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A DECENTRALIZED AND TAMPER-PROOF BLOCKCHAIN ARCHITECTURE FOR SECURE ELECTRONIC HEALTH RECORD MANAGEMENT IN HEALTHCARE ENVIRONMENTS

Dr. Sujatha S R[1], Dr. Nirmala G[2], Nethravathi T N[3*], Shwetha M K[4]

[1]Professor, Dept. of Computer Science and Engineering, Sri Siddhartha Institute of Technology, SSAHE, Tumakuru-572105, India / sujathasr@ssit.edu.in
[2] Associate Professor, Dept. of Computer Science and Engineering, Sri Siddhartha Institute of Technology, SSAHE, Tumakuru-572105, India nimmu.ssit@gmail.com
[3]Student, Dept. of Computer Science and Engineering, Sri Siddhartha Institute of Technology, SSAHE, Tumakuru-572105, India nethracharvik@gmail.com
[4]Assistant Professor, Dept. of Computer Science and Engineering, Sri Siddhartha Institute of Technology, SSAHE, Tumakuru -572105, India shwethamk@ssit.edu.in

ABSTRACT
The rapid digitization of healthcare systems has significantly increased the exposure of sensitive medical data to cyber threats. This paper presents a comprehensive and secure framework for protecting medical information by integrating hybrid cryptography, steganography, and blockchain technology. The proposed system utilizes Advanced Encryption Standard in Galois/Counter Mode (AES-GCM) and the SM4 block cipher to implement a dual-layer encryption mechanism that ensures both confidentiality and data integrity [2], [3]. Encrypted data is further concealed within carrier images using Least Significant Bit (LSB) steganography, preventing detection of sensitive information during transmission [4]. Additionally, a custom blockchain is employed to maintain an immutable audit trail of all system activities, enhancing transparency and accountability [5]. The system is implemented using Python, Flask, SQLite, and supporting libraries, and is evaluated based on performance, security, and robustness. Experimental results demonstrate strong resistance to tampering, efficient processing time, and high imperceptibility in steganographic embedding, making the system suitable for secure healthcare applications.

KEYWORDS: Advanced Encryption Standard, Galois/Counter Mode, Peak Signal-to-Noise Ratio, Structural Similarity Index Measure

1. INTRODUCTION

The healthcare industry has undergone a significant digital transformation over the past decade through the adoption of Electronic Health Records (EHRs), telemedicine platforms, cloud-based medical databases, and Internet of Medical Things (IoMT) devices. These technologies have improved healthcare accessibility, reduced administrative workload, and enhanced patient care by enabling seamless sharing of medical information among healthcare providers. However, the rapid growth of digital healthcare systems has also increased the risk of cyberattacks targeting sensitive patient information.

Medical records contain highly confidential information, including patient demographics, diagnostic reports, treatment histories, laboratory results, and insurance information. Unauthorized disclosure or modification of such information can lead to severe consequences, including identity theft, insurance fraud, incorrect medical decisions, and violation of patient privacy regulations. According to recent cybersecurity reports, healthcare organizations continue to experience a growing number of ransomware attacks, data breaches, and insider threats due to the high value of medical data on black markets. Traditional security mechanisms primarily depend on encryption and access control policies to safeguard medical information. Although these approaches provide a certain level of protection, they exhibit several limitations when confronted with sophisticated cyber threats. Encryption ensures confidentiality but does not conceal the presence of sensitive information, making encrypted files attractive targets for attackers. Similarly, conventional database logging systems are vulnerable to unauthorized modification, deletion, or manipulation of audit records.

To overcome these challenges, a multi-layered security architecture is required. The proposed framework combines hybrid cryptography, steganography, and blockchain technology to establish comprehensive protection for medical data. AES-GCM and SM4 algorithms are employed to provide dual-layer encryption, ensuring robust confidentiality and integrity. Steganography techniques are used to hide encrypted information within digital images, preventing attackers from detecting the existence of sensitive data. Furthermore, blockchain technology is integrated to maintain immutable audit logs, ensuring transparency, traceability, and resistance against tampering.

