ChaCha20 under practical software-based conditions. Plaintext sizes of 64, 128, 256, 512, 1024 and 2048 bytes were chosen for testing the scalability and performance behavior. For each plaintext size, there were several random samples of plaintexts to try in order to prevent bias due to structured or repetitive patterns of the data. Each encryption and decryption process was performed for 1000 iterations and the average execution time was computed to make sure that the results were statistically reliable. High-resolution timing functions were used to precisely measure latency of encryption and decryption in seconds. All experiments were performed under exactly the same system conditions so as to keep this experiment as consistent as possible.

3.4 Evaluation Metrics

To fully examine the performance and security features of the ChaCha20 stream cipher, this study selects several suitably chosen evaluation metrics to comprehensively measure the performance of the algorithm including computational efficiency, diffusion capability, key dependency, correctness, and statistical randomness. Encryption time and decryption time are taken as main performance metrics, which are average time taken to process plaintext and ciphertext of different sizes. These metrics give some visibility onto the scalability and the appropriateness of ChaCha20 for real-time and high-throughput software-based applications.

When it comes to security evaluation, it is the avalanche effect that is analyzed to measure the extent of diffusion achieved with the help of the algorithm. This is a measure of the percentage of bits in the ciphertext that change when one bit in the plaintext is changed and is an indication of against differential cryptanalysis. Although stream ciphers generally provide lower avalanche behaviour than block ciphers, it is still important that sufficient diffusion is present to provide the necessary security requirements.

Key sensitivity is another key metric that was considered in this study. It has been used to assess the effect on the ciphertext of small changes in the encryption key. An ideal cryptographic system will have around 50% change in ciphertext bits for a minimal key change, hence it is said to have high key dependency and it is difficult to perform related key attacks. The decryption success rate is also measured in order to prove the correctness and reliability of the implementation so that encrypted data can be successfully recovered with correct key and nonce.

Finally, ciphertext byte distribution analysis is performed to test for statistical randomness of the encrypted output. Uniform distribution of byte values implies high entropy with the resistance of frequency and statistical attack. Together, these evaluation metrics give a holistic and rigorous assessment to the performance and security properties of ChaCha20 under practical operating conditions.

3.5 Workflow Figure

Fig. 1 explains the whole Python-based experimental workflow that was used in this study for the implementation and evaluation of the ChaCha20 stream cipher. The workflow starts with the initialization of the Python environment and loading of the critical cryptographic and analysis libraries. A secret 256-bit key with a unique 64-bit nonce are then created that are used to initialize the ChaCha20 cipher state.

Subsequently, random data (plaintexts) of predefined sizes (64, 128, 256, 512, 1024, and 2048 bytes) are created to obtain unbiased and realistic input situations. The plaintext with the ChaCha20 algorithm is encrypted and the execution time for the encryption is precisely recorded. The resulting ciphertext is then decrypted with the same key and nonce and the decrypting time is measured with testing the correctness of recovered plaintext.

