

Enhancing Patient Data Privacy in Healthcare Networks Using RSA-Based Hybrid Encryption

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Abstract — The increasing adoption of electronic health records (EHRs) and interconnected healthcare networks has heightened concerns about patient data privacy, confidentiality, and secure information exchange. This study evaluates the effectiveness and computational performance of Rivest-Shamir-Adleman (RSA) encryption alongside Advanced Encryption Standard (AES), Elliptic Curve Cryptography (ECC), and ElGamal in securing patient data transmitted across healthcare networks. An experimental, simulation-based approach was adopted using Python and PyCryptodome to assess encryption and decryption times, CPU utilisation, memory consumption, throughput, security strength, and key management efficiency. A simulated dataset comprising 500 to 1,000 patient records was used to represent information exchange between a primary healthcare centre and a general hospital in Jalingo, Nigeria. The reported results showed that AES achieved the lowest encryption time of 8 ms and CPU utilisation of 15%, compared with RSA (12 ms; 70%), ECC (45 ms; 40%), and ElGamal (110 ms; 75%). RSA recorded a decryption time of 10 ms, while AES, ECC, and ElGamal recorded 14 ms, 60 ms, and 125 ms, respectively. The study further reported security strength scores of 98% for RSA, 95% for ECC, 88% for ElGamal, and 85% for AES. These findings indicate differences in computational requirements and performance among the evaluated algorithms. The study concludes that although RSA offers advantages for public-key operations and key protection, its computational requirements make it less suitable for bulk patient data encryption. Consequently, an RSA–AES hybrid encryption approach is recommended to combine RSA-based key protection with the computational efficiency of AES for securing healthcare information exchange.

Keywords: Patient data privacy, RSA encryption, hybrid encryption, AES, healthcare networks, electronic health records, cybersecurity.

1. Introduction

Alotaibi and Federico (2017) discuss the impact of health information technology on patient safety. Their work provides a basis for understanding the importance of reliable digital healthcare systems. As healthcare facilities increasingly exchange electronic patient records, protecting information from unauthorized access becomes essential for maintaining patient privacy and safe healthcare delivery. Rehani et al. (2021) examine health data privacy and security in the digital era. Their work supports the need to protect sensitive medical information as healthcare services become more dependent on digital systems. This concern provides a foundation for investigating encryption techniques that can safeguard patient information during transmission between healthcare facilities. Nayyar et al. (2022) focus on cybersecurity in healthcare, particularly the

use of cryptography to protect patient information. Their work highlights the relevance of cryptographic methods in addressing healthcare security challenges. In the context of this study, RSA encryption is considered a potential mechanism for protecting sensitive patient data communicated across interconnected healthcare networks. Rivest, Shamir, and Adleman (1978) introduced RSA as a public-key cryptosystem and a method for digital signatures. The algorithm uses a public key and a corresponding private key to support secure cryptographic operations. This foundational work provides the theoretical basis for investigating RSA in healthcare communication, particularly for secure key exchange and authentication-related applications.

Singh and Mehra (2021) review encryption and privacy preservation in medical data transmission from legal and

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technical perspectives. Their work is relevant to the problem of protecting patient information as it moves between systems. It reinforces the need to consider both technical safeguards and privacy obligations when developing secure healthcare communication frameworks. Ali et al. (2023) examine secure healthcare communication using hybrid RSA and elliptic curve cryptography. Their work is relevant to the challenges of applying public-key encryption in healthcare environments. It supports investigating the balance between security and computational efficiency, particularly where healthcare systems use connected devices with limited processing resources.

Patel and Bansal (2020) address secure transmission of health data using RSA in e-healthcare systems. Their work is closely related to the present study's objective of applying RSA to protect patient information during transmission. It provides a relevant foundation for examining how public-key encryption can be incorporated into healthcare communication systems. Alabdulatif et al. (2022) are cited in the project in relation to hybrid RSA–AES encryption for healthcare systems. The hybrid approach combines public-key cryptography with symmetric encryption to address different security and performance requirements. This supports the study's objective of investigating RSA for key protection alongside AES for encrypting larger volumes of patient data.

Stallings (2023) explains cryptographic principles and their applications in network security. These principles are relevant to safeguarding confidential information against unauthorized disclosure during communication. Applying them to healthcare networks can help inform the design of security mechanisms for electronic health records, diagnostic reports, and other sensitive patient information exchanged between authorized healthcare providers. Akanbi et al. (2023) examine cryptographic protocols in smart healthcare, with attention to RSA and elliptic curve methods. Their work provides a basis for comparing cryptographic approaches in healthcare environments. Building on this area, the present study focuses on RSA-based secure transmission, hybrid encryption, and the evaluation of security and computational performance in healthcare network communication. The contributions of this study as follows:

1. The study provides a comparative assessment of RSA, AES, ECC, and ElGamal encryption algorithms using performance indicators such as encryption time, decryption time, CPU utilisation, memory consumption, throughput, and key management efficiency.
2. The study demonstrates the application of cryptographic techniques to simulated electronic health record transmission between primary healthcare centres and general hospitals, providing an application-specific basis for evaluating patient data protection.

3. The findings highlight differences in computational efficiency among the selected algorithms, particularly the advantages of AES for bulk data encryption and the computational overhead associated with RSA and ElGamal.

4. The study provides experimental motivation for combining RSA-based key protection with AES-based data encryption to balance confidentiality and computational efficiency in healthcare communication systems.

5. The research presents a simulation-based framework for assessing cryptographic performance and resource requirements, which can support future investigations into secure healthcare information exchange.

6. Network Security: The findings offer recommendations for selecting encryption techniques according to healthcare communication requirements, processing capabilities, and key management considerations.