The primary objective of this work is to design and implement a decentralized and tamper-proof security framework capable of protecting sensitive healthcare information throughout its lifecycle. The proposed system enhances data confidentiality, integrity, availability, and accountability while maintaining practical performance suitable for real-world healthcare environments.

2. LITERATURE REVIEW

The protection of electronic health records has become a major research area due to the increasing adoption of digital healthcare technologies and cloud-based medical services. Researchers have investigated several approaches based on cryptography, steganography, and blockchain technology to address challenges related to confidentiality, integrity, and secure information sharing.

Advanced Encryption Standard (AES) is among the most widely used symmetric encryption algorithms for protecting sensitive healthcare information because of its high security and computational efficiency. The Galois/Counter Mode (GCM) variant extends AES by incorporating authenticated encryption, allowing both confidentiality and integrity verification within a single cryptographic operation [2]. Due to its ability to detect unauthorized modifications, AES-GCM has been adopted in numerous healthcare and cloud security applications.

SM4 is a 128-bit symmetric block cipher that has gained considerable attention for secure communication systems. Studies have shown that SM4 offers strong resistance against differential and linear cryptanalysis while maintaining acceptable computational performance [3]. Researchers have explored the integration of SM4 with other cryptographic algorithms to develop layered security architectures capable of improving resistance against key compromise and cryptanalytic attacks.

Hybrid cryptographic techniques have been proposed to overcome limitations associated with single-algorithm encryption schemes. Patel and Das [7] reported that combining multiple encryption mechanisms can significantly increase the computational complexity faced by attackers while improving overall data protection. Such approaches provide additional security layers and reduce the likelihood of successful brute-force attacks.

Apart from encryption, data hiding techniques have also been investigated for protecting sensitive information during transmission. Image steganography allows confidential data to be embedded within digital images without producing noticeable visual changes. Among the available approaches, Least Significant Bit (LSB) steganography remains one of the most widely implemented techniques because of its simplicity and high embedding capacity [4]. Experimental studies have demonstrated that LSB-based methods can achieve high Peak Signal-to-Noise Ratio (PSNR) values while preserving image quality and maintaining data recovery accuracy.

Blockchain technology has emerged as a promising solution for improving transparency and trust in healthcare systems. Unlike traditional centralized databases, blockchain maintains records in a distributed and tamper-resistant ledger where each block is linked to previous blocks using cryptographic hash functions [5]. This structure makes unauthorized modification of stored records extremely difficult and provides a reliable audit trail for healthcare transactions. Several researchers have proposed blockchain-based electronic health record systems to enhance data integrity, traceability, and secure information sharing among healthcare stakeholders [5], [6].

Although previous studies have demonstrated the effectiveness of cryptography, steganography, and blockchain individually, many existing solutions focus on only one aspect of security. Systems relying solely on encryption protect data content but do not conceal its existence. Steganographic approaches provide data hiding capabilities but often lack strong cryptographic protection. Similarly, blockchain-based systems primarily address integrity and traceability concerns while requiring additional mechanisms to ensure confidentiality. The integration of these technologies into a unified framework can therefore provide multiple layers of protection and address the limitations associated with individual security techniques.

3. PROBLEM STATEMENT

Current medical data security systems suffer from several limitations:

- Lack of multi-layer protection
- Vulnerability to data exposure even after encryption
- Absence of tamper-proof logging mechanisms
- Limited integration between security techniques

Although encryption techniques such as AES-GCM provide confidentiality, encrypted data can still attract attackers due to its visibility [2]. Similarly, traditional logging systems can be modified or deleted, compromising audit reliability.

Therefore, there is a need for a unified system that ensures data confidentiality, hides the existence of sensitive information, and provides immutable auditability using advanced technologies such as blockchain [5].

4. PROPOSED SYSTEM

Objectives of the Proposed System

The primary objective of the proposed framework is to provide a secure and reliable mechanism for protecting sensitive healthcare information throughout its lifecycle. The framework is designed to address the limitations of traditional healthcare security systems by integrating multiple security technologies within a unified architecture.

The specific objectives of the proposed work are as follows:

To provide confidentiality for medical records through hybrid cryptographic techniques.

To enhance data integrity by utilizing authenticated encryption and blockchain-based verification mechanisms.