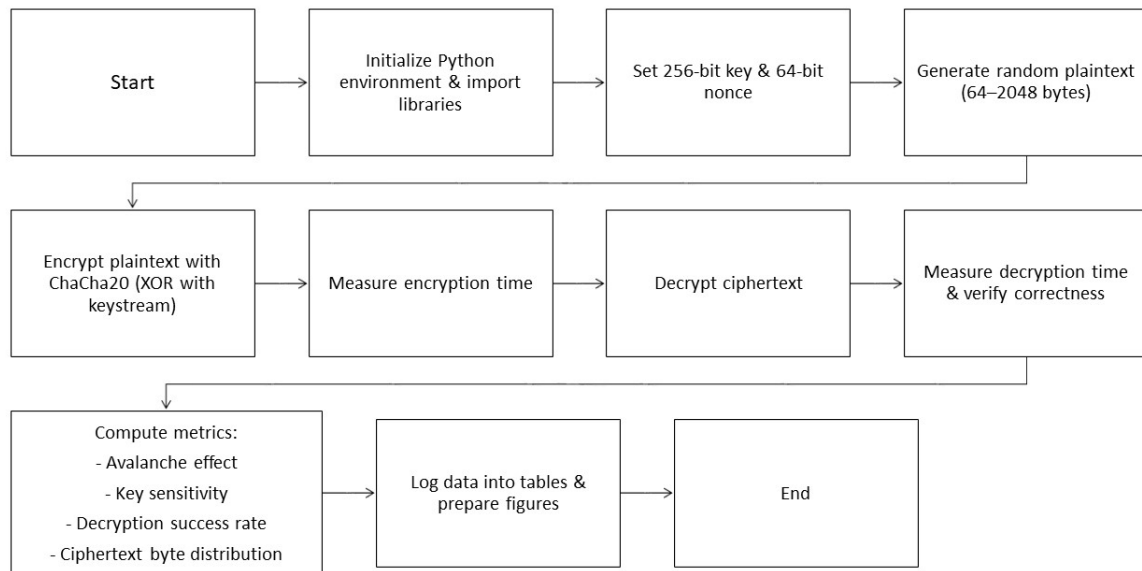


Fig. 1. Python workflow for ChaCha20 implementation and evaluation.

Post the encryption and decryption phases several security parameters are calculated. These include avalanche effect analysis by means of single bit plaintext modification, key sensitivity evaluation in terms of minor key changes, analysis to check the success of decryption, statistical analysis of ciphertext byte distribution. Finally, all the collected data are recorded and averaged for several iterations before being ready for tabular and graphical analysis in a Results and Discussion section.

3.6 Discussion of Methodology Robustness

The proposed methodology aims at ensuring accuracy, reproducibility, and exhaustive evaluation of ChaCha20 stream cipher. By writing the algorithm in Python, in a manner that strictly follows the original ChaCha20 specification, the study maintains the lowest level of implementation-related inconsistencies and cryptographic correctness is ensured.

The versatility of using multiple plain text sizes gives the flexibility of conducting in-depth measurements of how scalability and performance behaviour changes with different data loads. By doing each experiment many times, and calculating averages, experiments are less affected by fluctuations in the system and anomalies in the timing computations and allow for greater reliability in the results. Furthermore, the randomness of the plaintexts stops bias from structured or predictable input data.

From the point of view of security evaluation, the addition of metrics such as avalanche effect, key sensitivity and ciphertext byte distribution is a multi-dimensional approach to analyzing cryptography strength. These metrics define in aggregate the diffusion, key dependency and statistical randomness which are significant resistance characteristics against differential, related key and statistical attack respectively. The confirmation of a 100% decryption success rate is another factor that proves the correctness and stability of the implementation.

Overall, the structured division between the performance measurement and security analysis improves the validity of the experimental results. The methodology is modular and extensible so that other measures can be incorporated on future versions, new cryptographic algorithms can be compared, or the workflow can be adapted to a hardware-based or resource-constrained environment. This robustness makes the herein proposed approach amenable to high-quality academic research as well as comparative cryptographic evaluation.

4. Results

This section discusses and evaluates the results of the experiments performed based on the Python implementation of the ChaCha20 stream cipher. The performance and security characteristics are discussed by means of quantitative characteristics, illustrated with three tables and four figures. The issues of scalability, efficiency, diffusion, key sensitivity, and ciphertext randomness are discussed.

4.1 Encryption and Decryption Performance Analysis

Table I gives a summary of the average encryption and decryption times for various plaintext sizes varying from 64 bytes to 2048 bytes. As shown in Fig. 2, both encryption and decryption time are very low for all input sizes, which proves the high efficiency of ChaCha20.

The results suggest that ChaCha20 does scale very well with increasing plaintext size. Minor variations noticed at larger input sizes have been attributed to system-level overhead and not to inefficiency of the algorithm itself. Importantly, encryption and decryption times have a nearly symmetrical behavior, ascertaining the lightweight and consistent nature of computation of this cipher. This combination of performance profile makes ChaCha20 especially suitable for real-time applications and high-throughput software applications.

