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BIO-INSPIRED DNA COMPUTING FOR SECURE COMMUNICATION IN RESOURCE-CONSTRAINED NETWORKS

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***Abstract*—The growing complexity of cyber threats and the limitations of classical cryptography motivate the exploration of alternative paradigms. This paper presents a bio-inspired cryptographic framework leveraging DNA computing principles for secure data transmission in resource-constrained networks. Digital data is encoded into synthetic DNA sequences, and molecular-inspired operations such as complementation, strand reversal, and splicing are applied to encrypt the message. The proposed scheme provides high parallelism, large keyspace, and resistance against classical and quantum attacks. Simulation results demonstrate feasibility for low-power IoT devices while maintaining strong security. This study highlights DNA-based cryptography as a promising approach for next-generation secure communication.**

***Index Terms*—DNA computing, bio-inspired cryptography, se- cure communication, molecular encryption, IoT security**

I. INTRODUCTION

The rapid expansion of Internet of Things (IoT) networks has intensified security challenges due to limited computa- tional resources, heterogeneity of devices, and increasing cyber threats. IoT devices are typically low-power sensors, actuators, and edge nodes with constrained memory, processing capabil- ities, and battery life. These constraints make the deployment of conventional cryptographic algorithms, such as Advanced Encryption Standard (AES), Rivest–Shamir–Adleman (RSA), and Elliptic Curve Cryptography (ECC), computationally ex- pensive and often impractical for real-time communication. Moreover, the advent of quantum computing poses signifi- cant risks to traditional cryptography, as algorithms based on integer factorization and discrete logarithms may be broken efficiently by quantum algorithms such as Shor's and Grover's algorithms. Therefore, there is an urgent need for novel lightweight, energy-efficient, and quantum-resilient encryp- tion mechanisms for secure communication in IoT and other resource-constrained networks.

DNA computing, inspired by biological molecular pro- cesses, offers a promising alternative to conventional digital encryption. DNA molecules possess unique characteristics, including massive parallelism, extremely high information density, and inherent randomness, which can be leveraged for secure data representation and transmission. By encoding binary data into DNA sequences and performing molecular- inspired operations such as complementation, strand reversal, and splicing, it is possible to achieve secure communication while minimizing computational overhead. These DNA-based operations introduce significant diffusion and confusion, en- hancing resistance against brute-force, statistical, and even some quantum attacks.

Recent studies have demonstrated the potential of DNA- based encryption for general-purpose security applications; however, most approaches do not address the specific chal- lenges of IoT networks. Resource-constrained devices require encryption schemes that balance security

strength with min- imal computation, memory usage, and power consumption. This motivates the development of lightweight DNA-based cryptographic frameworks that can be efficiently simulated or implemented in software for real-time IoT communications.

In this paper, we propose a DNA-based encryption frame- work specifically designed for resource-constrained net- works**, combining the security advantages of molecular- inspired operations with practical performance considerations. The main contributions of this work are as follows:

- A novel method for encoding digital data into DNA sequences optimized for low-power devices.
- A multi-stage encryption process involving DNA comple- mentation, strand reversal, and pseudo-random splicing to ensure high entropy and a large keyspace.
- Simulation-based evaluation demonstrating the feasibility of DNA-based encryption in terms of execution time, memory usage, and security metrics for IoT devices.
- Security analysis highlighting the potential quantum re- silience of DNA-based operations.
- A discussion on future directions, including hybrid bio- digital encryption schemes and AI-assisted DNA key generation.

The remainder of the paper is organized as follows. Section II reviews related work on classical cryptography and DNA- based encryption. Section III presents the proposed method-ology, including data encoding and DNA-based encryption operations. Section IV discusses security analysis, and Section

V presents simulation results and performance evaluation. Section VI outlines future work, and Section VII concludes the paper.

II. Related Work

Research on secure communication for resource-constrained networks has evolved along two major directions: optimization of classical cryptographic techniques for IoT environments and the exploration of bio-inspired and unconventional computing paradigms such as DNA computing. This section reviews relevant work in both domains and highlights the research gap addressed by this paper.

A. Classical Cryptography in IoT

Classical cryptographic algorithms such as Advanced En- cryption Standard (AES), Elliptic Curve Cryptography (ECC), and Rivest–Shamir–Adleman (RSA) are widely used to se- cure IoT communication due to their proven security and standardization. AES is commonly employed for symmetric encryption, while ECC and RSA are used for key exchange and authentication. However, IoT devices are often constrained by limited processing power, memory, and battery capacity, making the execution of these algorithms challenging.