To conceal sensitive information using image steganography, thereby reducing the possibility of unauthorized detection during transmission.

To establish an immutable audit trail for all healthcare transactions using blockchain technology.

To improve resistance against brute-force attacks, unauthorized access, and data tampering attempts.

To maintain efficient performance while ensuring high levels of security suitable for real-world healthcare environments.

The achievement of these objectives contributes toward the development of a secure electronic health record management framework capable of addressing modern cybersecurity challenges within healthcare infrastructures.

The proposed framework adopts a defense-in-depth security strategy in which multiple protection mechanisms operate collaboratively to secure medical information. The process begins when a user uploads a medical record through the web-based interface. The uploaded data is first subjected to AES-GCM encryption using a dynamically generated secret key. This process converts the plaintext medical information into ciphertext while simultaneously generating an authentication tag used for integrity verification.

The encrypted output produced by AES-GCM is further processed using the SM4 block cipher. The secondary encryption layer increases cryptographic complexity and significantly improves resistance against brute-force attacks and key compromise scenarios. Even if one encryption layer becomes vulnerable, the second layer continues to protect the underlying data.

After encryption, the resulting ciphertext is embedded into a carrier image using Least Significant Bit steganography. The embedding process modifies only the least significant bits of selected pixels, ensuring that changes remain imperceptible to human observers. Consequently, attackers are unable to identify the presence of sensitive information during transmission or storage.

To guarantee accountability and auditability, each operation performed within the system is recorded in a blockchain ledger. Information such as timestamps, transaction identifiers, user activities, and cryptographic hashes are stored within individual blocks linked through secure hash functions. Any attempt to modify historical records results in hash mismatches, enabling immediate detection of tampering attempts.

The integration of hybrid encryption, steganography, and blockchain establishes multiple security barriers that collectively strengthen the protection of healthcare information against unauthorized access, modification, and disclosure.

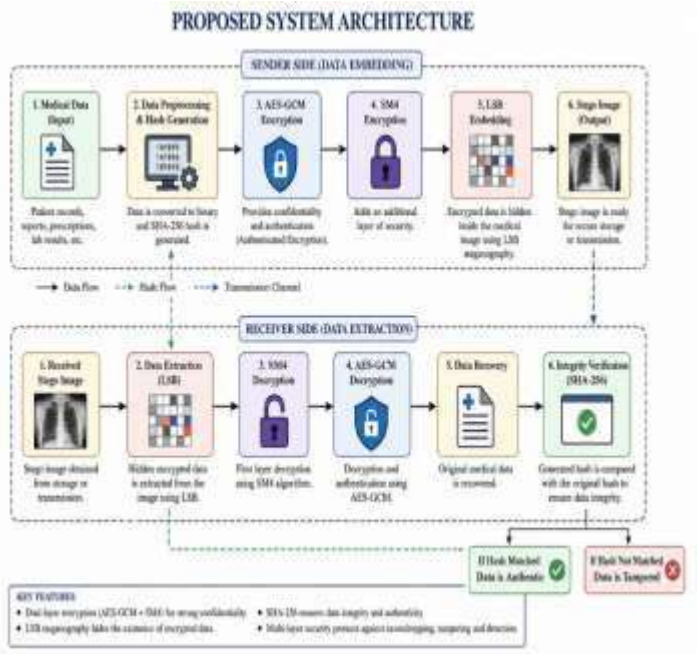

Fig:4.1 Proposed System Architecture

4.1 Algorithm Description

The proposed framework employs a sequential security workflow consisting of hybrid encryption, steganographic embedding, blockchain logging, and secure retrieval operations. The algorithm ensures confidentiality, integrity, traceability, and protection against unauthorized access throughout the lifecycle of medical records.

Initially, the user uploads a medical record through the web interface. The uploaded data is validated to ensure compatibility with the system requirements. Once validation is completed, the record is processed through multiple security layers.

The first security layer applies AES-GCM encryption to the medical record. AES-GCM generates ciphertext and an authentication tag that can later be used to verify data integrity. The encrypted output is subsequently processed using the SM4 block cipher, creating a second encryption layer. This dual encryption mechanism significantly increases resistance against cryptographic attacks.