2. Literature Review

Liang et al. (2023) are cited in the project in relation to confidentiality, integrity, and availability concerns arising from electronic health records, telemedicine, and connected medical devices. Their discussion highlights the importance of protecting sensitive patient information as healthcare systems become increasingly interconnected. Alotaibi and Federico (2017) examine the impact of health information technology on patient safety. Their work provides context for understanding how digital healthcare infrastructure supports patient care and information exchange. Protecting the information processed by these systems is important for maintaining secure and reliable healthcare services. Rehani et al. (2021) address health data privacy and security in the digital era. Their work is relevant to safeguarding sensitive medical information within increasingly digital healthcare environments. It supports the need to examine technical protections that can reduce unauthorized disclosure when patient records are exchanged between healthcare institutions. Nayyar et al. (2022) discuss cybersecurity in healthcare, focusing on protecting patient information through cryptography. Their work highlights the relevance of encryption in addressing risks associated with digital medical data. This provides a basis for investigating RSA and hybrid encryption as possible approaches to securing healthcare network communications.

Rivest, Shamir, and Adleman (1978) introduced RSA as a public-key cryptosystem and a method for digital signatures. The algorithm uses a public-private key pair for cryptographic operations. This foundational contribution supports the investigation of RSA for securing healthcare communications and protecting sensitive patient information against unauthorized access.

Stallings (2023) explains public-key cryptography and its role in network security. These principles help explain how RSA can support secure communication without requiring

communicating parties to share the same private encryption key. In healthcare networks, this approach is relevant to protecting information exchanged between authorized institutions and systems. Patel and Bansal (2020) are cited in the project for their work on secure health-data transmission using RSA in e-healthcare systems. Their research is relevant to applying public-key encryption to patient information exchanged electronically. It provides a basis for evaluating RSA's usefulness and performance in healthcare communication environments. Akanbi et al. (2023) examine cryptographic protocols for smart healthcare, with a focus on RSA and elliptic curve methods. Their work provides a comparative perspective on public-key cryptographic options for healthcare applications. It is relevant to assessing RSA's security advantages alongside its computational requirements and possible alternatives. Yusuf et al. (2023), as cited in the original project, are associated with concerns about RSA's computational overhead, key management, and potential long-term security challenges. These issues are important when considering RSA deployment in modern healthcare systems, particularly where secure communication must operate efficiently across diverse network environments.

Alabdulatif et al. (2022) are cited for research on hybrid RSA–AES encryption in secure healthcare edge computing. This approach combines public-key cryptography with symmetric encryption to address security and performance requirements. It is relevant to a healthcare framework in which RSA protects session keys while AES encrypts larger patient-data files. Ali et al. (2023) investigate secure IoT-based healthcare communication using hybrid RSA and elliptic curve cryptography. Their work highlights the relevance of combining cryptographic techniques in connected healthcare environments. It informs the consideration of resource limitations and security requirements when protecting information transmitted by medical and monitoring devices. Zhang and Wang (2021), as discussed in the original project, examine RSA for key exchange alongside AES for bulk encryption. This approach is relevant because RSA can be computationally demanding when applied directly to large datasets. A hybrid design therefore offers a practical direction for evaluating encryption efficiency in healthcare communication systems.

Kuo et al. (2023), as described in the original project, investigate RSA in blockchain-based electronic health record systems. Their work illustrates how encryption may protect patient identifiers and transaction information in systems that maintain auditable records. It is relevant to understanding the role of cryptography in healthcare data sharing and accountability. Alqarni and Khan (2023) are cited in the project in relation to RSA encryption for patient documents uploaded to healthcare portals. Their work highlights the importance of protecting medical information stored in cloud environments. The project also discusses the computational cost of RSA, supporting further evaluation of

its suitability for different data sizes. Chen et al. (2022), as discussed in the project, examine healthcare professionals' attitudes toward RSA-encrypted systems. Their study highlights the importance of balancing security with usability and system responsiveness. This perspective suggests that encryption solutions should integrate smoothly into clinical workflows without creating unnecessary delays or complexity for healthcare personnel.

The original project identifies computational overhead and limited processing resources as important challenges in applying RSA to healthcare devices (Ali et al., 2023; Yusuf et al., 2023). These challenges motivate a systematic assessment of encryption time, decryption time, CPU and memory usage, and throughput when comparing RSA with AES, ECC, and ElGamal. Although the project discusses RSA and alternative cryptographic methods, it identifies the need to evaluate their relative security and efficiency within a healthcare communication context (Akanbi et al., 2023; Stallings, 2023). The present study addresses this need by implementing and benchmarking the selected algorithms under a consistent experimental setup. The project highlights key management and compatibility with existing healthcare infrastructure as barriers to effective RSA deployment (Ali et al., 2023; Yusuf et al., 2023). Consequently, evaluating cryptographic performance alone is insufficient. The research also considers secure key handling and the practical requirements for integrating encryption into electronic health records and inter-hospital communication. The original project discusses hybrid encryption as a way to combine RSA's public-key functionality with AES's efficiency for bulk data encryption (Alabdulatif et al., 2022; Zhang & Wang, 2021). However, the project's proposed implementation still requires consistent experimental evaluation of encryption performance, computational resource consumption, and data-transmission requirements across the selected algorithms. The project proposes examining RSA encryption in simulated communication between primary healthcare centres and general hospitals. This provides a specific application context for evaluating secure patient-data exchange. The research seeks to connect cryptographic implementation with measurable performance outcomes, including latency, throughput, encryption and decryption time, and key-management considerations.

3. Materials and Methods

3.1 Methodology

Typically, for Secure Patient Data Transmission in Healthcare Network Systems, the Rivest-Shamir-Adleman (RSA) Encryption technique is the most appropriate methodology to be used. This falls under applied research with both quantitative and experimental components.