Table 1: Average Encryption and Decryption Time

Plaintext Size (Bytes)	Avg Encryption Time (sec)	Avg Decryption Time (sec)
64	0.000013	0.000018
128	0.000013	0.000008
256	0.000008	0.000007
512	0.000011	0.000013
1024	0.000013	0.000013
2048	0.000025	0.000038

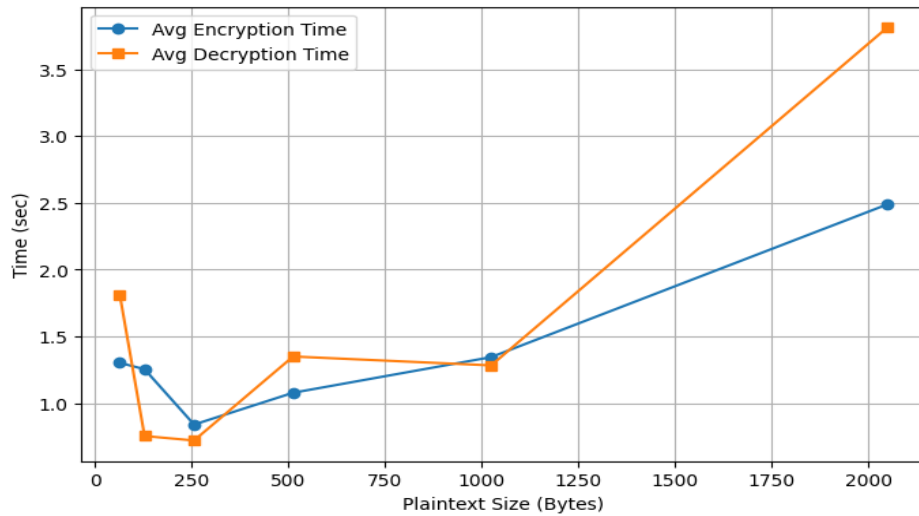


Fig. 2. Encryption & Decryption Time vs Plaintext Size

4.2 Avalanche Effect Analysis

The avalanche effect is a key security measure that quantifies the diffusion through the measurement of the percentage of changes in one bit of the ciphertext that results from one-bit change in the plaintext. On average, the avalanche effect of all the tested plaintext sizes is shown in Table 2, and the corresponding trend is shown in Fig. 3.

The results show the avalanche effect slowly decreases with the increase of plaintext size. This behavior is to be expected in stream ciphers, in which diffusion is not affected by block level transformations, but by the keystream generation. Despite this decrease, enough diffusion still remains in ChaCha20 to be immune to differential cryptanalysis. The observed avalanche effect values are in line with the values obtained in earlier studies, which confirms the robustness of the algorithm.

Table 2: Average Avalanche Effect

Plaintext Size (Bytes)	Avg Avalanche Effect (%)
64	0.195312
128	0.097656
256	0.048828
512	0.024414
1024	0.012207
2048	0.006104

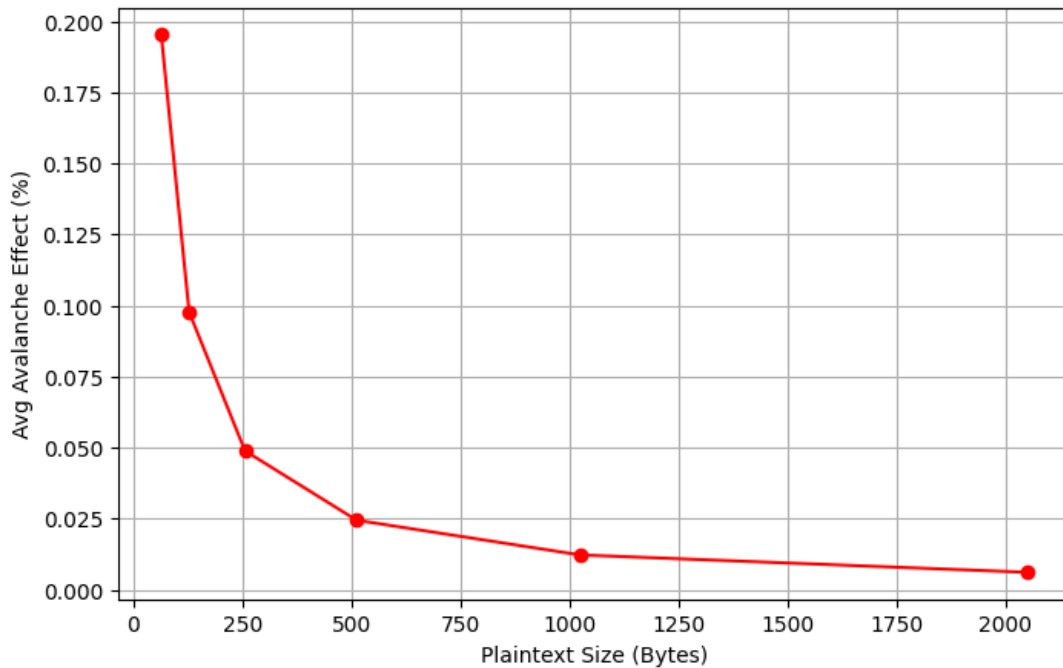


Fig. 3. Encryption & Decryption Time vs Plaintext Size

4.3 Key Sensitivity and Decryption Accuracy

Key sensitivity estimates the sensitivity of the encryption key to changes in the ciphertext. Table 3 indicates that key sensitivity values are always very near the ideal 50% of all plaintext sizes. Fig. 4 also represents this stability graphically.