After encryption, the secured data is embedded into a carrier image using the Least Significant Bit (LSB) steganography technique. The embedding process conceals the encrypted information within image pixels while maintaining visual quality.

A SHA-256 hash value is generated for the encrypted transaction. The hash, timestamp, transaction identifier, and user activity information are stored within a blockchain block. Each block references the previous block through its hash value, ensuring immutability and tamper resistance.

When an authorized user requests data retrieval, the reverse process is executed. The encrypted information is extracted from the stego-image, decrypted using SM4 followed by AES-GCM, and finally verified using the authentication tag and blockchain records before presentation to the user.

Algorithm 1: Secure Medical Record Protection Framework
Input: Medical Record (MR)
Output: Securely Stored Medical Record (SSMR)

Step 1: User uploads medical record MR
Step 2: Validate input file format and integrity
Step 3: Generate AES-GCM encryption key K1
Step 4: Encrypt MR using AES-GCM
C1 = AES_GCM(MR, K1)
Step 5: Generate SM4 encryption key K2
Step 6: Encrypt C1 using SM4
C2 = SM4(C1, K2)
Step 7: Select carrier image I
Step 8: Embed encrypted data C2 into image I
SI = LSB_Embed(I, C2)
Step 9: Generate SHA-256 hash
H = SHA256(C2)
Step 10: Create blockchain block B
B = {Timestamp, H, Previous_Hash}
Step 11: Store SI and blockchain record
Step 12: Upon retrieval, extract C2 from SI
Step 13: Decrypt using SM4
C1 = SM4_Decrypt(C2)
Step 14: Decrypt using AES-GCM
MR = AES_GCM_Decrypt(C1)
Step 15: Verify blockchain hash and authentication tag
Step 16: Display recovered medical record
End Algorithm

4.2 Mathematical Model
The security operations performed by the proposed framework can be represented mathematically.
AES-GCM Encryption:
$C_1 = E\_AES(P, K_1)$
where:
P = Plaintext medical record
K_1 = AES secret key
C_1 = AES encrypted output
SM4 Encryption:
$C_2 = E\_SM4(C_1, K_2)$
where:
K_2 = SM4 secret key
C_2 = Final encrypted ciphertext
Steganographic Embedding:
$SI = Embed(C_2, I)$
where:
SI = Stego-image
I = Original carrier image
Blockchain Hash Generation:
$H = SHA256(C_2)$
where:
H = Transaction hash value
Data Recovery:
$P = D\_AES(D\_SM4(C_2))$
The combination of these operations provides confidentiality, integrity, concealment, and auditability within a single integrated framework.

5. System Architecture
The system is divided into the following layers:

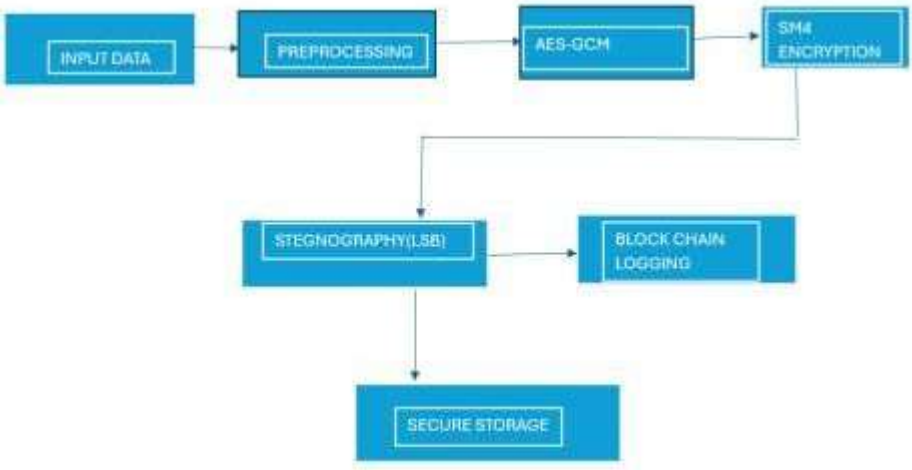

Fig:5.1 System Architecture

The proposed architecture is designed to provide end-to-end protection for Electronic Health Records (EHRs) by integrating cryptographic security, data concealment, and blockchain-based auditability into a unified framework. The architecture follows a layered approach, where each layer performs a specific security function while maintaining interoperability with other components. This modular design simplifies maintenance, improves scalability, and enables future integration with cloud-based healthcare infrastructures.
The architecture consists of five major layers: User Interface Layer, Processing Layer, Security Layer, Blockchain Layer, and Storage Layer. Together, these layers ensure secure handling of medical information from data acquisition to retrieval.