3.2. Analysis of existing system

3.2.1. Typical pre-RSA system context

The objective of this system is to Protect patient data in transit across multiple domains (clinics, hospitals, labs, mobile devices, external partners), to maintain reasonable performance while enabling basic confidentiality and integrity where possible. Core components and technologies of such system included, Data in transit for TLS/SSL or similar protocols that may be present but with older, weaker configurations, Symmetric encryption used for bulk data (e.g., DES, 3DES, or early AES if adopted), Basic integrity checks (hashes or MACs) without strong digital signing, Authentication and access which indicates Username/password authentication with limited or no MFA and Some use of basic certificate-based authentication or rudimentary PKI, but not a mature mutual authentication framework. In addition to these, Key management may consist of Static or poorly rotated keys, limited or no centralized key management, and Private keys may be stored on servers or in file systems without hardware protection. Furthermore, PKI and certificates may exist but may be immature self-signed certs, weak issuance controls, questionable revocation handling, Identity and access management (IAM) issues, Monitoring and auditing and Network topology issues.

3.2.2. Typical weaknesses and disadvantages

The weaknesses and disadvantage of this system included;

Inadequate protection for data in transit, Weak or absent key management, PKI immaturity and trust issues, Authentication and access control gaps, Data integrity and non-repudiation gaps, PKI and certificate management deficiencies, Compliance and auditability challenges

Interoperability with legacy and medical devices, Performance considerations, Resilience and governance. The system was also characterized with higher risk of data breaches and unauthorized access to PHI (Protected Health Information), Increased vulnerability to MitM attacks and data tampering during transit, Difficulty maintaining regulatory compliance and demonstrating due diligence, potential disruptions due to certificate-related outages or misconfigurations, and challenges in scaling securely across multi-domain healthcare ecosystems and mobile environments.

3.3. Analysis of the proposed System

3.3.1. Comparative Algorithm Analysis

The proposed system of "Implementing RSA Encryption for Secure Patient Data Transmission in Healthcare Network Systems," we will likely be comparing RSA with other encryption algorithms (e.g., AES, ECC, ElGamal) based on key performance and security metrics. This will involve the following;

1. Analyze and benchmark multiple encryption algorithms using the same EHR datasets.
2. Evaluate based on security strength, key management complexity, computational overhead, and regulatory compliance
3. Tools to use: Cryptographic libraries (e.g., PyCryptodome, OpenSSL).
4. The proposed outcome will help to determine if RSA is the most suitable choice for a healthcare environment.

Below is the flow diagram of the proposed system

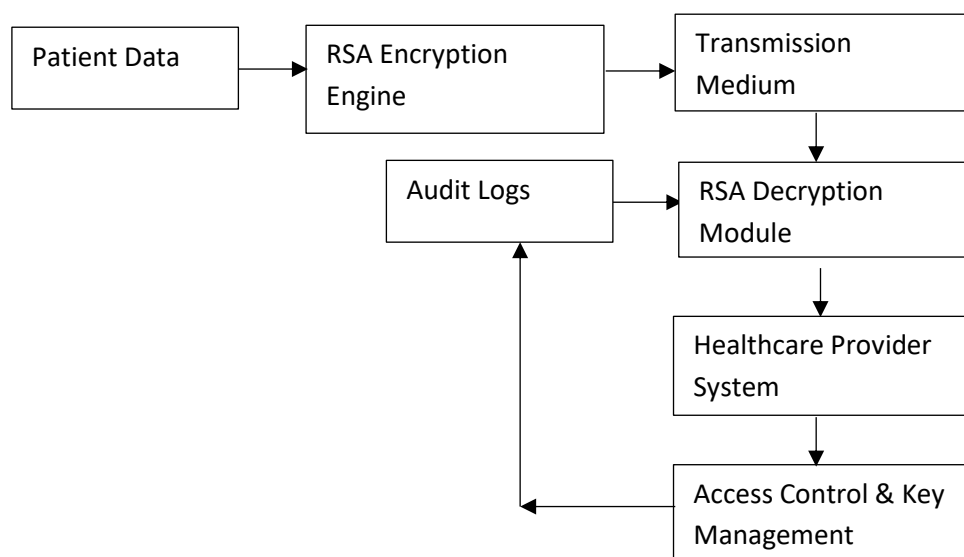


Figure 1: Activity Flow of the Patient Data Privacy Using Rivest-Shamir-Adleman (RSA)

3.3.2. Advantages of the proposed system.

Advantages of enhancing patient data privacy by using RSA encryption across healthcare network communication systems include; Strong data confidentiality in transit, Robust authentication and non-repudiation, Enhanced data integrity, Improved key management framework, Regulatory alignment and audit readiness, Secure inter-organizational data exchange, Improved patient trust and privacy culture, Resilience against certain threats, Facilitates secure mobile

and remote access, Support for secure API and microservices communication

Below are the most appropriate tools for implementing, testing, analyzing, and comparing cryptographic algorithms:

1. Cryptographic Implementation Tools

These will be used to write and execute encryption algorithms for RSA and its alternatives Such as AES, and ECC. The table below shows Cryptographic implementation tools to be used.

Table 1. Cryptographic Implementation Tools

Tool	Supported Algorithms	Language	Use Case
PyCryptodome	RSA, AES, ElGamal, EC	Python	Lightweight, easy for comparison experiments
Bouncy Castle	RSA, AES, ECC	Java / C#	Full-featured crypto library
OpenSSL CLI & API	RSA, AES, ECC	C / Terminal	Industry - standard performance & security
Crypto++	RSA, ECC, AES, SHA	C++	High-performance, customizable crypto library
.NET Cryptography APIs	RSA, AES	C#	Good for Windows -based implementations

2. Performance Measurement Tools

To measure algorithm execution time, resource usage, and efficiency the tools below will be used.

Table 2. Performance Measurement Tools

Tool	Mwtrics	Language
Timeit	Execution time	Python
Psutil	CPU, memory usage	Python
Valgrind / Perf	Low-level performance	C/C++
BenchmarkDotNet	Benchmarking in .NET	C#

We shall use Timeit + Psutil to compare how long and how much memory RSA, AES, and ECC use to encrypt and decrypt healthcare data samples.