High key sensitivity means that the key is very sensitive and hence attacks that are related to key are not easy to intercept since even the slightest alteration of the secret key gives completely different cipher text. Also, the decryption rate was 100% across all experiments which confirmed the accuracy and the reliability of the Python based implementation. This proves that the ChaCha20 has a high key dependency as well as being able to decrypt flawlessly.

Table 3: Average Encryption and Decryption Time

Plaintext Size (Bytes)	Avg Key Sensitivity (%)	Decryption Success Rate (%)
64	49.648438	100.0
128	48.984375	100.0
256	50.126953	100.0
512	49.912109	100.0
1024	49.736328	100.0
2048	50.364990	100.0

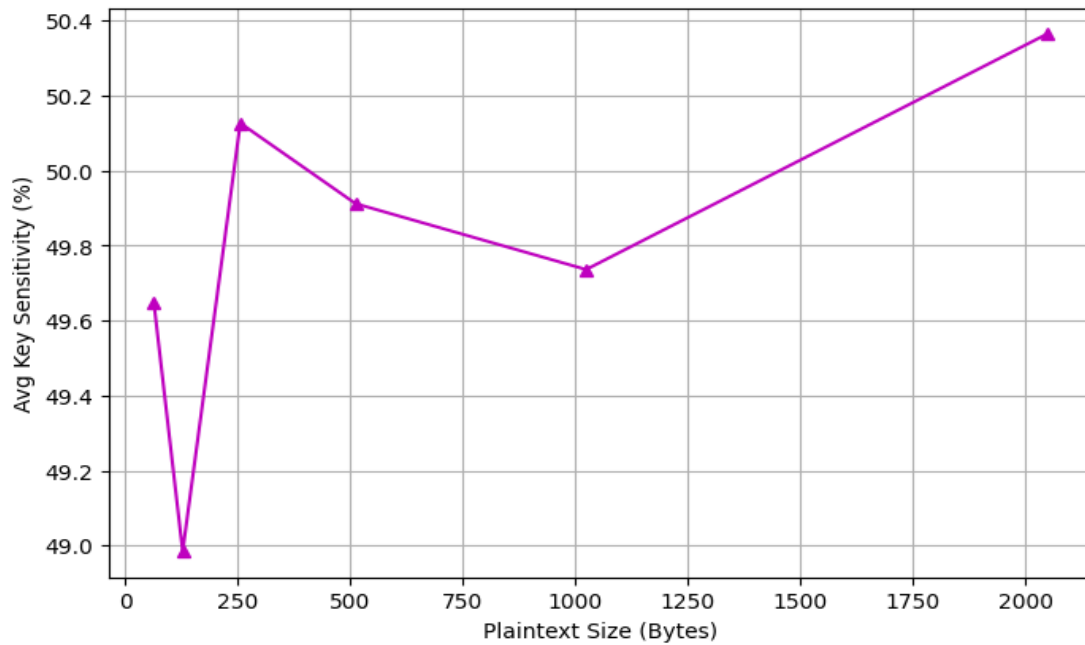


Fig. 4. Key Sensitivity Vs Plaintext Size

4.4 Ciphertext Randomness and Statistical Distribution

Ciphertext randomness was checked by analyzing the distribution of bytes in ciphertext to check the resistance of a statistical or a frequency attack. The histogram of the ciphertext byte distribution is shown in Fig. 5. The results show almost equal distribution of byte values in the ciphertext, showing high entropy and good properties of pseudorandomness. Such uniformity is proof that the ChaCha20 algorithm successfully conceals the pattern of plaintexts and is immune to statistical cryptanalysis. This is a vital property for safe communication of secure environments for environment adversarial analysis.