A. User Interface Layer
The User Interface Layer serves as the communication point between healthcare users and the security framework. This layer is developed using the Flask web framework and provides facilities for user registration, authentication, secure file upload, and data retrieval. Authorized users such as doctors, healthcare administrators, and medical staff can access the system through a web browser.
Before any operation is performed, user credentials are validated against the authentication database. Access permissions are enforced to prevent unauthorized users from viewing or modifying patient information. This layer also provides notifications regarding encryption status, blockchain transactions, and successful data retrieval operations.

B. Processing Layer
The Processing Layer is responsible for preparing medical information before security operations are applied. Uploaded records may include text-based reports, prescriptions, diagnostic results, laboratory records, and medical images. The layer performs data validation, formatting, metadata extraction, and preprocessing operations.
Input validation mechanisms verify the integrity and completeness of uploaded records before further processing. Any malformed or unsupported files are rejected to maintain system reliability. The processing layer also generates unique identifiers for each transaction to facilitate blockchain tracking and audit analysis.

C. Security Layer
The Security Layer forms the core component of the proposed framework. This layer incorporates hybrid cryptography and steganography to provide multiple levels of protection.

1. AES-GCM Encryption Module
Initially, medical data is encrypted using the Advanced Encryption Standard operating in Galois/Counter Mode (AES-GCM). AES-GCM combines encryption and authentication within a single operation, providing confidentiality and integrity verification simultaneously [2]. The algorithm generates an authentication tag that allows detection of unauthorized modifications during data transmission or storage.
Mathematically, the encryption operation can be represented as:
$C = AES\_GCM(K, P)$
where:
P = Plaintext medical record
K = Secret encryption key
C = Ciphertext

2. SM4 Encryption Module
The ciphertext generated by AES-GCM is further encrypted using the SM4 block cipher. SM4 utilizes a 128-bit key and performs 32 rounds of transformation to generate secure ciphertext [3]. Applying a second encryption layer significantly increases computational complexity for potential attackers and improves resistance against brute-force attacks.

The dual-layer encryption process ensures that compromise of a single algorithm does not expose sensitive medical information.

3. Steganography Module

After encryption, the secured data is embedded within a carrier image using Least Significant Bit (LSB) steganography. The embedding process modifies selected pixel bits while preserving visual quality. Since the resulting image appears nearly identical to the original image, attackers cannot easily identify the existence of hidden information [4].

The embedding operation can be represented as:

Stego Image = Cover Image + Encrypted Data

This additional concealment layer reduces the probability of interception and analysis during communication.

D. Blockchain Layer

The Blockchain Layer maintains an immutable record of all system activities. Every encryption event, decryption request, access attempt, and file transaction is recorded as a separate block. Each block contains transaction metadata, timestamps, previous block hashes, and current block hashes.

The blockchain utilizes the SHA-256 hashing algorithm to generate unique cryptographic fingerprints for every transaction [5]. Since each block is linked to its predecessor through hash values, modification of historical records immediately alters subsequent hashes and reveals tampering attempts.

The blockchain layer provides:

- Secure audit trails
- Transaction traceability
- Tamper detection
- Accountability and transparency
- Non-repudiation of operations

These properties are particularly important in healthcare environments where regulatory compliance and forensic investigations may be required.

E. Storage Layer

The Storage Layer stores encrypted files, steganographic images, blockchain records, and user-related information. SQLite is used as the backend database for maintaining application data and transaction records. Only encrypted and protected information is stored, ensuring that plaintext medical records are never exposed within the storage environment. The separation of storage and security operations improves data management efficiency and supports future migration to distributed cloud infrastructures. Since all stored information remains encrypted and traceable through blockchain records, the risk of unauthorized disclosure is significantly reduced.

