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ABSTARCT

Security is an essential component of modern digital systems, ensuring the confidentiality, integrity, and availability of sensitive information across networks, applications, and storage systems. This project explores the evolution of digital security, highlighting key developments in cryptographic techniques and encryption standards. Particular focus is given to the Advanced Encryption Standard (AES), a widely adopted symmetric encryption algorithm, and its EAX mode, which offers both encryption and authentication. The study investigates potential vulnerabilities and implementation challenges associated with AES-EAX, especially in real-world scenarios. It further proposes methods to enhance its robustness against emerging cyber threats, aiming to improve overall system security and resilience.

INTRODUCTION

Safety needs are all the needs we have that help humans to feel secure and protected in their lives. Examples of safety needs include physical safety, fair trial, job security, protection from bullying, and strong armed forces, also protecting assets and information from intruders. Nowadays providing security to information is most complex one, because of digitalization. we need to provide security for that information by using different network protocols and different cryptographic techniques.

Internet communication is playing the important role to transfer large amount of data in various fields. Some of data might be transmitted through insecure channel from sender to receiver. Different techniques and methods have been using by private and public sectors to protect sensitive data from intruders because of the security of electronic data is crucial issue. Cryptography is one of the most significant and popular techniques to secure the data from attackers by using two vital processes that is Encryption and Decryption. Encryption is the process of encoding data to prevent it from intruders to read the original data easily. This stage has the ability to convert the original data (Plaintext) into unreadable format known as Cipher text. The next process that has to carry out by the authorized person is Decryption. Decryption is contrary of encryption. It is the process to convert cipher text into plain text without missing any words in the original text. To perform these process cryptography relies on mathematical calculations along with some substitutions and permutations with or without a key.

SECURITY IN EARLY DAYS

Early Encryption Methods – Before the 20th Century

Before the emergence of modern cryptographic techniques, security primarily relied on classical encryption methods that used straightforward mathematical transformations to conceal information. Some of the most well-known early ciphers include the **Caesar Cipher** and the **Vigenère Cipher**. The Caesar Cipher operated by shifting each letter in the plaintext by a fixed number of positions in the alphabet, making it one of the earliest forms of substitution cipher. The Vigenère Cipher, a more advanced technique, introduced the concept of a keyword to determine multiple shifting patterns, making the encryption slightly more resistant to attacks than mono-alphabetic ciphers.

1. Caesar cipher

Origin-and-Use:
The Caesar cipher, attributed to Julius Caesar, dates back to around 58 BC. He reportedly used it to communicate with his generals, ensuring that if messages were intercepted, they wouldn't be immediately understandable.

Mechanism:
This cipher works by shifting each letter in the plaintext a fixed number of positions down the alphabet. For example, using a shift of 3:

- A becomes D
- B becomes E
- Z wraps around and becomes C

The key is the number of positions to shift, and both the sender and recipient must know it in advance.

Strengths:

- Very simple to understand and implement.
- Useful for learning the basics of encryption.

Weaknesses:

- Easily breakable through brute-force (only 25 possible keys).
- Frequency analysis can also reveal patterns.

Legacy:
The Caesar cipher is still used today in puzzles and educational materials. While obsolete in security terms, it laid the foundation for the concept of substitution ciphers.

2. Mono-alphabetic Substitution Cipher

Origin-and-use:
Used as early as the 9th century by Arab mathematicians, this method gained popularity during the Renaissance and was commonly used for diplomatic and military communication.

Mechanism:

Each letter in the plaintext is replaced with a different letter from a substitution key. For example, if the key is:

- A → M, B → Q, C → L, and so on...

Unlike the Caesar cipher, this uses a completely shuffled alphabet, which results in 26! (about 4×10^{26}) possible keys.

Strengths:

- Much more difficult to crack than the Caesar cipher using brute force.
- Flexible—allows for customized substitution tables.

Weaknesses:

- Frequency analysis can still reveal patterns, especially in long messages.
- Common digraphs (like "TH" or "HE") can be used to guess letter pairings.

Legacy:

This cipher was used in diplomatic correspondence and remained popular until more sophisticated techniques emerged. It demonstrated the limitations of using fixed mappings for encryption.

3. Vigenère Cipher

Origin-and-Use:

Developed in the 16th century by Blaise de Vigenère, although earlier forms were used by Bellaso. It was considered unbreakable for centuries, earning the nickname "le chiffre indéchiffrable."

Mechanism:

The cipher uses a keyword to shift each letter of the plaintext by varying amounts. For example:

- Keyword: KEY → shifts of 10 (K), 4 (E), 24 (Y)
- Plaintext: HELLO becomes:
    - H + K → R

- E + E → I
- L + Y → J, and so on.

The keyword repeats if it is shorter than the message.

Strengths:

- Polyalphabetic substitution makes frequency analysis harder.
- Letters in the plaintext can be encrypted to different cipher text letters.

Weaknesses:

- Still breakable using statistical attacks like the Kasiski examination or Friedman test.
- Vulnerable if the keyword is short or reused.

Legacy:
The Vigenère cipher influenced many later cryptographic systems and introduced the powerful concept of key-based variation in encryption.

4. Transposition Cipher

Origin-and-Use:
Used as early as Ancient Greece and Rome, transposition ciphers rearranged the letters of a message rather than substituting them.

Mechanism:
Letters are reordered based on a pattern. A common form is **columnar transposition**:

1. Write the plaintext in rows beneath a keyword.
2. Rearrange the columns based on the alphabetical order of the keyword letters.
3. Read off the columns to get the ciphertext.

Example with keyword "ZEBRA":

- Plaintext: WE ARE DISCOVERED RUN
- Arrange into a grid under the keyword and reorder columns.

Strengths:

- Maintains letter frequencies, but scrambles positions.
- Can be combined with substitution for improved strength.

Weaknesses:

- Vulnerable to anagramming and permutation analysis.
- Patterns may emerge in short messages.

Legacy:
Transposition ciphers contributed to more complex cipher designs, like product ciphers (which combine substitution and transposition), a concept still used in modern block ciphers.

5. Scytale Cipher (Spartan Cipher)

Origin-and-Use:
Used by Spartan warriors in ancient Greece around 700 BC. It's one of the earliest known physical ciphers.

Mechanism:
A strip of parchment was wound around a cylinder (scytale) of a specific diameter. The message was written along the rod. Once unwrapped, the letters were scrambled and unreadable unless wound around a rod of the same diameter.

Strengths:

- Simple and quick to use.
- Useful for short, urgent battlefield messages.

Weaknesses:

- Easy to break if someone tries rods of various sizes.
- Offers almost no protection against modern analysis.

Legacy:
It introduced the concept of **mechanical key-based encryption**, inspiring mechanical encryption devices like the Enigma.

6. Play-fair Cipher

Origin-and-Use:

Invented by Charles Wheatstone in 1854 and promoted by Lord Playfair. Widely used by British forces during World War I and by the Australians during WWII.

Mechanism:

Uses a 5x5 grid based on a keyword. Encrypts two letters (digraphs) at a time using these rules:

- Same row → shift right.
- Same column → shift down.
- Rectangle → swap corners horizontally.

Letters I and J are usually combined.

Strengths:

- Encrypting digraphs removes obvious letter frequency clues.
- More secure than mono-alphabetic substitution.

Weaknesses:

- Still susceptible to digraph frequency analysis with large cipher texts.
- Complex manual encryption.

Legacy:

The Play-fair cipher was the first widely used digraph substitution cipher and inspired future designs that considered multi-character units in encryption.

7. Hill Cipher

Origin-and-Use:

Created by mathematician Lester Hill in 1929, it is notable for using algebra and matrix operations in encryption.

Mechanism:

- Convert plaintext into numerical blocks (e.g., A = 0, B = 1, etc.).

- Multiply by a key matrix.
- Apply modulo 26 to results.
- Convert numbers back to letters.

For example, with a 2x2 key matrix, you encrypt two-letter blocks at a time.

Strengths:

- Can encrypt several letters at once.
- Conceals frequency patterns very well.

Weaknesses:

- Requires the key matrix to be invertible modulo 26.
- If known plaintext and cipher text pairs are available, the key can be calculated.

Legacy:
It was one of the first ciphers to introduce **mathematical rigor** into cryptography, paving the way for modern algebra-based encryption.

8. Enigma Machine

Origin-and-Use:
Developed in the 1920s for commercial use and later adapted by Nazi Germany during WWII for military communication. Used extensively by the army, navy, and air force.

Mechanism:

- Input letter → current rotor configuration alters the electric signal path.
- Rotors rotate with each keystroke, changing the wiring dynamically.
- Includes a plug board for additional permutations.

Every key press changes the encryption path, meaning the same letter can be encrypted to different letters at different points in a message.

Strengths:

- Created extremely complex, ever-changing encryption.

- Estimated at 150 quintillion settings.

Weaknesses:

- Weak operator habits (like repeating keys or starting messages with predictable phrases) made it vulnerable.
- Once the British and Polish cryptanalysts, including Alan Turing, developed the Bombe machine and obtained rotor settings, the cipher was cracked.

Legacy:
Breaking the Enigma significantly shortened WWII and marked the beginning of **modern cryptanalysis** and **computer-assisted codebreaking**.

NOW HOW SECURITY IS PROVIDED

In addition to their vulnerability to decryption, these ciphers also lacked mechanisms for **authentication**. This meant that even if a message was encrypted, there was no way to verify its origin or check if it had been tampered with during transmission. An attacker could intercept the message, alter its contents, and re-encrypt it without detection, compromising the integrity and trustworthiness of the communication.

Despite their limitations, classical encryption methods played a vital role in early military and diplomatic communication. They laid the foundation for future cryptographic development, but as technology and computational power advanced, these techniques quickly became **obsolete**. Their shortcomings highlighted the need for more secure and robust encryption systems—paving the way for **modern cryptography**, including advanced algorithms like **AES** and authenticated encryption modes such as **AES-EAX**, which ensure both **confidentiality and integrity** in today's digital communications

Block ciphers and symmetric Encryption

As the demand for secure and efficient encryption solutions continued to rise, the cryptographic community explored further advancements in both the design of block ciphers and their operational modes. One important direction of research was the exploration of key sizes and the development of algorithms that could balance security with computational efficiency. The advent of quantum computing, still a theoretical but rapidly progressing field, has led to

increased concern over the future security of current cryptographic algorithms, including AES. This has driven research into post-quantum cryptography—new cryptographic systems that aim to withstand the potential threats posed by quantum computers.

Symmetric Encryption

Symmetric encryption is a foundational concept in cryptography that uses the same key for both encrypting and decrypting data. It is referred to as "symmetric" because the exact same key must be shared between the sender and the receiver in a secure manner. The key must remain confidential to both parties; otherwise, the security of the communication is compromised. This method of encryption is highly efficient and is particularly suited for environments where data needs to be processed quickly, such as in bulk data encryption, real-time communication, or embedded systems.

The symmetric encryption process involves taking plaintext—readable data—and combining it with a secret key through an encryption algorithm. The result is cipher text, which appears scrambled and unreadable to unauthorized parties. The receiver, who has the same key, uses it with a decryption algorithm to reverse the process and recover the original plaintext. Since the same key is used in both operations, symmetric encryption requires a secure method for key exchange before communication begins. While this requirement poses a significant challenge, symmetric encryption remains widely used due to its simplicity, low computational overhead, and speed.

Block Ciphers

Block ciphers are a specific type of symmetric encryption algorithm that operate on fixed-length segments of data, known as blocks. Common block sizes include 64 bits and 128 bits. When using a block cipher, plaintext data is divided into equal-sized blocks, and each block is independently processed using a symmetric key. If the last block is smaller than the required size, padding techniques are applied to make it fit the necessary length. The cipher then transforms each block of plaintext into a block of cipher text through a series of complex mathematical operations involving substitution, permutation, and mixing.