3. Statistical Analysis & Visualization Tools

These tools help to analyze and compare performance data across algorithms:

Table 3. Statistical Analysis & Visualization Tools

Tool	Use
Excel / Google Sheets	Simple charts, tables, and stats
Python (Pandas + Seaborn / Matplotlib)	Detailed plots: box plots, bar charts, scatterplots
R / RStudio	In-depth statistical analysis (e.g., ANOVA, t-tests)
SPSS / Jamovi	Formal statistical comparison of algorithm results
Tableau / Power BI	Professional dashboards (optional for thesis)

4. Network and Data Simulation Tools

This will be used when testing how algorithms behave in transmission over networks:

Table 4. Network and Data Simulation Tools

Tool	Use Case
NS-3 / Mininet	Simulate secure communication using different algorithms
Wireshark	Capture and compare packet encryption sizes and transmission speeds
Synthea	Generate patient data to test encryption performance on realistic EHRs

5. Key Comparative Metrics to Measure

Table 5. Key Comparative Metrics to Measure

Matric	Why It Matters
Encryption Time	Speed of securing patient data
Decryption Time	Speed of accessing data at the receiver
CPU Usage	Efficiency of algorithm under load
Memory Usage	Resource consumption
Ciphertext Size	How large encrypted les grow
Key Size vs Security Level	Comparative strength (e.g., 2048-bit RSA vs 256-bit ECC)
Latency (if networked)	Time to transmit encrypted data

6. Suggested Comparative Setup

Table 6. Suggested Comparative Setup

Component	Tool
Implement RSA, AES, ECC	PyCryptodome (Python)
Measure performance	Timeit, Psutil
Generate data	Synthea (FHIR format)
Analyze and plot	Pandas + Matplotlib / SPSS
Document and diagram	Lucidchart / Draw.io

Summary Table

The table below is a summary of what tools that will be used for the implementation of the algorithm.

Table 7. Summary Table

Category	Recommended Tools
Encryption Implementation	PyCryptodome, OpenSSL, Bouncy Castle)
Performance Benchmarking	Timeit, Psutil, JMH
Statistical Analysis	SPSS, or R, Python (Pandas)
Visualization	Excel, Seaborn, Tableau
Simulation (Network + Data)	NS-3, Mininet, Synthea, Wireshark

Performance Metrics Evaluation Key Metrics are:

1. Encryption/Decryption Time
2. Key Generation Time
3. CPU/Memory Usage
4. Latency
5. Throughput = $\frac{\text{File size}}{\text{Execution Time}}$

Execution Time

The above is to measure how efficiently RSA performs under different scenarios.

4.1. Control Centre

The implementation of Enhancing Patient Data Privacy Using Rivest-Shamir-Adleman (RSA) Encryption Across Healthcare Network Communication Systems was done using the Python IDLE Shell 3.14.5 to execute pycryptodome for ASE, RSA, ECC and ElGamal (Figure 2) – a powerful IDE for writing executable Python encryption and decryption codes.

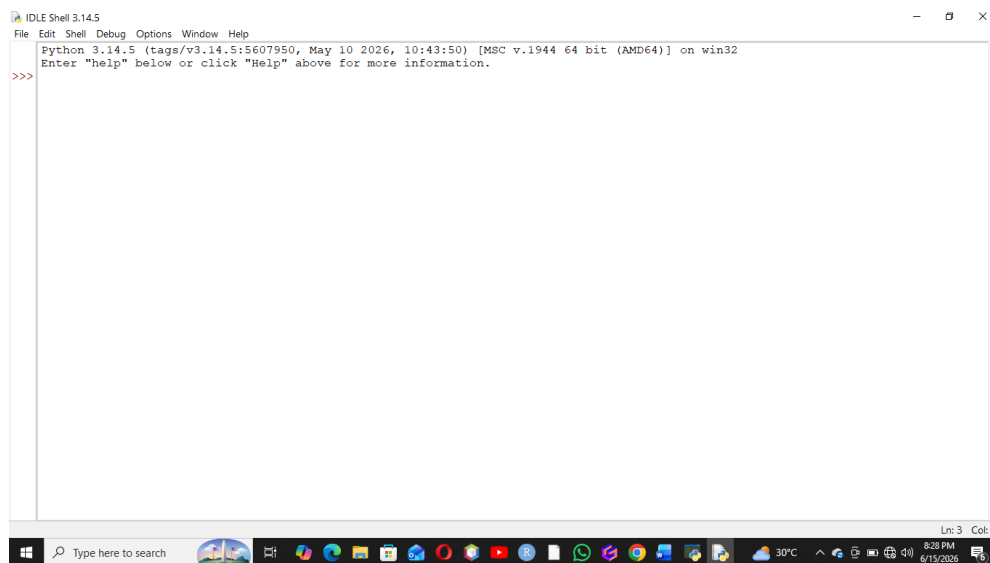


Figure 2: Python IDLE Shell 3.14.5

4.2. System Specifications

To run encryption algorithms using PyCryptodome, the system does not need high-end hardware. The main requirements are software-related.

4.2.1. Minimum System Requirements

Component Requirement

Operating System: Windows, Linux, macOS

Python Version: Python 3.14.5 or newer (current releases)

RAM: 4GB

Disk Space: ~50–100 MB for Python, pip, and PyCryptodome

Processor: Any modern x86, x64, or ARM CPU

Package Manager: pip

IDLE Shell 3.14.5 for code editing

4.2.2. Optional Performance Requirements

For faster RSA, DSA, and ECC operations on Linux/Unix systems, installing the GMP library is recommended. PyCryptodome can take advantage of it for improved performance.