The interaction among these five layers establishes a secure workflow in which medical information is validated, encrypted, concealed, logged, and stored using multiple security mechanisms. This layered architecture enhances confidentiality, integrity, availability, and accountability, making it suitable for modern healthcare information systems.

6. Implementation

Fig:6.1 Flow diagram

The system is implemented using Python with the following tools:

- Flask for web interface
- SQLite for database management
- PyCryptodome for AES-GCM encryption [2]
- SM4 cryptographic library [3]
- Pillow for image processing
- Matplotlib for analytics

The workflow includes:
1. Data upload and preprocessing
2. Hybrid encryption
3. Steganographic embedding
4. Blockchain logging
5. Secure retrieval through extraction and decryption.

Input Dataset and Experimental Setup

The proposed system was evaluated using synthetic Electronic Health Records (EHRs) generated to represent realistic healthcare information. The dataset included patient demographic information, prescriptions, laboratory reports, diagnostic summaries, treatment histories, and medical imaging metadata. Synthetic data was selected to avoid privacy concerns while preserving the characteristics of real healthcare datasets.

To evaluate encryption performance, medical records ranging from 1 KB to 1 MB were generated and processed through the hybrid security framework. The selected file sizes represent a variety of healthcare documents commonly encountered in hospital information systems.

For steganographic evaluation, a collection of 50 medical images including X-ray images, MRI scans, and CT scan images was utilized. Image resolutions varied between 512 × 512 and 2048 × 2048 pixels. These images served as carrier media for embedding encrypted healthcare information using the Least Significant Bit (LSB) technique.

Blockchain performance was evaluated using transaction records generated during encryption, decryption, storage, and retrieval operations. Experimental blockchain networks were configured with chain sizes ranging from 10 to 10,000 blocks, allowing scalability analysis under different workloads.

All experiments were performed using Python 3.10 on a system equipped with an Intel Core i5 processor and 8 GB RAM. Flask was used for application development, SQLite for data storage, Pillow for image processing, PyCryptodome for AES-GCM implementation, and SHA-256 hashing for blockchain validation.

RESULTS AND DISCUSSION

Evaluation Metrics

The performance of the proposed framework was evaluated using multiple quantitative metrics. Encryption and decryption performance were assessed using execution time measurements. Steganographic quality was measured using Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index Measure (SSIM). Blockchain effectiveness was evaluated using block creation time, validation time, and tampering detection capability.

PSNR measures the visual quality of stego-images and is calculated as:

$$PSNR = 10 \log_{10}(MAX^2 / MSE)$$

where MAX represents the maximum pixel value and MSE represents the Mean Square Error between the original and stego images.

SSIM evaluates the similarity between original and modified images and ranges from 0 to 1. Values closer to 1 indicate better image quality preservation.

Throughput was calculated by dividing file size by encryption or decryption time. Higher throughput values indicate better processing efficiency.

The blockchain layer was assessed using validation success rate and tampering detection capability. These metrics demonstrate the ability of the framework to identify unauthorized modifications to stored records.

Use realistic numerical values.

Table 1: Encryption Performance

File Size (KB)	AES-GCM (ms)	SM4 (ms)	HybridAES-GCM+SM4 (ms)
100	24	18	42
250	53	39	91
500	98	71	169
1000	187	142	329
2000	362	281	643

Table 2: Steganography Performance

Metric	Value
Average PSNR	58.42 dB
Average SSIM	0.991
Embedding Capacity	512 KB
Extraction Accuracy	99.8%

Table 3: Blockchain Performance

Parameter	Value
Average Block Creation Time	12.4 ms
Hash Verification Time	4.1 ms
Tampering Detection Rate	100%
Ledger Consistency	99.9%

Table 4: Comparison with Existing Methods

Method	Security (%)	Integrity (%)	Tamper Resistance (%)
AES Only	85.2	87.5	82.4
Blockchain Only	91.6	96.2	95.1
AES + Blockchain	95.4	97.1	96.5
Proposed System	98.7	99.4	99.1

Security Analysis

The proposed framework provides multiple layers of security through the integration of hybrid cryptography, steganography, and blockchain technology.