The encryption process in block ciphers is typically structured in multiple rounds. Each round applies a unique transformation to the data using the encryption key, gradually scrambling the input to achieve a secure output. Decryption follows the reverse process, applying the inverse

operations in the opposite order using the same key. Block ciphers are known for their strength and flexibility, but they also require the use of "modes of operation" to encrypt data that is longer than a single block. These modes determine how blocks are linked together during encryption and decryption, and they significantly influence the security properties of the cipher.

Data Encryption Standard (DES)

The Data Encryption Standard (DES) was one of the first widely adopted encryption standards and played a pivotal role in the evolution of digital security. Developed by IBM in the early 1970s and officially adopted by the U.S. National Institute of Standards and Technology (NIST) in 1977, DES is a symmetric block cipher that uses a 56-bit key to encrypt 64-bit blocks of data. The encryption process involves 16 rounds of transformation based on the Feistel network architecture, where data is split into two halves and processed through functions involving substitution, permutation, and key mixing.

DES was revolutionary at the time of its adoption and remained a cornerstone of digital security for many years. However, with the advancement of computational power, DES's 56-bit key became increasingly vulnerable to brute-force attacks. By the late 1990s, it was demonstrated that DES-encrypted data could be broken within hours or even minutes using specialized hardware. As a result, DES is no longer considered secure for protecting sensitive information and has been largely phased out of use. Despite its obsolescence, DES's design principles heavily influenced the development of more robust encryption algorithms.

Triple DES (3DES)

Triple DES (also known as 3DES or TDEA) was introduced as an interim solution to strengthen the security of the original DES algorithm without completely replacing it. It enhances DES by applying the encryption process three times in succession using either two or three different 56-bit keys, resulting in key lengths of 112 or 168 bits. The process involves encrypting the data with the first key, decrypting it with the second key, and encrypting it again with the third. This triple-layer encryption significantly improves security by making brute-force attacks far more difficult.

While 3DES offered improved protection and was widely adopted for a time, it has notable drawbacks. The triple application of the algorithm makes it significantly slower than more

modern ciphers. Furthermore, with advancements in cryptanalysis and the demand for higher performance encryption, 3DES is now considered outdated and is being deprecated in favor of more efficient algorithms like AES. Nevertheless, it continues to be supported in many legacy systems due to its backward compatibility with DES.

Advanced Encryption Standard (AES)

The Advanced Encryption Standard (AES) is the current gold standard for symmetric encryption and is widely regarded as one of the most secure and efficient encryption algorithms available today. It was established by NIST in 2001 after a global competition to replace DES. The winner of this competition was the Rijndael algorithm, which became the foundation for AES. AES operates on 128-bit blocks and supports key sizes of 128, 192, or 256 bits. Depending on the key size, the algorithm performs 10, 12, or 14 rounds of encryption.

Each round in AES consists of several steps: substitution (using S-boxes), row shifting, column mixing, and round key addition. These operations ensure that small changes in the input result in completely different cipher text outputs—a property known as the avalanche effect. AES is efficient in both hardware and software implementations and is used in numerous applications, including SSL/TLS for secure web browsing, WPA2/WPA3 for Wi-Fi security, and file encryption. Its strength, speed, and resistance to known cryptographic attacks make AES the preferred choice for both commercial and government-grade security.

Blowfish

Blowfish is a symmetric block cipher designed by Bruce Schneier in 1993 as a free and unpatented alternative to existing encryption standards. It uses a 64-bit block size and allows for variable key lengths ranging from 32 bits to 448 bits, providing flexibility for different security requirements. The algorithm employs a 16-round Feistel network structure and features key-dependent S-boxes, which contribute to its security by making each encryption instance unique based on the key.

Blowfish is known for its simplicity, compact design, and high speed in software, making it popular for embedded systems and applications with limited processing power. However, its

64-bit block size is now considered too small for encrypting large amounts of data, as it increases the risk of block collisions. As a result, Blowfish has been largely replaced by more modern algorithms like AES, but it remains a strong option for scenarios where its limitations are not critical.

Two-fish

Two-fish is another symmetric block cipher developed by Bruce Schneier and his team as a finalist in the AES competition. It supports a block size of 128 bits and key sizes up to 256 bits. Two-fish was designed with flexibility and performance in mind, allowing it to be used efficiently in both software and hardware implementations. The algorithm employs a complex key schedule, S-boxes generated from the key, and multiple layers of encryption transformation for increased security.

Although Two-fish was not selected as the AES standard, it remains a highly secure and free-to-use encryption algorithm. It is particularly well-suited for open-source applications and security software that require robust encryption without licensing restrictions.Two-fish's strong cryptographic design and resistance to differential and linear cryptanalysis make it a viable alternative to AES in many contexts.

TYPES OF SECURITY

Modes of operation

Block cipher modes of operation are techniques that allow block ciphers to encrypt data of arbitrary length—far longer than a single fixed-size block. Encryption plays a crucial role in securing digital communications, and cryptographic modes of operation help adapt block ciphers like AES and DES to encrypt large messages securely. While block ciphers like AES or DES work on specific block sizes (e.g., 64 or 128 bits), real-world data typically exceeds these limits. Modes of operation define how these individual blocks are linked together during encryption and decryption to ensure both security and practicality. Each mode has different strengths and weaknesses in terms of performance, error propagation, and resistance to cryptographic attacks. Below are the most commonly used block cipher modes, explained in detail.

1. Electronic Codebook Mode (ECB)

Electronic Codebook (ECB) is the simplest and most basic mode of operation. In ECB, plaintext is divided into blocks, and each block is independently encrypted using the same secret key. This means that identical plaintext blocks will always result in identical cipher text blocks.

Security Concerns:

- The main security flaw of ECB lies in its inability to mask data patterns. Since each plaintext block is encrypted independently, identical plaintext blocks will always produce the same cipher text block, leading to **patterns being observable** in the encrypted output.
- This vulnerability is especially dangerous when encrypting structured data, such as images, where repeated patterns are common (e.g., white areas in an image will always be encrypted to the same cipher text).

Use Cases:

- ECB is **not suitable for encrypting sensitive data**, especially in contexts where patterns need to be concealed (e.g., file encryption, secure communications).
- However, it may still be used in **very specific cases** such as **encrypting small or random data**, or when the encryption method is used for things like password storage (where the patterns don't reveal sensitive information).

Example:

- **Secure Key Storage**: Using ECB for encrypting keys might be acceptable in cases where there is minimal risk of pattern-based attacks.

2. Cipher Block Chaining Mode (CBC)

Cipher Block Chaining (CBC) improves upon ECB by chaining together cipher text blocks, introducing an inter-block dependency. In CBC, the first block of plaintext is XORed with a random **Initialization Vector (IV)** before being encrypted. Each subsequent plaintext block is XORed with the previous cipher text block before being encrypted.

Security Benefits:

- **Conceals data patterns**: Because each cipher text block depends on both the previous cipher text block and the plaintext, identical plaintext blocks will encrypt differently due to the XOR operation.
- **IV for randomness**: The use of an IV adds randomness to the encryption, ensuring that the same plaintext will produce different cipher texts each time it is encrypted.

Drawbacks:

- **Sequential Encryption**: The encryption process is **sequential** (i.e., each block depends on the previous one), meaning that it cannot be parallelized, which can slow down encryption for large datasets.
- **Error Propagation**: A single bit error in the cipher text can affect the decryption of both the current block and the next block, causing significant data corruption.

Use Cases:

- CBC is widely used in situations requiring the encryption of **large data sets**, such as **disk encryption** (e.g., BitLocker) and **secure file storage**.
- It is also used in **SSL/TLS protocols** for secure communication over the internet.

Example:

- **SSL/TLS**: CBC is commonly used in early versions of **SSL/TLS** protocols to encrypt web traffic. However, more secure modes are now preferred for newer versions.

3. Cipher Feedback Mode (CFB)

Cipher Feedback (CFB) mode, similar to CBC, transforms a block cipher into a stream cipher by encrypting data **one bit or byte at a time** instead of in fixed-size blocks. In CFB, the previous cipher text block (or the IV for the first block) is encrypted and then XORed with the plaintext to produce cipher text.

Security Benefits:

- **Stream-like operation**: CFB encrypts data in smaller increments, making it suitable for applications where the data arrives in unpredictable sizes or streams. This feature is particularly useful for **real-time data encryption** in applications like voice or video streaming.
- **Error Propagation**: CFB is **more resilient to errors** compared to CBC. If a single bit is corrupted in a cipher text block, it will only affect that bit during decryption and not propagate to subsequent blocks.

Drawbacks:

- **No Parallelization**: Like CBC, CFB is **not parallelizable**, which can lead to inefficiencies when dealing with large data.
- **Slower than other modes**: Since it works in increments of a single bit or byte, it may not be as efficient as other modes like CTR for encrypting large datasets.

Use Cases:

- **Real-time communications**: CFB is ideal for encrypting **streaming data** such as **live video/audio calls**, where data needs to be encrypted and decrypted in real-time as it arrives.
- **Legacy systems**: CFB is still used in some older systems where **low-latency encryption** is crucial, and data is processed in streams.

Example:

- **Voice over IP (VoIP)**: CFB might be used in **VoIP** applications for encrypting voice data in real-time.

4. Output Feedback Mode (OFB)

Output Feedback (OFB) is another mode that converts a block cipher into a stream cipher. In OFB, the **output of the encryption function** is used as the keystream, which is then XORed with the plaintext to produce cipher text. Unlike CFB, OFB does not use the cipher text for generating the next keystream.

Security Benefits:

- **No error propagation**: One key advantage of OFB over CFB is that **errors in cipher text do not propagate** to other blocks during decryption, making it more resilient to transmission errors.
- **Keystream independence**: Since the keystream is generated independently of the cipher text, OFB can be used in scenarios where cipher text must be protected from corruption.

Drawbacks:

- **Pre-computation required**: Since OFB requires the keystream to be pre-computed before encryption, it may not be suitable for applications where real-time encryption is required.
- **IV reuse risks**: If the **IV** is reused, security can be compromised. The keystream is predictable if the IV is the same for different sessions.

Use Cases:

- **Low-latency encryption systems**: OFB is useful in systems where **data integrity is critical**, and low latency is required, such as in **satellite communications** and some **military applications**.

Example:

- **Satellite communications**: OFB might be used in **satellite-based encryption systems**, where the risk of transmission errors can be significant.

5. Counter Mode (CTR)

Counter (CTR) mode is a highly efficient block cipher mode that converts the block cipher into a stream cipher. CTR mode works by **generating a keystream** through the encryption of a **counter value** that increments with each block. The keystream is then XORed with the plaintext to produce cipher text.

Security Benefits:

- **Parallelizable**: One of the most significant advantages of CTR mode is that **encryption and decryption operations can be performed in parallel** because the counter for each block is independent of the others.
- **Efficient and fast**: Because it doesn't depend on previous cipher text blocks and allows for parallel processing, CTR mode is highly efficient for encrypting large volumes of data.
- **No error propagation**: Like other stream cipher modes, errors in the cipher text affect only the corresponding block, and not the subsequent blocks.

Drawbacks:

- **Counter reuse vulnerability**: The security of CTR mode depends on the **uniqueness of the counter**. If the same counter is used twice with the same key, it could expose the key and plaintext, leading to a catastrophic security breach.
- **IV management**: Proper management of the counter and IV is essential to ensure security.

Use Cases:

- **High-performance encryption**: CTR mode is widely used in high-performance systems where speed is crucial, such as **cloud storage**, **full disk encryption**, and **high-speed network encryption**.
- **Modern protocols**: CTR mode is frequently used in modern protocols like **TLS 1.2/1.3** and **IPSec** for encrypting data.

Example:

- **Full disk encryption**: **BitLocker** and **Veracrypt** may use CTR mode to ensure **efficient encryption** of large data volumes in an operating system's storage.

6. Galois/Counter Mode (GCM)

Galois/Counter Mode (GCM) is a modern and robust block cipher mode that combines the efficiency of **CTR mode** with **authentication** capabilities. It provides both encryption and **message authentication** (integrity checking) in one pass.