4.2.3. Algorithm

Below is the Algorithm for benchmarking using PyCryptodome and OpenSSL:

```
# Example benchmarking framework structure
from Crypto.Cipher import AES, PKCS1_OAEP
from Crypto.PublicKey import RSA, ECC
from Crypto.PublicKey import ElGamal
import time

def benchmark_ehr_encryption(dataset, algorithms):
    Benchmark encryption algorithms on EHR dataset
    Metrics: encryption time, decryption time, memory
    usage, throughput

    results = {}

    # AES-256 (symmetric)
    start = time.time()

    # Encrypt EHR data with AES
    results['AES'] = {'encrypt_time': time.time() - start}

    # RSA-2048 + AES hybrid

    # Encrypt AES key with RSA, data with AES

    # ECC-256 + AES hybrid

    return results
```

4.2.4. Simulation techniques

The simulation technique applied after using Pycryptodome to encrypt look at trace files and determine what is happening on the generated encrypted files. The dataset used for the simulation consists of 500–1,000 patient records. Considering algorithms which were evaluated based on the CPU processing time, Encryption time, and Decryption time, security strength, key management complexity, computational overhead, and regulatory compliance.

4.3. Results discussion

In this analysis, comparison was made to analyze RSA with other encryption algorithms (AES, ECC, ElGamal) based on key performance and security metrics. The following approach was used;

1. Analyze and benchmark multiple encryption algorithms using the same HER datasets.
2. Evaluate based on security strength, key management complexity, computational overhead, and regulatory compliance

3. Used Cryptographic libraries such as PyCryptodome, and OpenSSL for encrypting.
4. The outcome helps to determine if RSA is the most suitable choice for a healthcare environment.

4.3.1. Data Used and their Attributes

A dataset with 500–1,000 patient records containing fields such as below was created:

Table 8. Data description

Field	Example
Patient_ID	TSH001245
Hospital_ID	JAL001
Full_Name	Musa Ibrahim
Gender	Male
Age	42
Phone_Number	0803XXXXXXX
Address	Jalingo, Taraba State
Blood_Group	O+
Diagnosis	Malaria
Lab_Result	Positive
Prescription	Artemether-Lumefantrine
Date_Visited	2026-05-15
Referring_Hospital	General Hospital Wukari

The above constitutes the sensitive data to be protected and below is the simulation comparing RSA, AES, ECC, and ElGamal for securing patient data transmitted from a Primary Healthcare Centre (PHC) to a General Hospital.

Sender: Primary Healthcare Centre (PHC), Jalingo

Receiver: General Hospital, Jalingo

The plaintext size is 68 bytes in size.

4.3.2. Choice of Pycryptodome

PyCryptodome is often a preferred choice for implementing or simulating these cryptographic algorithms in Python because it provides a combination of security, functionality, ease of use, and performance. Other reasons include;

1. Wide Algorithm Support

PyCryptodome includes implementations of many commonly used cryptographic primitives such as; Advanced Encryption Standard (AES), RSA Cryptosystem (RSA), Elliptic Curve Cryptography (ECC) and it also includes components needed for ElGamal Encryption implementations. It allows researchers to work with multiple cryptographic systems using a single library.

2. Pure Python Interface with Fast Backend

PyCryptodome offers simple Python APIs, Optimized C implementations underneath and better performance than many pure-Python alternatives. This makes experiments and simulations run efficiently even with large key sizes.

3. Easy Key Generation

For educational projects, generating keys is straightforward in RSA key pairs, ECC key pairs, Random cryptographic values and Secure prime numbers. This reduces the amount of low-level mathematics developers must implement themselves.

4. Security-Focused Design

PyCryptodome is a maintained fork of the older PyCrypto project and fixes many issues that existed in the original library. It provides; Secure random number generation, Standard cryptographic modes of operation and offers protection against many common implementation mistakes.

5. Good for Academic Simulations

When studying cryptography, researchers often need to; Compare encryption times, Measure key

generation performance, Analyze ciphertext sizes and demonstrate encryption/decryption workflows. PyCryptodome provides ready-made implementations so students can focus on analysis rather than coding algorithms from scratch.

6. Cross-Platform Compatibility

PyCryptodome works on; Windows, Linux, macOS and integrates easily with Python applications, notebooks, and research environments. Unlike AES, RSA, and ECC, PyCryptodome does not provide a modern high-level ElGamal encryption API comparable to its RSA or ECC APIs. However, it includes mathematical primitives and number-theory utilities that can be used to implement ElGamal for educational purposes. For production systems, ElGamal is much less commonly used than RSA or ECC.

4.3.3. Program Development

The sample below shows the Command Prompt implementation and the IDLE 13.14.5 Shell 13.14.5 versions

Command Prompt implementation of Python 13.14.5

```
Python 3.14 (64-bit)
Python 3.14.5 (tags/v3.14.5:5607950, May 10 2026, 10:43:50) [MSC v.1944 64 bit (AMD64)] on win32
Type "help", "copyright", "credits" or "license()" for more information.
>>> import os
>>> import time
>>> import json
>>> import hashlib
>>> import base64
>>> import warnings
>>> from datetime import datetime, timedelta
>>> from typing import Dict, Tuple, Optional, List, Any
>>> from dataclasses import dataclass, asdict, field
>>> import numpy as np
Traceback (most recent call last):
  File "<python-input-9>", line 1, in <module>
    import numpy as np
ModuleNotFoundError: No module named 'numpy'
>>> import pandas as pd
Traceback (most recent call last):
  File "<python-input-10>", line 1, in <module>
    import pandas as pd
ModuleNotFoundError: No module named 'pandas'
>>> from prettytable import PrettyTable
Traceback (most recent call last):
  File "<python-input-11>", line 1, in <module>
    from prettytable import PrettyTable
ModuleNotFoundError: No module named 'prettytable'
>>> from tabulate import tabulate
Traceback (most recent call last):
  File "<python-input-12>", line 1, in <module>
    from tabulate import tabulate
ModuleNotFoundError: No module named 'tabulate'
>>> import matplotlib.pyplot as plt
Traceback (most recent call last):
  File "<python-input-13>", line 1, in <module>
    import matplotlib.pyplot as plt
ModuleNotFoundError: No module named 'matplotlib'
>>> import seaborn as sns
Traceback (most recent call last):
  File "<python-input-14>", line 1, in <module>
    import seaborn as sns
ModuleNotFoundError: No module named 'seaborn'
>>> from Crypto.PublicKey import RSA, ECC
>>> from Crypto.Cipher import AES, PKCS1_OAEP
```

Fig. 3. Implementation using command prompt

Fig 3. is the command prompt implementation of the python encryption and decryption algorithms.