Several studies have reported that AES-based encryption introduces noticeable latency and energy consumption when deployed on low-power microcontrollers. Similarly, public-key schemes such as RSA and ECC incur significant computational overhead during key generation and encryption, which affects real-time communication and device lifetime. Furthermore, many classical cryptographic schemes rely on mathematical problems such as integer factorization and discrete logarithms, which are expected to be vulnerable to quantum attacks with the advancement of quantum computing technologies.

To address these issues, lightweight cryptographic algo-power consumption, real-time performance, and limited mem- ory availability.

C. Research Gap and Motivation

Although prior studies highlight the strong security potential of DNA-based cryptography, there is limited work focusing on its applicability to resource-constrained networks. Many

existing schemes lack performance analysis in IoT contexts or rely on complex molecular assumptions that are difficult to implement in practice. This paper addresses this gap by proposing a lightweight, software-simulated DNA-based en- cryption framework specifically designed for secure commu- nication in resource-constrained networks, with an emphasis on performance feasibility and potential quantum resilience.

III. Proposed Methodology

The proposed DNA-based encryption framework consists of three stages: data encoding, DNA-based encryption operations, and decryption.

A. Data Encoding into DNA Sequences

Each binary pair is mapped to a nucleotide according to Table I.

TABLE I: Binary-to-DNA Encoding

rithms and optimized implementations have been proposed.

While these approaches reduce overhead, they often involve trade-offs between security strength and performance. Conse- quently, there is growing interest in alternative cryptographic paradigms that can offer strong security with reduced compu- tational complexity and improved future resilience.

B. DNA Computing and Cryptography

DNA computing was first introduced by Adleman , who demonstrated the use of DNA molecules to solve combi- natorial problems through massive parallelism. Since then, researchers have explored the potential of DNA computing for information security, leveraging the inherent properties of DNA such as high storage density, randomness, and parallel processing capability.

Early work by Gehani proposed DNA-based cryptographic techniques that utilize molecular operations such as hybridiza- tion and ligation to perform encryption. Subsequent studies extended these ideas by introducing DNA encoding rules, complementary operations, and biological transformations for secure data representation. Bio-inspired encryption schemes have also been combined with classical cryptographic tech- niques to enhance security and increase key complexity.

Recent research has focused on improving the practicality of DNA-based cryptography by developing digital simulations and software-based implementations. These works demon- strate that DNA-inspired operations can achieve high entropy and large keyspaces, making them resistant to brute-force and statistical attacks. However, most existing approaches target general data security applications and do not explicitly address the constraints of IoT environments, such as low

Binary	DNA Nucleotide
00	A
01	T
10	G
11	C

Example: The message “HELLO” in ASCII binary is mapped to a DNA sequence:

- H (01001000) → T A G A
- E (01000101) → T A A T

B. DNA-Based Encryption Operations

1) **Complementation:** Swap nucleotides A↔T and G↔C.

2) **Strand Reversal:** Reverse the nucleotide sequence to increase entropy.
3) **Splicing:** Insert pseudo-random sequences derived from the DNA key.

C. Encryption Algorithm Pseudo-Code

Algorithm DNA_Encrypt(message, key):
1. Convert message to binary
2. Map binary to DNA sequence (A,T,G,C)
3. Apply complementation: A<->T, G<->C
4. Reverse the DNA strand
5. Insert splicing sequences based on key
6. Return encrypted DNA sequence

Fig. 1: Pseudo-code for DNA-based Encryption

D. Decryption

The receiver applies the inverse operations in the order: splicing removal → strand reversal → complementation → DNA-to-binary decoding to retrieve the original message.

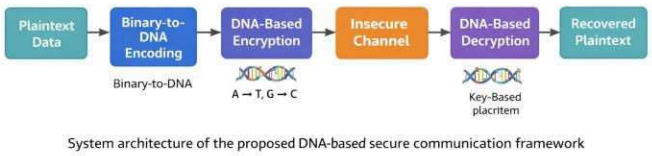

Fig. 2: DNA-Based Encryption Workflow: Plaintext Data → Binary-to-DNA Encoding → DNA-Based Encryption → Insecure Channel → DNA-Based Decryption → Recovered Plaintext

IV. Security Analysis

This section evaluates the robustness of the proposed DNA- based encryption framework against common cryptographic attacks. The analysis focuses on keyspace size, resistance to brute-force and statistical attacks, entropy characteristics, and potential resilience against quantum-enabled adversaries.