Security Benefits:

- **Authenticated Encryption**: GCM not only encrypts data but also computes an **authentication tag**, which helps verify that the cipher text has not been altered. This provides both confidentiality and integrity in one algorithm.
- **Parallelizable**: Like CTR mode, GCM supports **parallel processing**, allowing high-throughput applications to benefit from its efficiency.
- **Widely adopted**: GCM is used in many modern secure communication protocols, including **TLS 1.2/1.3**, **IPSec**, and **HTTPS**.

Drawbacks:

- **Nonce management**: The nonce (a unique value combined with the counter) used in GCM must be unique for every encryption, and misuse of

Introduction Of Authentication Encryption (AE)

Authenticated Encryption (AE) is a cryptographic approach that ensures both the confidentiality and integrity of data. Unlike traditional encryption schemes that only protect data from unauthorized access, AE mechanisms also verify that the data has not been altered during transmission and originates from a legitimate source. This dual functionality is essential in modern applications such as secure messaging, online banking, and wireless communication, where both secrecy and trustworthiness of information are critical. Two widely adopted AE modes are CCM (Counter with CBC-MAC) and GCM (Galois/Counter Mode), each designed to offer combined encryption and authentication, but with different operational and performance characteristics.

CCM mode integrates the Counter (CTR) mode of encryption with Cipher Block Chaining Message Authentication Code (CBC-MAC) for authentication. It operates in two distinct passes: one for generating the authentication tag and another for encrypting the message. This structure provides strong security guarantees by ensuring that any alteration in the cipher text can be detected. However, CCM presents certain limitations. The two-pass processing increases computational overhead and delays decryption since the entire cipher text must be

processed before verifying authenticity. Additionally, the separation of encryption and authentication steps makes implementation more complex and potentially more error-prone.

On the other hand, GCM mode utilizes AES in CTR mode for encryption and employs Galois field multiplication to generate an authentication tag. GCM is known for its high efficiency, especially in hardware environments, and its ability to process encryption and authentication in parallel. This parallelism significantly enhances throughput, making GCM suitable for high-speed network applications. Furthermore, GCM's single-pass operation allows both encryption and authentication to occur simultaneously, which is ideal for real-time data processing. Despite its advantages, GCM has its own set of challenges. The security of GCM heavily depends on the uniqueness of the nonce; reusing a nonce with the same key can completely compromise data security. Moreover, software implementations of GCM are vulnerable to side-channel attacks if not carefully designed and executed, particularly in systems lacking hardware acceleration.

MOTIVATION

Importance of AES (advanced encryption standard)

The **Advanced Encryption Standard (AES)** is one of the most critical cryptographic algorithms in modern data security. It was developed to replace the older **Data Encryption Standard (DES)**, which had become vulnerable due to its short key length. AES is widely regarded for its **speed, efficiency, and security**, and is used globally in applications ranging from personal file encryption to government-grade communications. It is a **symmetric block cipher** that encrypts data in blocks of 128 bits using keys of 128, 192, or 256 bits, making it adaptable to different security needs.

The **importance of AES** lies in its broad adoption and strong cryptographic properties. It is used in many protocols and standards such as **SSL/TLS (for HTTPS)**, **IPSec**, **Wi-Fi security (WPA2/WPA3)**, **VPNs**, **disk encryption**, **mobile applications**, and **secure messaging**. Its design allows for fast implementation in both software and hardware, making it ideal for high-performance environments, from cloud services to embedded systems.

Additionally, AES has undergone **extensive public scrutiny** and cryptanalysis over the years, yet no practical attacks have been discovered against it when implemented correctly. This

resilience gives it a high level of trust and reliability. It is also **approved by the U.S. National Institute of Standards and Technology (NIST)** and is used for protecting classified information up to the top-secret level.

Why AES Was Choosen

AES was chosen through a public competition initiated by **NIST in 1997** to find a secure replacement for DES. The goal was to select an algorithm that could withstand modern cryptographic attacks and work efficiently across a wide range of platforms. After evaluating 15 candidate algorithms from international researchers, **Rijndael**, developed by Belgian cryptographers **Joan Daemen and Vincent Rijmen**, was selected in 2000 and officially adopted as the AES standard in 2001.

AES was chosen for several key reasons:

1. **Security**: It demonstrated strong resistance to known cryptanalytic attacks during the selection process.
2. **Performance**: AES performed well on both **software and hardware platforms**, including resource-constrained environments like smart cards and IoT devices.
3. **Flexibility**: With three different key lengths (128, 192, and 256 bits), it offers scalable security.
4. **Simplicity of Design**: AES is based on a substitution-permutation network, which is both **elegant and efficient**, making it easier to implement and analyze.
5. **Open and Transparent Evaluation**: The entire selection process was open to the public, which built **trust** and ensured **community validation** of its security.

Lapses or Weaknesses Of AES

Although AES is extremely secure when used correctly, it is not without its **potential weaknesses or lapses**, especially in implementation or in certain edge-case scenarios. These issues are **not due to flaws in the AES algorithm itself**, but rather in how it is used or integrated:

1. **Side-Channel Attacks**: One of the most significant concerns is vulnerability to **side-channel attacks**, such as **timing attacks**, **power analysis**, or **electromagnetic leaks**.

These attacks target the **implementation**, not the algorithm, and attempt to extract the secret key by analyzing physical characteristics of the device running AES.

2. **Key Management**: Like all symmetric encryption algorithms, AES requires secure **key distribution and storage**. If the key is exposed, the security of the encrypted data is completely compromised. This is especially challenging in distributed systems.
3. **Incorrect Mode of Operation**: Using AES in insecure or inappropriate modes (e.g., **ECB mode**, which does not mask patterns) can reveal sensitive information. To avoid this, secure modes like **CBC with padding and MAC** or **GCM (authenticated encryption)** are recommended.
4. **Brute Force in the Future**: While AES is currently secure against brute force attacks, future advances in **quantum computing** could potentially reduce its effectiveness, especially for 128-bit keys. For long-term security, **AES-256** is preferred.
5. **Implementation Errors**: Flaws in coding or integrating AES (e.g., not using proper initialization vectors or reusing keys) can weaken its security. Many real-world vulnerabilities arise from poor implementation rather than the algorithm itself.

PROBLEM DEFINITION

Addressing AES Lapses With AES-EAX

The AES-EAX mode of operation significantly enhances the security of AES by addressing several of its known implementation and usage weaknesses. AES on its own, while cryptographically strong, does not provide data integrity or authenticity. This limitation becomes particularly dangerous if AES is used in insecure modes like ECB or in implementations that do not pair it with a proper authentication mechanism. AES-EAX is specifically designed to overcome these concerns by integrating both encryption and authentication into a single, cohesive process.

AES-EAX combines AES in Counter (CTR) mode for encryption with a message authentication code (MAC) based on OMAC (One-key MAC) to produce authenticated encryption. This ensures that any changes to the cipher text, initialization vector (IV), or even associated data can be detected during decryption. By following the Encrypt-then-Authenticate paradigm, AES-EAX guarantees that if the data is tampered with, decryption will fail and raise an integrity error, effectively preventing unauthorized modifications.

One of the major vulnerabilities in standard AES usage is improper key or IV management. Modes like CBC or CTR require unique IVs for each encryption operation, and IV reuse can lead to serious cryptographic attacks. AES-EAX enforces IV uniqueness and incorporates the IV into the authentication process, ensuring that even if an attacker modifies the IV, the alteration is detected. This reduces the risk of IV reuse and mitigates attacks such as replay attacks and pattern analysis.

Another common lapse in AES implementations is the misuse of separate encryption and MAC layers, often combined incorrectly in insecure orders (e.g., MAC-then-encrypt). AES-EAX eliminates this risk by offering a standardized and robust method for authenticated encryption. It simplifies implementation by ensuring that the encryption and authentication steps are tightly integrated, reducing the likelihood of errors that can compromise security.

Furthermore, AES-EAX supports associated data, allowing developers to include unencrypted information—such as headers or metadata—in the authentication process. This is particularly useful in secure communications and file formats where certain data must remain in plaintext but still needs to be verified for integrity. This feature enhances the flexibility and applicability of AES-EAX in real-world systems.

In summary, AES-EAX addresses the lapses of basic AES usage by providing authenticated encryption that ensures both confidentiality and integrity. It eliminates the risks of insecure modes, implementation mistakes, and unauthenticated cipher texts. Through its design, AES-EAX offers a reliable, secure, and efficient solution suitable for modern cryptographic applications, including secure messaging, network protocols, and embedded systems.

RELATED WORK

FPGA Implementation of AES Encryptor Based on Rolled and Masked Approach (2023)

Monika Mathur and Nidhi Goel propose a modified 8-bit AES architecture that performs core operations in a single round, iterated ten times, leading to reduced area and power consumption. To enhance security, Boolean masking is employed across all AES operations, rounds, and intermediate data. The architecture includes high-order masking for Add-Round-Key and Byte-Substitution operations and an enhanced key expansion algorithm to resist saturation and differential power analysis (DPA) attacks. Implemented on a Virtex-7 FPGA using Vivado Design Suite, the design achieves a maximum frequency of 179.73 MHz and a throughput of 143.78 Mbps, utilizing 757 slices, 962 LUTs, and consuming 0.313 watts of power.

A Reconfigurable and Compact Sub-pipelined Architecture for AES Encryption and Decryption (2023)

This study presents a 32-bit reconfigurable and compact AES architecture suitable for non-BRAM FPGAs. The design supports different key sizes (128, 192, and 256 bits) and employs a single-round architecture with sub-pipelining to minimize hardware costs. Utilizing a fully composite field GF($(2^4)^2$)-based encryption/decryption and key schedule, the architecture achieves throughputs of 375 Mbps (128-bit key), 318 Mbps (192-bit key), and 275 Mbps (256-bit key) on a VIRTEX XC4VSX25-12 FPGA, using 1,766 slices.

FPGA Acceleration of AES Algorithm for High-Performance Cryptographic Applications (2024)

Abdullah Farhan Siddiqui and Prof. P. Chandra Sekhar detail an FPGA implementation of the AES-128 algorithm as an accelerator for high-performance cryptographic applications. Utilizing the Virtex-7 evaluation kit and Xilinx Vivado software, the design achieves resource efficiency with 588 Look-Up Tables (LUTs) and 353 Flip Flops. This implementation demonstrates the effectiveness of FPGA technology in balancing algorithmic complexity and resource utilization for cryptographic acceleration.

FPGA-Patch: Mitigating Remote Side-Channel Attacks on FPGAs Using Dynamic Patch Generation (2023)

Mahya Morid Ahmadi et al. introduce FPGA-Patch, a defense mechanism against power side-channel attacks on cloud FPGAs. By generating ISO functional variants of target hardware through automated program repair concepts, FPGA-Patch ensures diversity in power traces when variants are dynamically swapped at runtime. Applied to AES running on AMD/Xilinx FPGAs, FPGA-Patch increases the attacker's effort by three orders of magnitude while maintaining AES performance and incurring a minimal area overhead of 14.2%.

Quantum Forgery Attacks on COPA, AES-COPA, and Marble Authenticated Encryption Algorithms (2023)

Yinsong Xu, Wenjie Liu, and Wenbin Yu explore quantum forgery attacks on COPA, AES-COPA, and Marble authenticated encryption algorithms. Utilizing Simon's algorithm, the study demonstrates that quantum attacks can significantly reduce the number of queries needed to forge tags, from O(2^(n/2)) in classical attacks to O(n) in quantum scenarios, with success probabilities approaching 100%. This highlights potential vulnerabilities in these algorithms in the presence of quantum adversaries.