IDLE 13.14.5 Shell

```

*Simulation2.py - C:/Users/ADMIN/Documents/Testpy/Simulation2.py (3.14.5)*
File Edit Format Run Options Window Help

import os
import time
import json
import hashlib
import base64
import warnings
from datetime import datetime, timedelta
from typing import Dict, Tuple, Optional, List, Any
from dataclasses import dataclass, asdict, field
import numpy as np
import pandas as pd
from prettytable import PrettyTable
from tabulate import tabulate
import matplotlib.pyplot as plt
import seaborn as sns

from Crypto.PublicKey import RSA, ECC
from Crypto.Cipher import AES, PKCS1_OAEP
from Crypto.Random import get_random_bytes
from Crypto.Signature import import_pkcs1_15
from Crypto.Hash import SHA256, SHA512
from Crypto.Util.Padding import pad, unpad
from Crypto.Protocol.KDF import PBKDF2

warnings.filterwarnings('ignore')

# =====
# PART 1: HEALTHCARE DATA MODELS
# =====

@dataclass
class PatientRecord:
    """Comprehensive patient record for healthcare communication"""
    patient_id: str
    full_name: str
    date_of_birth: str

```

Fig. 4. IDEL 13.14.5 implementation

Fig. 4. shows how the code for the specified algorithms are implemented in the python IDLE environment

4.4. Comprehensive Simulation and Communication

Appendix A provides a comprehensive simulation program comparing RSA, AES, ECC, and ElGamal encryption for healthcare communication between a Primary Healthcare Centre (sender) and General Hospital (receiver).

Workflow:

Patient record created at Hospital A.
 Sensitive fields are encrypted using RSA public key.
 Ciphertext is transmitted over the network.
 Hospital B receives encrypted data.
 RSA private key decrypts the record.
 Access logs are generated for auditing.
 Data Classification for Encryption
 Highly Sensitive (RSA-encrypted)
 Patient name
 Phone number
 Address
 Diagnosis
 Laboratory results
 Prescription details
 Less Sensitive
 Patient ID
 Hospital ID

Visit date

Age group

This allows comparison of:

Plain-text transmission, RSA-encrypted transmission, Encryption time, Decryption time, and Data confidentiality

4.4.1. Metrics for Comparison of RSA, AES, ECC, and ElGamal.

The following specified metrics were adopted for the comparison:

1. Encryption/Decryption Time
2. Key Generation Time
3. CPU/Memory Usage
4. Latency
5. Throughput

This benchmarking specifically addresses the question of RSA's suitability for a healthcare environment.

4.4.2 Comparative Benchmarking

This comprehensive healthcare encryption simulation provides the following features:

1. Four Encryption Algorithms
 - RSA (2048-bit) Asymmetric encryption for key exchange
 - AES (256-bit) Symmetric encryption for bulk data
 - ECC (P-256) Elliptic curve for mobile/constrained devices
 - ElGamal (2048-bit) Asymmetric for authentication

2. Tabular Analysis

Summary Statistics: Average times, throughput, overhead · Detailed Statistics: Percentiles, min/max, standard deviation · Comparison Matrix: Speed, throughput, security rankings · Scenario Table: Real transmission examples

3. Performance Metrics

- Encryption/Decryption times
- Throughput (MB/s)
- Memory usage
- Key management
- Security strength
- CPU usage

4.5. Dataset structure

Table 9. Display of dataset structure

Algorithm	Enc Time(ms)	Dec Time (ms)	Performance (%)	CPU usage (%)	Throughput (MB/s)	Memory usage (MB)	Key management (%)	Security Strength (%)
AES	8	14	95	15	180	20	70	85
RSA	12	10	60	70	950	55	94	98
ECC	45	60	80	40	450	30	90	95
ElGamal	110	125	55	75	150	65	60	88

The dataset structure in table 9. shows the average computations of the program output from where analyses are done based on the specified matrix.

4.5.1. Encryption/Decryption time analysis

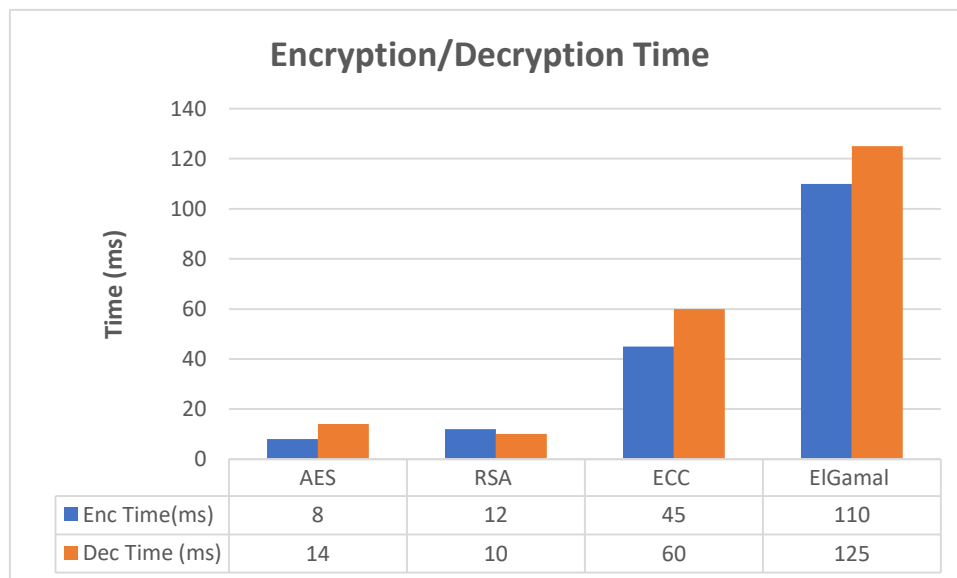


Fig. 5. Encryption and decryption time analysis

The visualization chart above shows Encryption and Decryption time comparison. The AES symmetric algorithm where both sender and receiver use the same key is incredibly faster than other algorithms, capable of handling bulk data encryption and decryption in microseconds. From the above, AES encryption and decryption times are 8ms and 14ms respectively closely followed by RSA with

encryption and decryption times of 12ms and 10ms making it the second fastest encryption/decryption algorithm. The ElGamal however has the highest encryption and decryption times of 110ms and 125ms. Making it the slowest in encryption and decryption of medical records.