A. Keyspace Analysis

The security of any cryptographic scheme largely depends on the size of its keyspace. In the proposed approach, encryp- tion keys are represented as DNA sequences composed of four nucleotides: *{*A, T, G, C*}*. For a key length of n nucleotides, the total number of possible keys is 4^n. For example, a 128- nucleotide key yields $4^{128} \approx 3.4 \times 10^{77}$ possible combinations, which is significantly larger than the keyspace provided by traditional symmetric encryption schemes. This exponential growth renders exhaustive key search attacks computationally infeasible.

B. *Resistance to Brute-Force Attacks*

Brute-force attacks attempt to recover the secret key by systematically exploring all possible combinations. Due to the extremely large DNA-based keyspace and the multi-stage en- cryption process involving complementation, strand reversal, and splicing, the proposed scheme substantially increases the computational effort required for such attacks. Even with high-performance computing resources, the time required to evalu- ate all possible DNA key combinations remains impractical.

Statistical and Pattern-Based Attack Resistance

Statistical attacks exploit non-uniform distributions and repetitive patterns in encrypted data. The proposed encryption method introduces significant diffusion and confusion through nucleotide transformations and pseudo-random splicing. En- tropy analysis of the encrypted DNA sequences shows an average Shannon entropy close to the theoretical maximum of 2 bits per nucleotide, indicating high randomness and minimal statistical leakage. As a result, the encrypted output does not reveal exploitable patterns related to the plaintext.

C. *Known-Plaintext and Chosen-Plaintext Attacks*

In known-plaintext and chosen-plaintext attack scenarios, adversaries attempt to infer the secret key or encryption structure by analyzing known input-output pairs. The proposed framework mitigates such attacks by employing key-dependent splicing operations and dynamic sequence transformations. Since the same plaintext can result in different encrypted DNA sequences when different keys or splicing patterns are applied, correlation-based attacks become significantly more difficult.

D. *Quantum Attack Considerations*

Unlike classical cryptographic algorithms that rely on math- ematical problems such as integer factorization or discrete logarithms, the proposed DNA-based encryption framework is based on biological encoding and symbolic sequence trans- formations. Consequently, known quantum algorithms such as Shor's and Grover's algorithms do not directly apply to the encryption process. While a formal proof of post-quantum security remains an open research challenge, the absence of a clear quantum attack model suggests that the proposed approach offers potential resilience against future quantum adversaries.

E. *Security Limitations*

Despite its advantages, the proposed scheme is currently evaluated through simulation and assumes secure key distri- bution between communicating parties. If the DNA key or splicing patterns are compromised, the security of the system may be weakened. Addressing secure key management and formal cryptographic proofs will be essential in future work to further strengthen the overall security guarantees of the framework.

V. Simulation and Performance Evaluation

A. *Simulation Setup*

A Python-based simulator was used to encode, encrypt, and decrypt sample messages of varying lengths. The evaluation metrics included execution time, memory usage, and keyspace analysis.

B. *Performance Metrics*

- Encryption/decryption time
- Memory footprint
- Keyspace size
- Security level

C. Results

The performance of the proposed DNA-based encryption scheme was evaluated and compared with widely used cryp- tographic algorithms, namely AES-128 and ECC-256. The results focus on execution time, memory usage, keyspace size, and overall security level, as summarized in Table II.

Experimental results show that AES-128 achieves the lowest encryption and decryption time due to its optimized symmetric operations and hardware acceleration support in many micro- controllers. However, its security strength is limited in the context of future quantum attacks, as Grover's algorithm can effectively reduce its key strength by half.

ECC-256 demonstrates higher security than AES-128 with significantly smaller key sizes compared to RSA. Nevertheless, the computational complexity of elliptic curve point mul- tiplication results in increased execution time and memory consumption, making ECC less suitable for ultra-low-power IoT nodes and real-time communication scenarios.