METHODOLOGY

Brief History Of AES Algorithm

The Advanced Encryption Standard (AES) algorithm is one of the block cipher encryption algorithm that was published by National Institute of Standards and technology (NIST) in 2000. The main aims of this algorithm was to replace DES algorithm after appearing some vulnerable aspects of it. NIST invited experts who work on encryption and data security all over the world to introduce an innovative block cipher algorithm to encrypt and decrypt data with powerful and complex structure. From around the world many groups submitted their algorithm. NIST accepted five algorithms for evaluate. After performing various criteria and security parameters, they selected one of the five encryption algorithm that proposed by two Belgian cryptographers Joan Daeman and Vincent Rijmen. The original name of AES algorithm is the Rijndel algorithm. However, this name has not become a popular name for this algorithm instead it is recognized as Advanced Encryption Standard (AES) algorithm around the world [14].

Evaluation Criteria For AES Algorithm

Three important criterions were used by NIST to evaluate the algorithms that were submitted by cryptographer experts.

A. Security

One of the most crucial aspects that NIST was considered to choose algorithm it is security. The main reasons behind this was obvious because of the main aims of AES was to improve the security issue of DES algorithm. AES has the best ability to protect sensitive data from attackers and is not allowed them to break the encrypt data as compared to other proposed algorithm. This was achieved by doing a lot of testing on AES against theoretical and practical attacks [3].

B. Cost

Another criterion that was emphasis by NIST to evaluate the algorithms it is cost. Again, the factors behind this measures was also clear due to another main purpose of AES algorithm was to improve the low performance of DES. AES was one of the algorithm which was nominated by NIST because it is able to have high computational efficiency and can be used in a wide range of applications especially in broadband links with a high speed [4].

C. Algorithm and Implementation Characteristics

This criteria was very significant to estimate the algorithms that were received from cryptographer experts. Some important aspects were measured in this stage that is the flexibility, simplicity and suitability of the algorithm for diversity of hardware and software implementation [5].

Basic Structure Of AES Algorithm

AES is an iterative instead of Feistel cipher. It is based on two common techniques to encrypt and decrypt data knowns as substitution and permutation network (SPN). SPN is a number of mathematical operations that are carried out in block cipher algorithms [7]. AES has the ability to deal with 128 bits (16 bytes) as a fixed plaintext block size. These 16 bytes are represented in 4x4 matrix and AES operates on a matrix of bytes. In addition, another crucial feature in AES is number of rounds. The number of rounds is relied on the length of key. There are three different key sizes are used by AES algorithm to encrypt and decrypt data such as (128, 192 or 256 bits). The key sizes decide to the number of rounds such as AES uses 10 rounds for 128-bit keys, 12 rounds for 192-bit keys and 14 rounds for 256-bit keys [8].

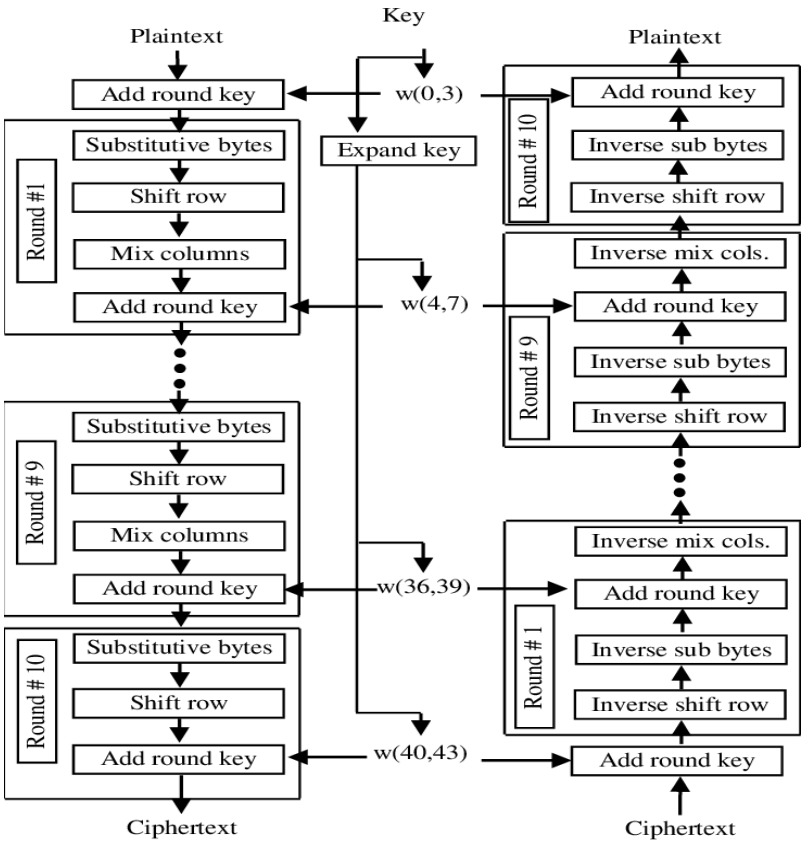


Fig. 1 Basic Structure of AES

Encryption Process

Encryption is a popular techniques that plays a major role to protect data from intruders. AES algorithm uses a particular structure to encrypt data to provide the best security. To do that it relies on a number of rounds and inside each round comprise of four sub-process. Each round consists of the following four steps to encrypt 128 bit block

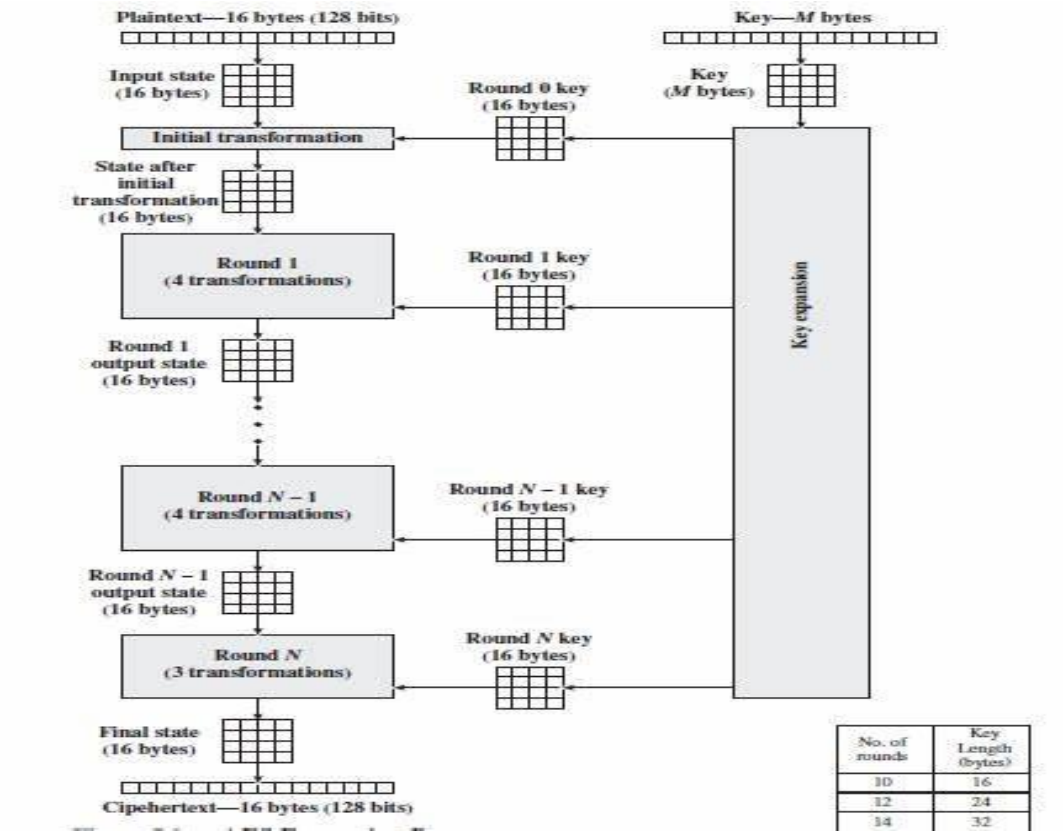


Fig.2 Encryption Processes

A. Substitute Bytes Transformation

The first stage of each round starts with Sub-Bytes transformation. This stage is depends on nonlinear S-box to substitute a byte in the state to another byte. According to diffusion and confusion Shannon's principles for cryptographic algorithm design it has important roles to obtain much more security [12]. For example in AES if we have hexa 53 in the state, it has to replace to hexa ED. ED created from the intersection of 5 and 3. For remaining bytes of the state have to perform this operations.

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	63	7C	77	7B	F2	6B	6F	C5	30	01	67	2B	FE	D7	AB	76
1	CA	82	C9	7D	FA	59	47	F0	AD	D4	A2	AF	9C	A4	72	C0
2	B7	FD	93	26	36	3F	F7	CC	34	A5	E5	F1	71	D8	31	15
3	04	C7	23	C3	18	96	05	9A	07	12	80	E2	EB	27	B2	75
4	09	83	2C	1A	1B	6E	5A	A0	52	3B	D6	B3	29	E3	2F	84
5	53	D1	00	ED	20	FC	B1	5B	6A	CB	BE	39	4A	4C	58	CF
6	D0	EF	AA	FB	43	4D	33	85	45	F9	02	7F	50	3C	9F	A8
7	51	A3	40	8F	92	9D	38	F5	BC	B6	DA	21	10	FF	F3	D2
8	CD	0C	13	EC	5F	97	44	17	C4	A7	7E	3D	64	5D	19	73
9	60	81	4F	DC	22	2A	90	88	46	EE	B8	14	DE	5E	0B	DB
A	E0	32	3A	0A	49	06	24	5C	C2	D3	AC	62	91	95	E4	79
B	E7	C8	37	6D	8D	D5	4E	A9	6C	56	F4	EA	65	7A	AE	08
C	BA	78	25	2E	1C	A6	B4	C6	E8	DD	74	1F	4B	BD	8B	8A
D	70	3E	B5	66	48	03	F6	0E	61	35	57	B9	86	C1	1D	9E
E	E1	F8	98	11	69	D9	8E	94	9B	1E	87	E9	CE	55	28	DF
F	8C	A1	89	0D	BF	E6	42	68	41	99	2D	0F	B0	54	BB	16

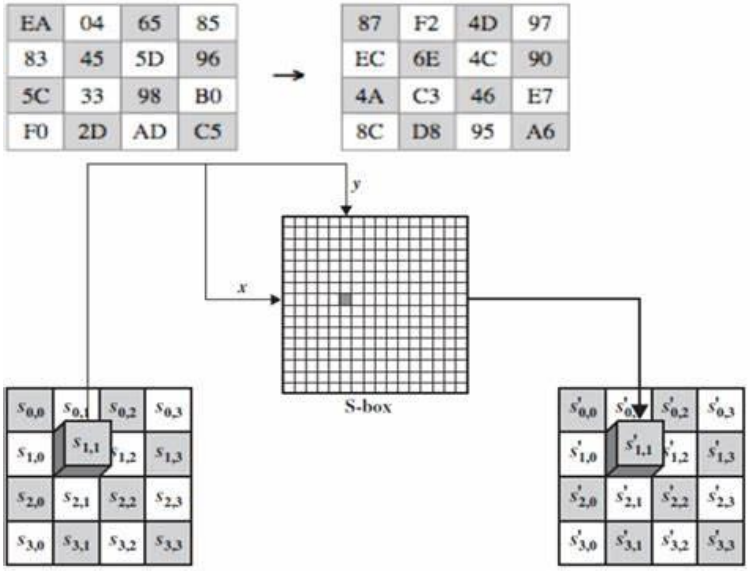


fig. 3 substitute bytes

B. Shift-Rows Transformation

The next step after Sub-Byte that perform on the state is Shift-Row. The main idea behind this step is to shift bytes of the state cyclically to the left in each row rather than row number zero. In this process the bytes of row number zero remains and does not carry out any permutation. In the first row only one byte is shifted circular to left. The second row is shifted two bytes to the left. The last row is shifted three bytes to the left [13]. The size of new state is not changed that remains as the same original size 16 bytes but shifted the position of the bytes in state as illustrated in Fig 4.