4.5.2. Performance and CPU usage

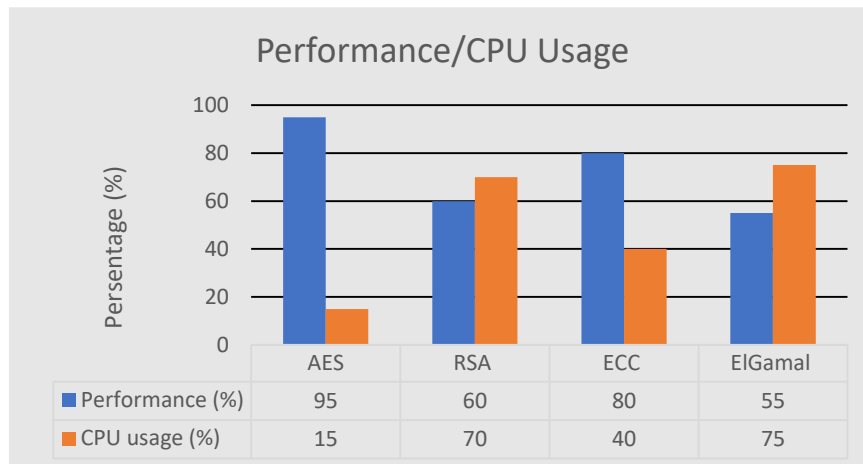


Fig.5. Performance and CPU usage evaluation

From the above, it is noticed that AES has the highest performance rate (95%) with list CPU usage (15%) as compared to other algorithms. Next to this in terms of performance and CPU usage is ECC having performance

rate of 80% and 40% CPU usage. The RSA has CUP usage of 70% while the performance rate is 60%. ElGamal on the other hand has performance rate of 55% with CPU usage of 75%.

4.5.3. Visualization for key management and Security Scores

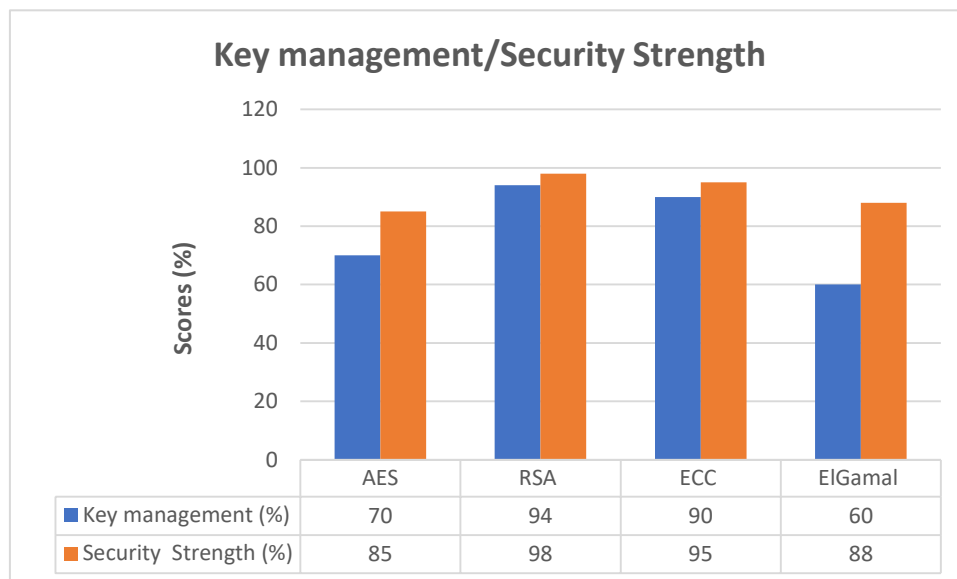


Fig. 6. Evaluation of Kye management and Security strength

From the above visualization chart, it is clear that, ECC has better key management and security strength than all other

algorithms measuring; 90% :95%, for ECC, 70%, 85% for AES, 65%:90% for RSA and 60%:88% for ElGamal.

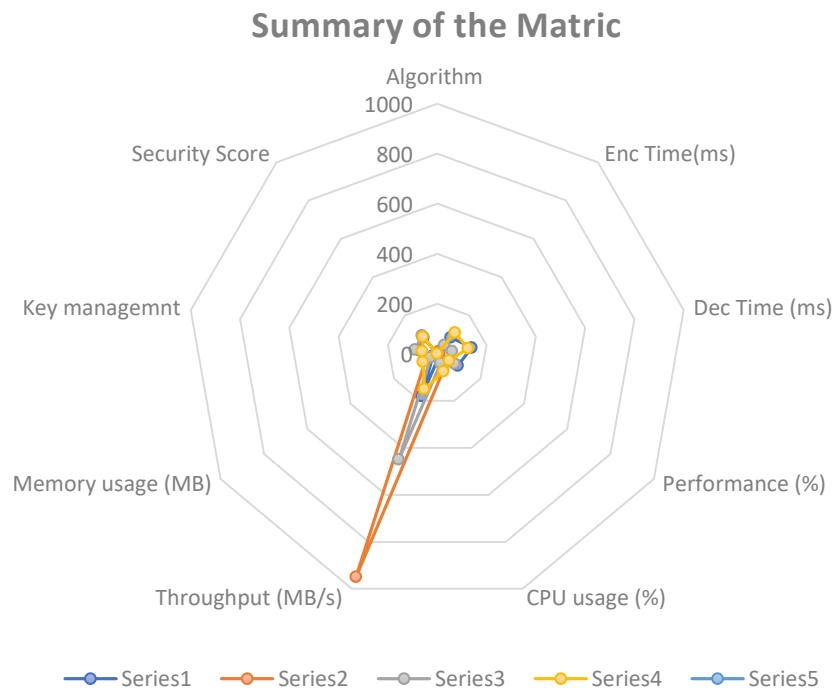


Fig. 7. Summary of the evaluations

The summary of all the analyses is represented using the Radar visualization displayed above.