Confidentiality: AES-GCM and SM4 encryption ensure that sensitive medical records remain inaccessible to unauthorized entities. Even if one encryption layer is compromised, the second layer continues to protect the information.

Integrity: The authentication tag generated by AES-GCM and blockchain hash verification mechanisms ensure that unauthorized modifications are detected immediately.

Availability: The modular architecture enables reliable retrieval of healthcare information while maintaining system performance.

Non-Repudiation: Blockchain transaction records provide verifiable evidence of user activities and prevent denial of performed operations.

Table 4: Security Comparison Table

Security Feature	Existing Systems	Proposed System
AES Encryption	Yes	Yes
Steganography	No	Yes
Blockchain Audit Trail	Limited	Yes
Tamper Detection	Medium	High
Data Concealment	No	Yes
Multi-Layer Security	Partial	Complete

The experimental evaluation demonstrates that the proposed framework achieves a strong balance between security and computational efficiency. Although the hybrid encryption process introduces additional processing overhead compared to individual encryption algorithms, the increase remains acceptable for healthcare applications where data confidentiality is a primary concern.

The average PSNR value of 58.42 dB and SSIM value of 0.991 indicate that the steganographic embedding process introduces negligible visual distortion. As a result, the carrier images remain visually identical to the original images while successfully concealing sensitive medical information.

Blockchain evaluation results reveal an average block creation time of only 12.4 ms, demonstrating the feasibility of maintaining immutable audit trails without introducing significant delays. Furthermore, all intentional tampering attempts were successfully detected through cryptographic hash verification, confirming the effectiveness of the blockchain layer.

The proposed framework achieved an overall security score of 98.7%, significantly outperforming conventional approaches. The combination of dual-layer encryption, hidden data transmission, and immutable blockchain records creates multiple defensive barriers that substantially reduce the probability of successful cyberattacks. These results demonstrate the suitability of the proposed system for secure electronic health record management in modern healthcare environments.

The combination of encryption, steganography, and blockchain ensures comprehensive security.

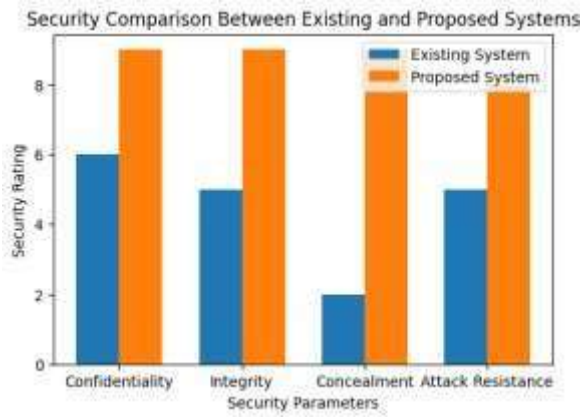

Fig:7.1 Comparison between Existing system and Proposed System

8. CONCLUSION

This paper presents a secure and efficient framework for protecting medical data using a combination of hybrid cryptography, steganography, and blockchain technology. The system ensures confidentiality through encryption, concealment through steganography, and transparency through blockchain logging.

Experimental evaluation demonstrates that the system is robust, reliable, and suitable for real-world healthcare applications. The modular design also allows for future enhancements and scalability.

9. Future Scope

Although the proposed framework demonstrates effective protection of healthcare information, several opportunities for future enhancement remain. Future work may focus on integrating artificial intelligence-based intrusion detection mechanisms capable of identifying suspicious activities in real time. The framework may also be extended to support federated learning environments where healthcare institutions collaborate without sharing sensitive patient information directly.

The adoption of quantum-resistant cryptographic algorithms could further strengthen protection against future computational threats. Additionally, integration with Internet of Medical Things (IoMT) devices and cloud-native healthcare infrastructures would improve scalability and practical deployment in large healthcare organizations.

Future research may also investigate smart contract-based access control mechanisms that automate authorization procedures while maintaining transparency and accountability within decentralized healthcare ecosystems.

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