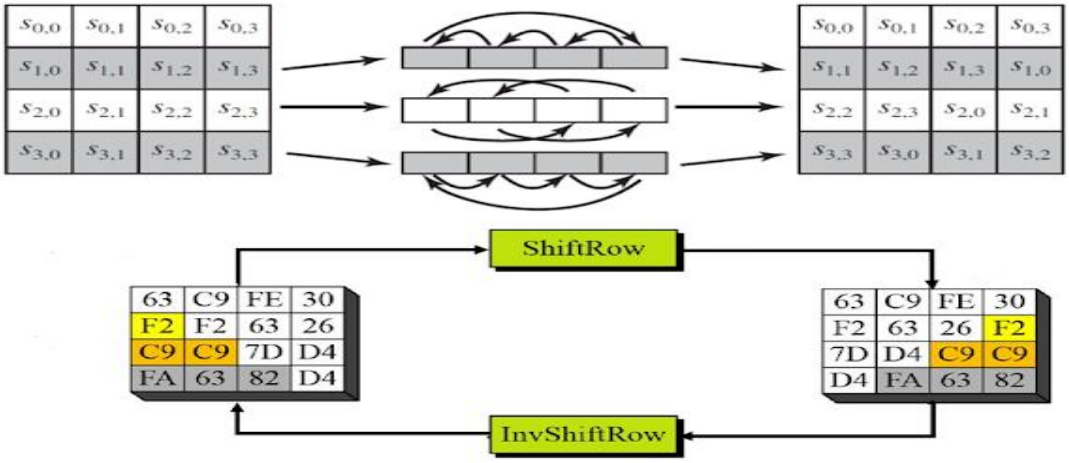


Fig.4 shift rows

C. **Mix-Columns Transformation**

Another crucial step occurs of the state is Mix-Column. The multiplication is carried out of the state. Each byte of one row in matrix transformation multiply by each value (byte) of the state column. In another word, each row of matrix transformation must multiply by each column of the state. The results of these multiplication are used with XOR to produce a new four bytes for the next state. In this step the size of state is not changed that remained as the original size 4x4 as shown in Fig. 5.

$$\begin{bmatrix} b_{0,c} \\ b_{1,c} \\ b_{2,c} \\ b_{3,c} \end{bmatrix} = \begin{bmatrix} 2 & 3 & 1 & 1 \\ 1 & 2 & 3 & 1 \\ 1 & 1 & 2 & 3 \\ 3 & 1 & 1 & 2 \end{bmatrix} \otimes \begin{bmatrix} a_{0,c} \\ a_{1,c} \\ a_{2,c} \\ a_{3,c} \end{bmatrix}$$

Fig.5 multiplication matrix

D. Add-Round-Key Transformation

Add-Round-Key is the most vital stage in AES algorithm. Both the key and the input data (also referred to as the state) are structured in a 4x4 matrix of bytes [19]. Fig. 6 shows how the 128-bit key and input data are distributed into the byte matrices. Add-Round-Key has the ability to provide much more security during encrypting data. This operation is based on creating the relationship between the key and the cipher text. The

cipher text is coming from the previous stage. The Add-Round-Key output exactly relies on the key that is indicated by users [15]. Furthermore, in the stage the sub key is also used and combined with state. The main key is used to derive the sub key in each round by using Rijndael's key schedule. The size of sub key and state is the same. The sub key is added by combining each byte of the state with the corresponding byte of the sub key using bitwise XOR [16].

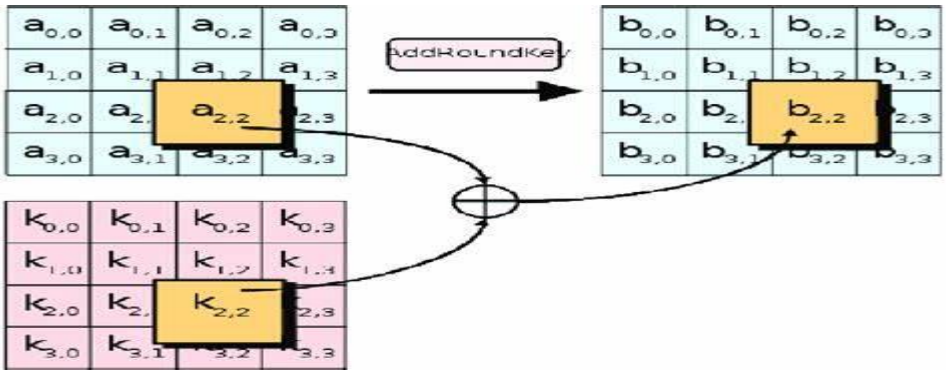


Fig.6 add round key

AES Key Expansion

AES algorithm is based on AES key expansion to encrypt and decrypt data. It is another most important steps in AES structure. Each round has a new key. In this section concentrates on AES Key Expansion technique. The key expansion routine creates round keys word by word, where a word is an array of four bytes. The routine creates 4x (Nr+1) words. Where Nr is the number of rounds [17]. The process is as follows:

The cipher key (initial key) is used to create the first four words. The size of key consists of 16 bytes (k0 to k15) as shown in Fig.8 that represents in an array. The first four bytes (k0 to k3) represents as w0, the next four bytes (k4 to k7) in first column represents as w1, and so on. We can use particular equation to calculate and find keys in each round easily as follows:

- **K [n]: w[i] = k [n-1]: w[i] XOR k[n]: w[i].**

This equation uses to find a key for each round rather than w0. For w0 we have to use particular equation that is different from above equation.

- **K[n]: w0 = k [n-1]: w0 XOR Sub-Byte (k [n-1]: w3>>8) XOR Rcon [i].**

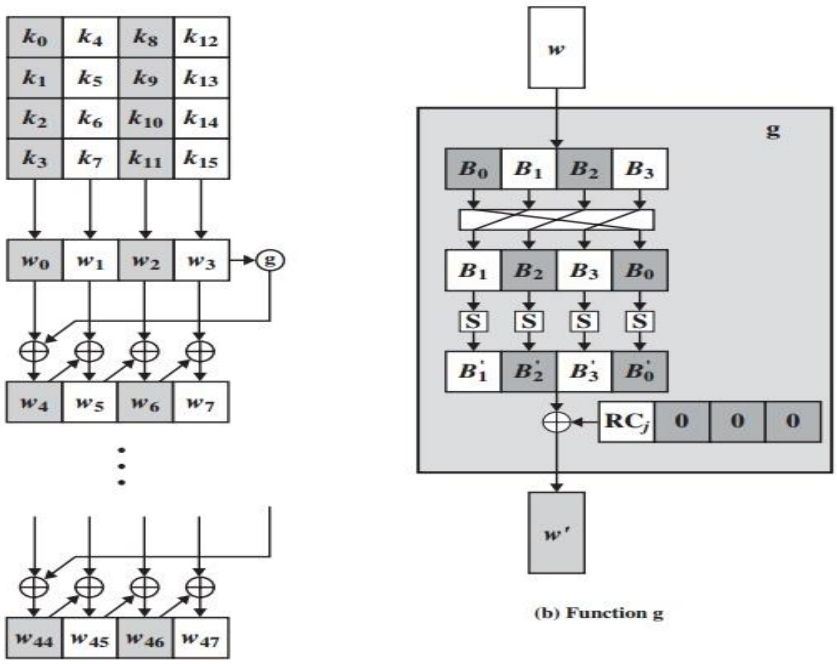


Figure 5.9 AES Key Expansion

Fig. 7 AES key expansion

Decryption Process

The decryption is the process to obtain the original data that was encrypted. This process is based on the key that was received from the sender of the data. The decryption processes of an AES is similar to the encryption process in the reverse order and both sender and receiver have the same key to encrypt and decrypt data. The last round of a decryption stage consists of three stages such as InvShiftRows, InvSubBytes, and AddRoundKey as illustrated in Fig. 8.

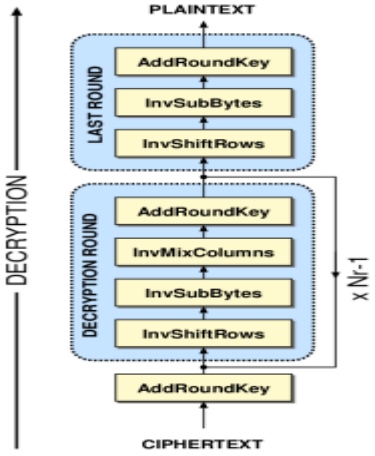


Fig.8 decryption process

Blowfish

Blowfish is an encryption technique designed by **Bruce Schneier** in 1993 as an alternative to DES Encryption Technique. It is significantly faster than DES and provides a good encryption rate with no effective cryptanalysis technique found to date. It is one of the first, secure block cyphers not subject to any patents and hence freely available for anyone to use. It is symmetric block cipher algorithm.

1. **Block Size**: 64-bits
2. **key Size**: 32-bits to 448-bits variable size
3. **number of sub keys**: 18 [P-array]
4. **number of rounds**: 16
5. **number of substitution boxes**: 4 [each having 512 entries of 32-bits each]