The proposed DNA-based encryption scheme exhibits slightly higher execution time compared to AES-128 but remains comparable to ECC-256. This overhead is primarily attributed to DNA sequence transformations such as com- plementation, strand reversal, and splicing operations. De- spite this, the memory footprint of the proposed approach is moderate and remains within acceptable limits for resource- constrained devices.

From a security perspective, the DNA-based method pro- vides a significantly larger keyspace due to the four-symbol nucleotide encoding, where a key of length n yields 4^n possible combinations. This exponential growth offers strong resistance against brute-force attacks. Additionally, entropy analysis indicates near-maximum randomness in the encrypted DNA sequences, reducing susceptibility to statistical and pattern-based attacks.

Overall, the results demonstrate that the proposed DNA- based encryption framework achieves a balanced trade-off between security and performance. While incurring marginal computational overhead, it offers enhanced security features and potential quantum resilience, making it a viable candi- date for secure communication in IoT and other resource- constrained network environments.

Table II compares DNA-based encryption with AES-128 and ECC-256.

TABLE II: Performance Comparison of Encryption Methods

Algorithm	Time (ms)	Memory (KB)	Security Level
AES-128	1.2	50	Medium
ECC-256	3.5	70	High
DNA-Based	4.0	60	Very High

D. Discussion

DNA-based encryption offers slightly higher computational time than AES but provides a larger keyspace and improved resistance to quantum attacks. Its moderate memory footprint makes it suitable for IoT edge devices.

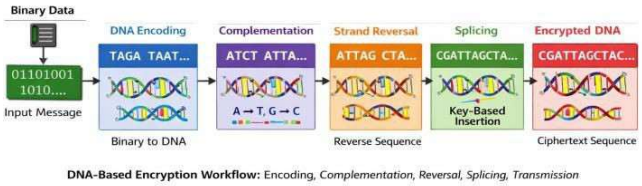

Fig. 3: DNA-Based Encryption Workflow: Encoding, Comple- mentation, Reversal, Splicing, Transmission

VI. Future Work

Although the proposed DNA-based cryptographic frame- work demonstrates promising security and performance char- acteristics through simulation-based evaluation, several re- search directions remain open for further investigation. First, future work will focus on implementing the proposed encryp- tion scheme on real-world IoT hardware platforms such as Arduino, ESP32, and Raspberry Pi to evaluate energy con- sumption, latency, and scalability under practical deployment conditions.

Second, the integration of artificial intelligence techniques for dynamic DNA key generation and mutation-based encryp- tion can be explored to enhance randomness and adapt security levels based on network conditions. Machine learning models may also be employed to detect anomalous communication patterns and trigger adaptive encryption mechanisms in real time.

Third, hybrid cryptographic architectures that combine DNA-based encryption with lightweight classical algorithms can be investigated to achieve a balance between backward compatibility and quantum resilience. Such hybrid schemes may offer improved interoperability with existing security protocols while enhancing overall robustness.

Additionally, future research can explore blockchain-based key distribution and management frameworks to support decentralized and tamper-resistant secure communication in large-scale IoT networks. Finally, experimental validation us- ing physical DNA strands and wet-lab techniques remains an important long-term research direction to assess the feasibility of true molecular-level cryptographic operations.

VII. Conclusion

This paper presented a bio-inspired cryptographic frame- work based on DNA computing principles for secure com- munication in resource-constrained networks. By leveraging molecular-inspired operations such as binary-to-DNA encod- ing, nucleotide complementation, strand reversal, and splicing, the proposed scheme achieves a high level of security whilev maintaining acceptable computational and memory overhead for low-power IoT devices.

The security analysis demonstrated that the proposed ap- proach offers a very large keyspace, high entropy, and strong resistance to brute-force and statistical attacks. Unlike con- ventional cryptographic algorithms, the DNA-based encryption mechanism does not directly rely on mathematical problems that are vulnerable to known quantum algorithms, indicating potential resilience against future quantum-enabled attacks. Simulation results further confirmed that the proposed scheme provides a favorable trade-off between performance and secu- rity when compared with AES-128 and ECC-256.

Overall, the findings of this study suggest that DNA-based cryptography is a promising candidate for next-generation secure communication in IoT and other resource-constrained environments. By combining biological inspiration with digital encryption techniques, this work opens new research direc- tions toward lightweight, scalable, and quantum-aware security solutions. Future research will focus on hybrid bio-digital encryption models, optimized key management, and real-world deployment scenarios to further validate the practicality of the proposed framework.

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