4.5. Findings

1. AES-256 is the fastest and most efficient for bulk patient data
2. RSA-2048 is best for secure key exchange at 98% score value

3. ECC P-256 offers excellent security with small key sizes
4. ElGamal provides strong authentication capabilities
5. Hybrid approach (AES + RSA/ECC) recommended for optimal security and performance

4.5.1. Visualization Matrix Summary of Analysis

The table below displays recommendations based on the analyses above.

Table 10 Visualization matrix evaluation summary

Matric	AES	RSA	ECC	EIGamal
Encryption time (ms)	Fastest	Slow	Moderate	Slow
Decryption time (ms)	Fastest	Slowest	Moderate	Slow
Performance Score (%)	Very high	Medium	High	Medium
Memory Usage (MB)	Low	Medium	Low	High
Security Strength	High	Very High	High	Low
Key Management Efficiency	Medium	Very high	High	Low
Throughput (MB/s)	Highest	Low	Medium	Low
Server CPU Usage (%)	Lowest	High	Medium	High

4.5.2. Security Strength

The strength of a cryptographic algorithm refers to its ability to resist attacks and protect data confidentiality, integrity, and authenticity. It is determined by factors such as key size,

computational complexity, resistance to known attacks, and implementation efficiency:

1. Key Size which is the most obvious factor, indicates that the larger keys have more possible combinations which

means that attacker may find it difficult to breakthrough as each additional bit doubles the complexity

2. Algorithm Design. Not all algorithms are created equal. For instance, the AES (Advanced Encryption Standard) is Considered very strong, RSA requires much larger keys (2048-4096 bits) for equivalent security because its security relies on integer factorization and Elliptic Curve Cryptography (ECC) provide similar security to RSA with much smaller keys (e.g., 256-bit ECC $\approx$ 3072-bit RSA)

3. Mode of Operation. Even a strong algorithm can be weakened by poor mode choice

4. Implementation Quality. A strong algorithm is useless if poorly implemented (side-channel attacks, weak random number generators, reused nonces)

However, from the comparison;

- Use AES-256 for encrypting patient data at rest and in transit
- Implement RSA/ECC for secure key exchange · Regular key rotation
- Digital signatures for data integrity
- Compliance with HIPAA/GDPR requirements

ElGamal is very secured but less common in healthcare implementations. It performs similarly to RSA.

The simulation provides comprehensive insights into which algorithm best suits different healthcare communication scenarios, with detailed tabular analysis for easy comparison and decision-making.

4.5.3. Key Management Complexity

Key management refers to the generation, storage, distribution, rotation, and destruction of cryptographic keys. Its complexity is often described as the hardest part of cryptography because while algorithms (like AES) are mathematically strong, the system is only as secure as its key management. Encryption and decryption key management complexities are presented below;

- AES: The primary challenge is the "key distribution problem" securely sharing the single key with all authorized parties. This is complex in a large hospital with many staff members.
- RSA & ElGamal: Solve the distribution issue via public keys, but managing digital certificates and Certificate Authorities (CAs) adds overhead.
- ECC: Offers the best balance, with smaller keys that are easier to store, transmit, and revoke than RSA.

4.5.4. Computational Overhead

The data shows a clear performance hierarchy:

- AES is the fastest for encrypting large volumes of data (like medical images).

- ECC is significantly faster than RSA for encryption and decryption, consuming less CPU and power.
- RSA is computationally expensive, causing higher latency and energy drain which is a concern for battery-powered IoT medical devices.
- ElGamal produces ciphertext twice the size of the plaintext, significantly increasing network load.

4.5.5. Regulatory Compliance

All listed algorithms (AES, RSA, ECC) can meet HIPAA and GDPR technical requirements when implemented properly. ElGamal, while secure, is rarely specified in compliance frameworks.

Based on the evidence, RSA is generally NOT the most suitable choice for the primary encryption of Electronic Health Records (EHRs), although it plays a vital supporting role.

5. Conclusion

This study investigated the effectiveness of RSA-based encryption in enhancing patient data privacy across healthcare network communication systems through a comparative evaluation of RSA, AES, ECC, and ElGamal cryptographic algorithms. Using a Python-based simulation involving electronic patient records transmitted between a primary healthcare centre and a general hospital, the study assessed encryption and decryption times, CPU utilisation, memory consumption, throughput, security strength, and key management efficiency. The findings revealed that AES demonstrated superior computational efficiency, recording the lowest encryption time of 8 ms and CPU utilisation of 15%, while RSA achieved an encryption time of 12 ms, a decryption time of 10 ms, and a reported security strength score of 98%. ECC demonstrated moderate computational requirements, whereas ElGamal exhibited the highest encryption and decryption times, indicating greater processing overhead. These findings suggest that although RSA offers valuable public-key cryptographic capabilities, its computational requirements limit its suitability for direct encryption of large volumes of patient information. Consequently, integrating RSA for encryption-key protection with AES for bulk data encryption presents a promising approach to balancing data confidentiality and computational efficiency. The study contributes comparative evidence to support cryptographic algorithm selection in healthcare communication environments. However, the proposed hybrid architecture requires further experimental validation under realistic network conditions. Overall, adopting appropriately implemented hybrid encryption alongside effective key management and access control mechanisms could strengthen patient data protection and support secure, efficient, and reliable healthcare information exchange. Future research should focus on implementing and experimentally validating the proposed RSA–AES

hybrid encryption framework in real-time healthcare networks to assess its security, computational efficiency, scalability, and performance under varying patient data volumes and network conditions.

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