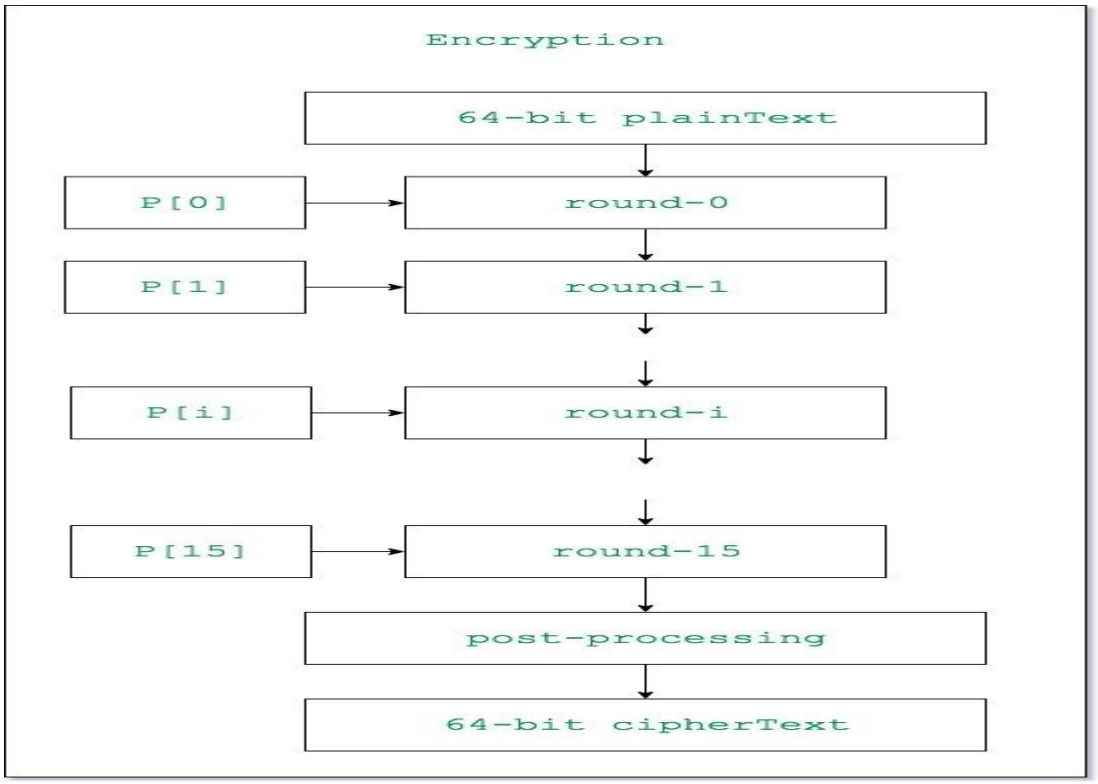


Fig. encryption of blowfish

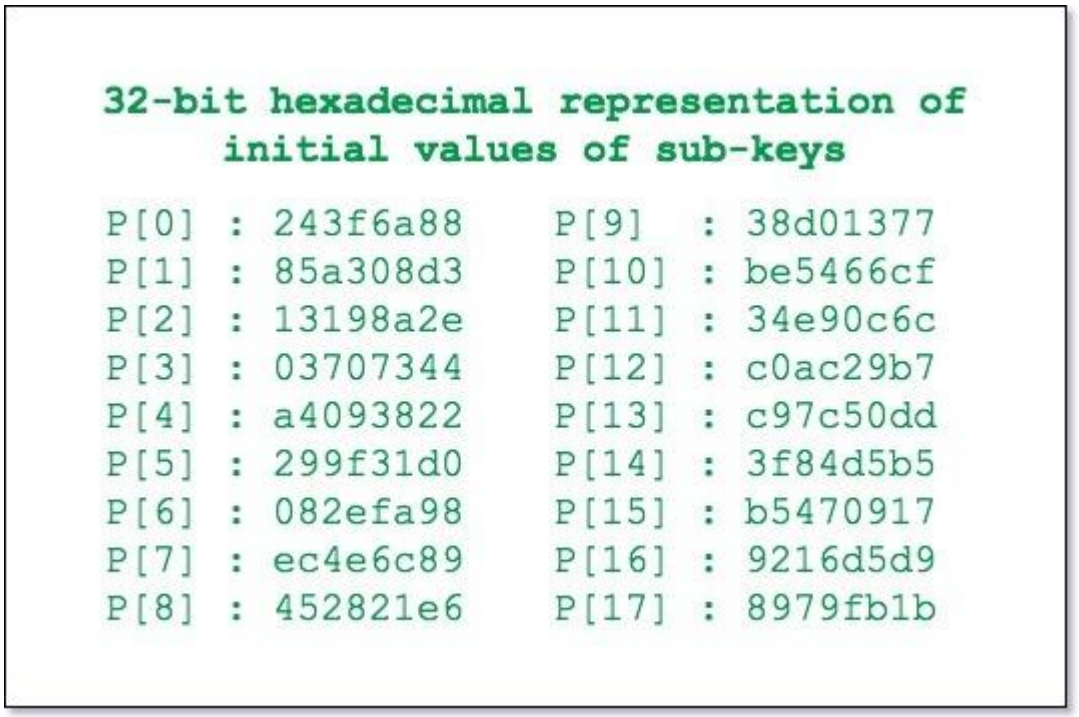
Blowfish Encryption Algorithm

Step1: Generation of sub keys:

- 18 sub keys {P[0]…P[17]} are needed in both encryption as well as decryption process and the same sub keys are used for both the processes.
- These 18 sub keys are stored in a P-array with each array element being a 32-bit entry.

- It is initialized with the digits of pi(?).
- The hexadecimal representation of each of the sub keys is given by:

P[0] = "243f6a88"
P[1] = "85a308d3"
.
.
.
P[17] = "8979fb1b"



- Now each of the sub key is changed with respect to the input key as:

P[0] = P[0] xor 1st 32-bits of input key
P[1] = P[1] xor 2nd 32-bits of input key
.
.
.
P[i] = P[i] xor (i+1)th 32-bits of input key (roll over to 1st 32-bits depending on the key length)
.

.

.

P[17] = P[17] xor 18th 32-bits of input key (roll over to 1st 32-bits depending on key length)

The resultant P-array holds 18 sub keys that is used during the entire encryption process

Step2: initialise Substitution Boxes:

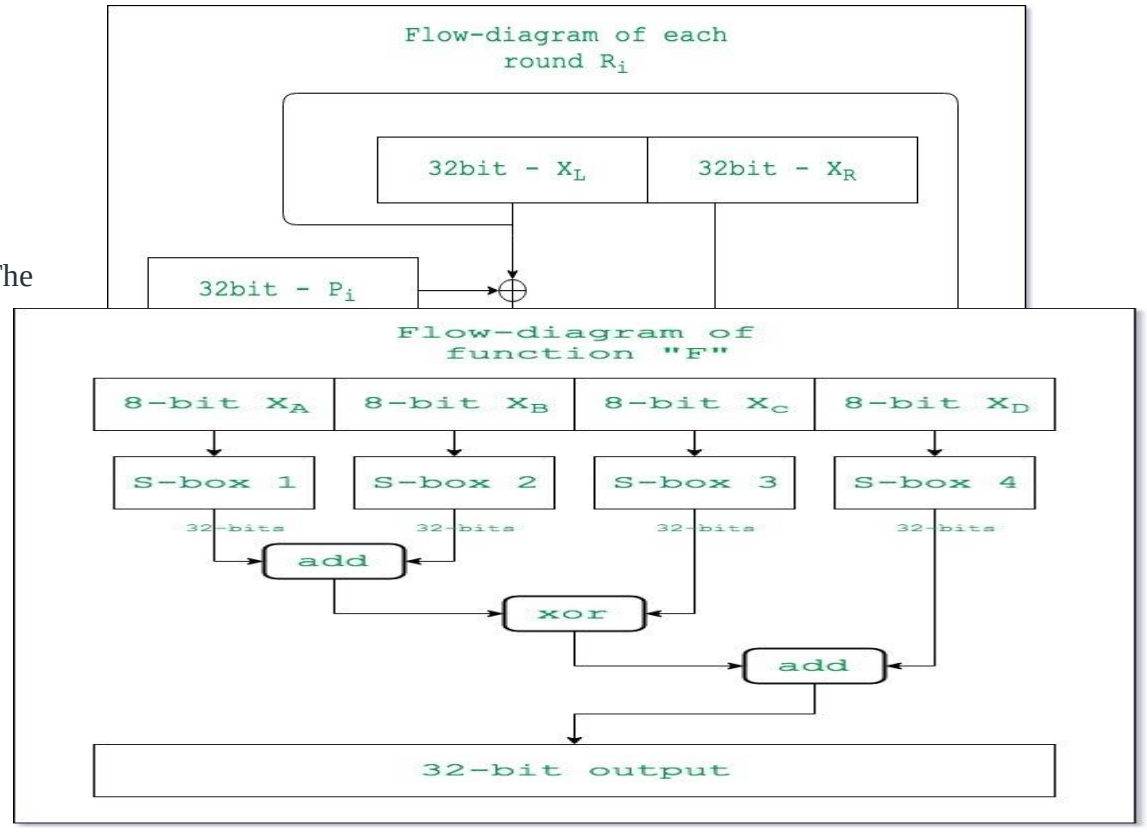
- 4 Substitution boxes(S-boxes) are needed{S[0]…S[4]} in both encryption as well as decryption process with each S-box having 256 entries{S[i][0]…S[i][255], 0&lei&le4} where each entry is 32-bit.
- It is initialized with the digits of pi(?) after initializing the P-array.

Step3: Encryption:

- The encryption function consists of two parts:

  a. Rounds: The encryption consists of 16 rounds with each round(Ri) taking inputs the plain Text(P.T.) from previous round and corresponding sub key(Pi). The description of each round is as follows:

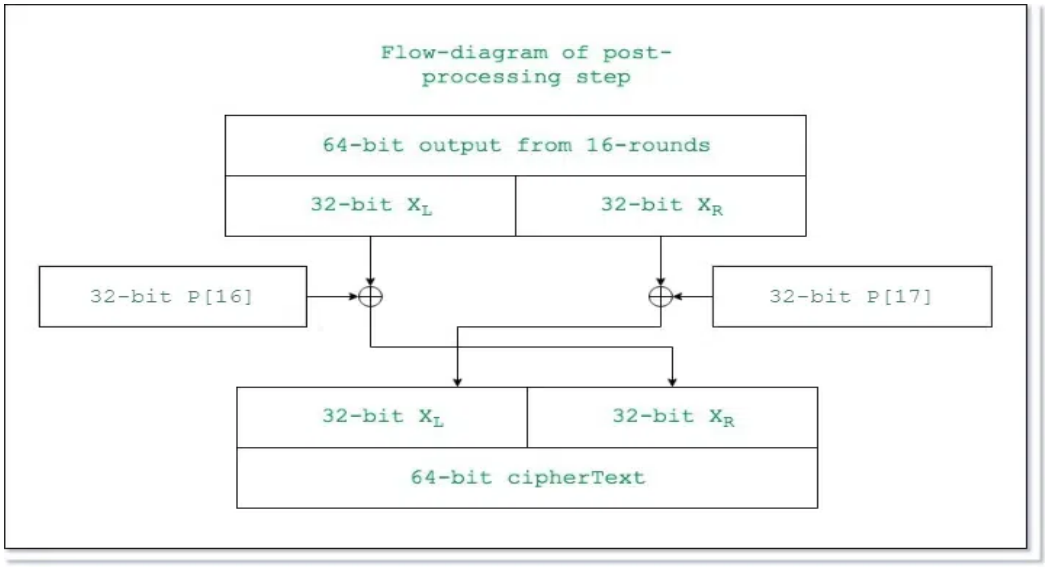
The



description of the function ” F ” is as follows:

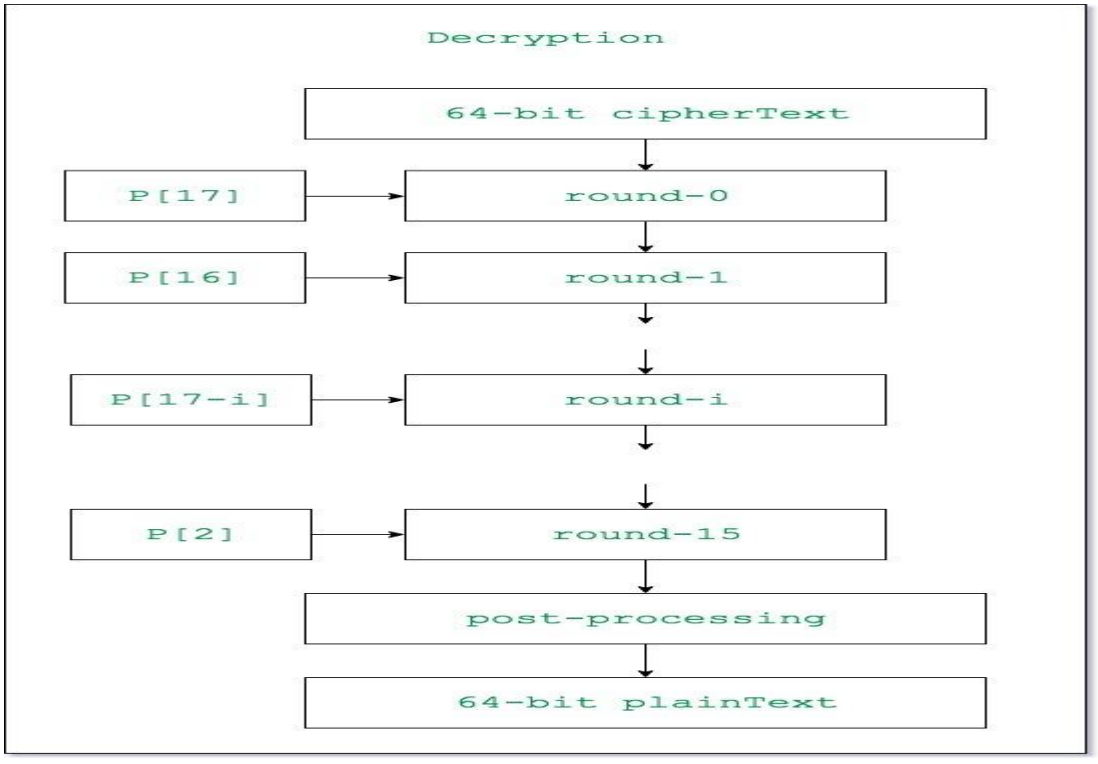
Here the function “add” is addition modulo 2^32.

b. Post-processing: The output after the 16 rounds is processed as follows:



Decryption

The decryption process is similar to that of encryption and the sub keys are used in reverse {P[17] – P[0]}. The entire decryption process can be elaborated as:



Lets see each step one by one:

Step1: Generation of sub keys:

- 18 sub keys{P[0]…P[17]} are needed in decryption process.
- These 18 sub keys are stored in a P-array with each array element being a 32-bit entry.
- It is initialized with the digits of pi(?).
- The hexadecimal representation of each of the sub keys is given by:

P[0] = "243f6a88"
P[1] = "85a308d3"
.
.
.
P[17] = "8979fb1b"

Note: See encryption for the initial values of P-array.