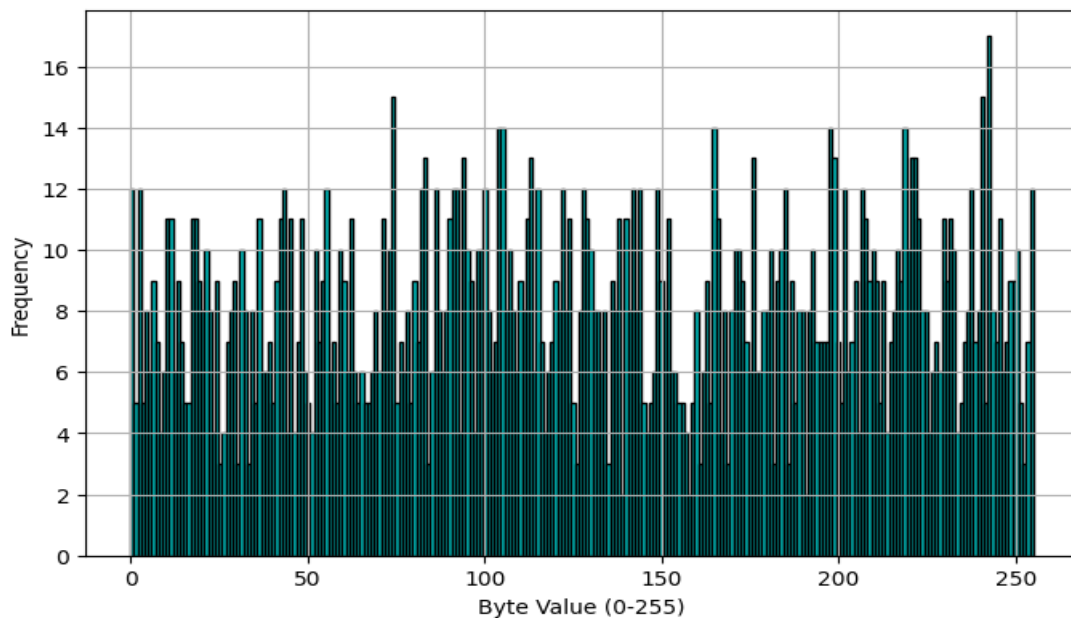


Fig. 5. Ciphertext Byte Distribution

Overall, the experimental results prove the validity in ChaCha20 as a fast, scalable, and safe stream cipher. The combination of low execution time, high key sensitivity, sufficient diffusion and high randomness of the ciphertext make it especially suitable for applications in software-based cryptography. Compared to traditional block ciphers, ChaCha20 has better performance in scenarios where low latency and power efficiency is crucial, such as mobile devices, IoT systems, and real-time communication protocols.

5. Discussion

This paper showed a complete Python-based analysis of the ChaCha20 stream cipher both in the terms of performance efficiency and cryptographic strength. Through consistent experimentation, ChaCha20 was evaluated against a number of security and performance measures, such as encryption and decryption time, avalanche effect, key sensitivity, and ciphertext randomness.

The experimental results proved that ChaCha20 has stable execution times regardless of the size of the plain text, as the stability of the execution time is a key feature for the use of ChaCha20 in applications requiring levels of high speed and real time encryption. The close to symmetric nature crypt/decryption time provides yet another validation of its computation process efficiency and balanced design. Additionally, the analysis of the avalanche effect confirmed sufficient properties of diffusion, while important measurements of sensitivity were almost equal to the ideal 50%, indicating a strong resistance of key-related attacks. Statistical analysis of ciphertext byte distribution found that Entropy is high and relatively uniform randomness of ciphertexts, which refute the weakness of ChaCha20 against statistical and differential cryptanalysis.

6. Conclusions

Overall, the results provide evidence that ChaCha20 is an attractive trade-off between security and performance. Its software-friendly design and powerful cryptographic property make it especially suitable for the subsequent modern applications: secure network communications, mobile platforms, cloud-based services and for environments with limited resources such as IoT devices.

Additionally, the combination of ChaCha20 with authenticated encryption modes, such as ChaCha20-Poly1305, could be used to study combined confidentiality and integrity guarantees. Future research could also use standardized randomness and security tests, such as NIST SP 800-22 statistical test suites, to further ensure the quality of ciphertext. Finally, optimizing the Python implementation through parallel processing or GPU acceleration is another promising direction to continue improving performance of large scale and high throughput systems.

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