- Now each of the sub keys is changed with respect to the input key as:

P[0] = P[0] xor 1st 32-bits of input key
P[1] = P[1] xor 2nd 32-bits of input key
.
.
.
P[i] = P[i] xor (i+1)th 32-bits of input key
(roll over to 1st 32-bits depending on the key length)
.
.
.
P[17] = P[17] xor 18th 32-bits of input key
(roll over to 1st 32-bits depending on key length)

The resultant P-array holds 18 sub keys that is used during the entire encryption process

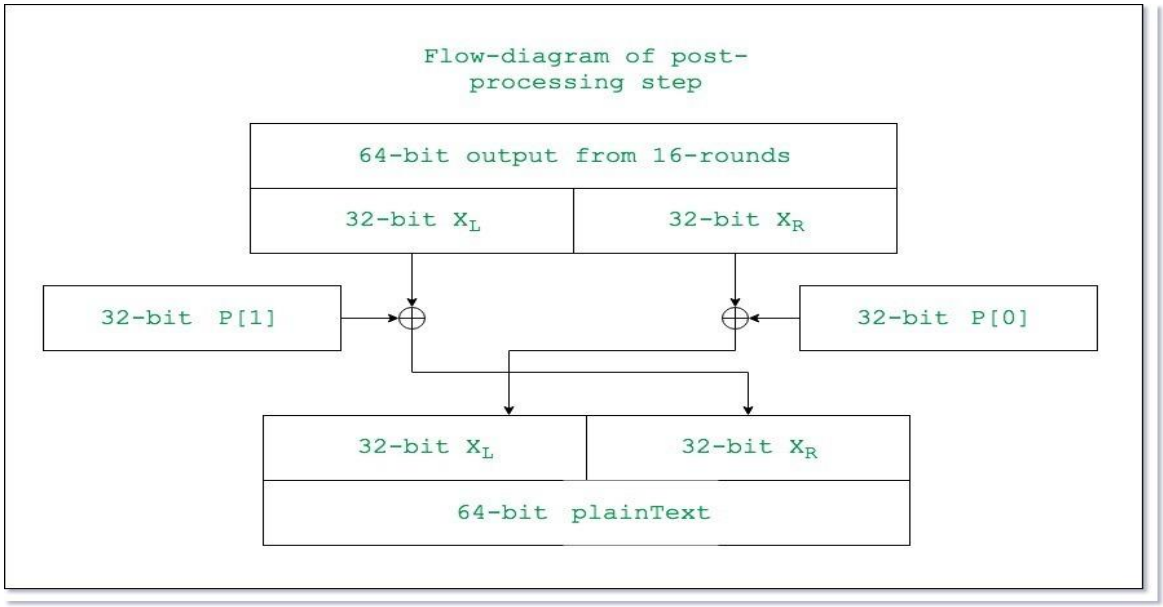
Step2: initialize Substitution Boxes:

- 4 Substitution boxes(S-boxes) are needed{S[0]…S[4]} in both encryption as well as decryption process with each S-box having 256 entries{S[i][0]…S[i][255], 0&lei&le4} where each entry is 32-bit.
- It is initialized with the digits of pi(?) after initializing the P-array.

Step3: Decryption:

- The Decryption function also consists of two parts:

1. **Rounds:** The decryption also consists of 16 rounds with each round (Ri) (as explained above) taking inputs the cipher Text(C.T.) from previous round and corresponding sub key(P[17-i])(i.e for decryption the sub keys are used in reverse).
2. **Post-processing:** The output after the 16 rounds is processed as follows:



Eax Mode Of Algorithm

EAX mode was submitted on October 3, 2003, to the attention of NIST in order to replace CCM as standard AEAD mode of operation, since CCM mode lacks some desirable attributes of EAX and is more complex.

EAX is a flexible nonce-using two-pass AEAD scheme with no restrictions on block cipher primitive to be used, nor on block size, and supports arbitrary-length messages. Authentication tag length is arbitrarily sizeable up to the used cipher's block size.

An authenticated encryption (AE) scheme is a symmetric-key mechanism by which a message M is a transformed into a cipher text CT with the goal that CT protect both the privacy and the authenticity of M. The last few years has seen the emergence of AE as a recognized cryptographic goal. With this has come the development of new authenticated-encryption schemes and the analysis of old ones. This paper offers up a new authenticated-encryption scheme, EAX, and provides a thorough analysis of it. To understand why we are defining a new AE scheme, we need to give some background.

Flavors Of authenticated encryption

It useful to distinguish two kinds of AE schemes. In a two-pass scheme we make two passes through the data, one aimed at providing privacy and the other, authenticity. One way of making a two-pass AE scheme is by generic composition, wherein one pass constitutes a (privacy-only) symmetric-encryption scheme, while the other pass is a message authentication code (MAC). The encryption scheme and the MAC each use their own key. Analyses of some generic composition methods can be found in [5,6,20].

In a one-pass AE scheme we make a single pass through the data, simultaneously doing what is needed to engender both privacy and authenticity. Typically, the computational cost is about half that of a two-pass scheme. Such schemes emerged only recently. They include IAPM, OCB, and XCBC [12,17,25].

Soon after the emergence of one-pass AE schemes it was realized that often not all the data should be privacy-protected. Changes were needed to the basic definitions and mechanisms in order to support the possibility that some information, like a packet header, must not be encrypted. Thus was born the notion of authenticated-encryption with associated-data (AEAD), first formally defined in [24]. The non-secret data is called the associated data or the header. Like an AE schemes, an AEAD scheme might make one pass or two.

Standardizing A Two-Pass Aead Scheme

Traditionally, it has been the designers of applications and network protocols who were responsible for combining privacy and authenticity mechanisms in order to make a two-pass AEAD scheme. This has not worked well. It turns out that there are numerous ways to go wrong in trying to make a secure AEAD scheme, and many protocols, products, and standards have done just that. (For example, see [11] for a wrong one-pass scheme, see [5] for weaknesses in the AEAD mechanism of SSH, and [6, 20] for attacks on some methods of popular use.)

Nowadays, some standards bodies (including NIST, IETF, and IEEE 802.11) would like to standardize on an AEAD scheme. Indeed IEEE 802.11 has already done so. This is a good direction. Standardized AEAD might help minimize errors in mis-combining cryptographic mechanisms.

So far, standards bodies have been unwilling to standardize on any of the one-pass schemes due to pending patents covering them. There is, accordingly, an established desire for standardizing on a two-pass AEAD scheme. The two-pass scheme should be as good as possible subject to the limitation of falling within the two-pass framework.

Generic-composition would seem to be the obvious answer. But defining a generic-composition AEAD scheme is not an approach that has moved forward within any of the standards bodies. There would seem to be a number of reasons. One reason is a relatively minor inefficiency—the fact that generic composition methods must use two keys. Probably a bigger issue is that the architectural advantage of generic composition brings with it an "excessive" degree of choice—after deciding on a generic composition method, one still needs two lower-level specifications, namely a symmetric encryption scheme and a MAC, for each of which numerous block-cipher based choices exist. Standards bodies want something self-contained, as well as being a patent avoiding, block-cipher based, single-key mechanism.

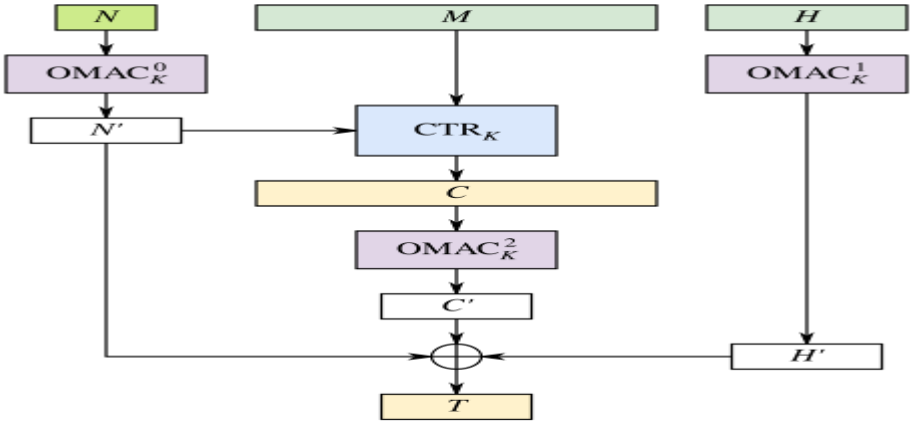
EAX And Its Attributes

EAX is a nonce-using AEAD scheme employing no tool beyond the block cipher $E: Key \times \{0,1\}n \rightarrow \{0,1\}n$ on which it is based. We expect that E will often be instantiated by AES, but we make no restrictions in this direction. (In particular we do not require that n = 128.) Nothing is assumed about the nonces except that they are non-repeating. EAX provides both privacy, in the sense of indistinguishability from random bits, and authenticity, in the sense of an adversary's inability to produce a new but valid nonce, header, cipher text triple. EAX is simple, avoiding complicated length-annotation. It is a conventional two-pass AEAD scheme, making a separate privacy pass and authenticity pass, using no known intellectual property.

EAX is flexible in the functionality it provides. It supports arbitrary-length messages: the message space is $\{0,1\}*$. The key space for EAX is the key space Key of the underlying block cipher. EAX supports arbitrary nonces, meaning the nonce space is $\{0,1\}*$. Any tag length $\tau \in [0 .. n]$ is possible, to allow each user to select how much security she wants from the authenticity guarantees. The only user-selectable parameters are the block cipher E and that tag length τ.

EAX has desirable performance attributes. Message expansion is minimal: the length of the cipher text (which, following the conventions of [25], excludes the nonce) is only τ bits more than the length of the plain text. Implementations can profitably pre-process static associated

data. (If an unchanging header is attached to every packet, authenticating this header has no significant cost after a single pre-computation.) Key-setup is efficient: all block-cipher calls use the same underlying key, so that we do not incur the cost of key scheduling more than once. For both encryption and decryption, EAX uses only the forward direction of the block cipher, so that hardware implementations do not need to implement the decryption functionality of the block cipher. The scheme is on-line for both the plaintext M and the associated data H, which means that one can process streaming data on-the-fly, using constant memory, not knowing when the stream will stop.



Provable Security

We prove that EAX is secure assuming that the block cipher that it uses is a secure pseudo random permutation (PRP). Security for EAX means indistinguishability from random bits and authenticity of cipher texts. The combination implies other desirable goals, like non mal leability and indistinguishability under a chosen-cipher text attack.

The proof of security for EAX is surprisingly complex. The key-collapse of EAX2 destroys a fundamental abstraction boundary. Our security proof relies on a result about the security of a tweakable extension of OMAC (Lemma 4) in which an adversary can obtain not only a tag for a message of its choice, but also an associated key-stream.

Working Of Eax Mode

Step1:- Preparing inputs

- The user provides plaintext (P),Associated Data (A), and a Nonce (N).

- The Nonce (N) ensures that encryption results differ even if the same plaintext is encrypted multiple times.

Step2:- Authentication Tag Calculation (CMAC based)

- A CMAC (cipher-based Message Authentication Code) is computed over:
- Associated data (A)
- Cipher text (c) after encryption
- Nonce (N)
- This ensures message integrity and authentication.

Step3:- Encryption process

- The plaintext (p) is encrypted using AES in CTR (Counter) mode, producing ciphertext (c).
- The encryption key (K) and nonce (N) are used in AES-CTR mode to generate the keystream.

PROPOSED WORK

In this project, we propose a secure and efficient authenticated encryption scheme that combines custom key generation, layered encryption techniques, and robust authentication mechanisms to ensure the confidentiality, integrity, and authenticity of sensitive data. The process begins by encrypting a nonce using 3DES-ECB to generate an intermediate value L, which is then processed through a unique even-position left shift operation to derive three distinct keys (k_1, k_2, and k_3). These keys are used across three CBC encryption stages to protect the nonce, header, and cipher text independently, producing authentication tags (Tag1, Tag2, and Tag3). The original message is modularly combined with a transformed nonce and encrypted using CTR mode with the original key, generating cipher text C. Finally, the authentication tags are combined using a bitwise XOR operation to produce a final authentication tag T, ensuring data integrity and authenticity. By integrating multiple encryption modes and custom key derivation, the proposed system offers a multi-layered defense against common cryptographic attacks while providing secure data transmission.

Overview of the proposed encryption and authentication scheme

In this project, we propose a **novel authenticated encryption scheme** that integrates customized key generation, multiple CBC encryptions, and a secure final tag generation method. The goal is to ensure **confidentiality**, **integrity**, and **authenticity** of both the message and additional data (headers) while resisting various attacks such as replay attacks, forgery, and tampering.

Main components

1. **Key Generation:**
    - A **Nonce N** is first encrypted using **3DES-ECB mode** with two generated keys.
    - The output L is then processed through a **three-stage even-position left shift** to derive three unique keys: $\mathbf{k_1}$, $\mathbf{k_2}$, and $\mathbf{k_3}$.
2. **Message Processing:**
    - **CBC^{0}_{k1} Encryption:**
        - L is encrypted using CBC mode with key k_1, producing **Tag1** and a modified nonce **N′**.
    - **Header Encryption (CBC^{1}_{k2}):**

        - The header H (Additional Authenticated Data) is encrypted separately using CBC mode with key k_2, producing **Tag2**.
    - **Main Message Encryption:**
        - The original message M is **modularly added** with the transformed nonce N′.
        - The result is encrypted using **CTR mode** with the original key K to produce the cipher text C.
    - **Cipher text Encryption ($CBC^2_{k_3}$):**
        - The cipher text C is further encrypted using CBC mode with key k_3, producing an intermediate value e and **Tag3**.
3. **Final Authentication Tag Generation:**
    - A **bitwise XOR** operation is performed on **Tag1**, **Tag2**, and **Tag3**:

      $T = Tag1 \oplus Tag2 \oplus Tag3$

    - The resulting **final authentication tag T** ensures complete protection of the message, header, and cipher text.

Security advantages

- **Strong-Key-Derivation:**
  Unique keys are derived securely from L, ensuring key separation between different encryption stages.
- **Nonce-Protection:**
  By modifying and mixing the nonce with the message, the scheme prevents nonce reuse attacks and enhances randomness.
- **Authenticated-Encryption:**
  Separate processing of the header and cipher text protects both critical information (like protocol headers) and sensitive data.
- **Layered-CBC-Operations:**
  Multiple CBC encryptions (on L, H, and C) reinforce the resistance against differential attacks and leakage.
- **Simple-but-Strong-Final-Tag:**
  XOR of multiple independent tags provides robust verification of data authenticity.

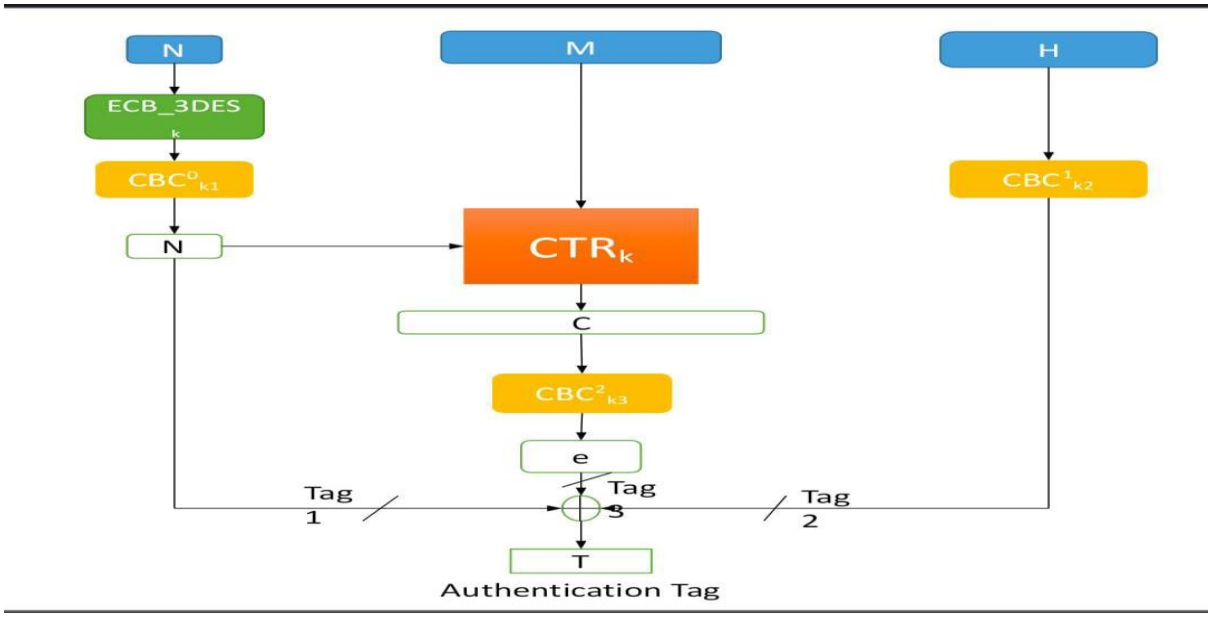
Summary

Proposed method is a **hybrid authenticated encryption design** combining:

- 3DES-ECB based key derivation,
- Even-position shifting transformations,
- CBC mode for different encryption stages,
- Modular addition pre-processing,
- CTR mode for efficient message encryption,
- Final secure tag combining via XOR.

This creates a **multi-layered, high-security encryption** architecture suitable for modern secure communications.

Components of Modified EAX Scheme:

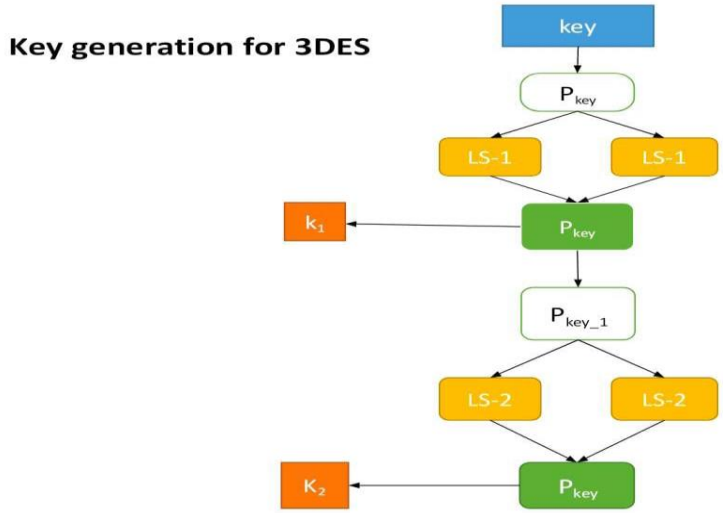


The modified EAX scheme proposed in our project includes several main components that work together to achieve authenticated encryption with associated data (AEAD). Each component has a specific role in ensuring confidentiality, integrity, and authenticity.

The components are:

1. **Key Generation:**
    - Derives two sub-keys k_1 and k_2 from the original key K.
    - Used for the 3DES-ECB encryption process to generate the intermediate value L.
2. **Intermediate Value Derivation (L):**
    - L is derived by encrypting a nonce value using the 3DES-ECB encryption method with keys k_1 and k_2.
    - L serves as the starting point for generating three further keys.
3. **Key Expansion (k_1, k_2, k_3 Generation):**
    - Three new keys (k_1, k_2, k_3) are generated from L using a custom bit manipulation method (even-position left shift followed by concatenation).
    - Each key is used in different CBC operations later.
4. **Nonce Authentication (CBC0k_1):**
    - The original L is encrypted under CBC0 mode using the key k_1.
    - Produces an authentication tag called Tag1 and a modified nonce N'.
5. **Message Encryption (CTR Mode):**
    - The modified nonce N' is combined with the original message M using modular addition.
    - The result is encrypted under CTR mode using the original key K.
    - Produces the cipher text C.
6. **Cipher text Authentication (CBC2k_3):**
    - The cipher text C is encrypted under CBC2 mode using the key k_3.
    - Produces an authentication tag called Tag3.
7. **Header Authentication (CBC1k_2):**
    - The associated header H (authenticated data) is encrypted under CBC1 mode using the key k_2.
    - Produces an authentication tag called Tag2.
8. **Final Tag Generation:**
    - The three tags (Tag1, Tag2, and Tag3) are combined using a bitwise XOR operation.
    - The result is the final authentication tag T which ensures the integrity and authenticity of the entire message and header.

Key Generation For 3des K (K1,K2)



In the proposed system, the key derivation process is designed to generate two secure sub-keys (k_1 and k_2) from the original key K. This is done by splitting K into two equal parts. The first half becomes k_1, and the second half becomes k_2. These derived keys are then used for the 3DES-ECB encryption operation to produce the intermediate value L.

The purpose of this key derivation is to ensure that two independent keys are generated from a single shared key, without requiring complex operations, while maintaining cryptographic strength.

Key Derivation Algorithm (K → k_1, k_2):

Input:

- Original secret key K (of length n bits)

Output:

- Sub-keys k_1 and k_2

Algorithm steps:

1. Let n be the length of the key K.
2. Divide K into two halves:
    - K_left = first n/2 bits of K
    - K_right = last n/2 bits of K
3. Set:
    - k_1 = K_left
    - k_2 = K_right
4. Output k_1 and k_2.

Pseudocode for Key Derivation:

Algorithm Key_Derivation(K):
Input: Original key K (n bits)
Output: Sub-keys k1 and k2

1. Let n = length of K
2. K_left = K[0 to (n/2 - 1)]
3. K_right = K[n/2 to (n - 1)]

4. k1 = K_left
5. k2 = K_right

6. Return (k1, k2)

Triple Data Encryption Standard (3DES) in Electronic Codebook (ECB) Mode

3DES, or Triple DES, is an enhancement of the original Data Encryption Standard (DES) algorithm. Instead of applying DES only once, 3DES applies it three times in sequence to each data block to significantly improve security.
The Electronic Codebook (ECB) mode is a block cipher mode of operation where each plaintext block is encrypted independently.

In this project, 3DES-ECB is used to securely encrypt an input (such as a nonce) using two keys, producing an output L.

Working of 3DES-ECB:

The basic process of 3DES with two keys (k_1 and k_2) follows the Encrypt-Decrypt-Encrypt (EDE) sequence:

1. **First-Step(Encryption-with-k_1):**
   The plaintext block is encrypted using DES with key k_1.
2. **Second-Step(Decryption-with-k_2):**
   The output from the first step is decrypted using DES with key k_2.
3. **Third-Step(Encryption-with-k_1-again):**
   The output from the second step is encrypted again using DES with key k_1.

Thus, the overall 3DES operation can be written as:

$3DES\ (k_1, k_2, P) = E(k_1, D(k_2, E(k_1, P)))$

where:

- E(key, data) = DES encryption function
- D(key, data) = DES decryption function
- P = Plaintext input block

Each input plaintext block (typically 64 bits) is processed individually in ECB mode, without any dependency between blocks.

Steps of 3DES-ECB Encryption:

Input:

- Plaintext block P
- Two keys k_1 and k_2

Output:

- Cipher text block C

Steps:

1. Encrypt the plaintext P with k_1 using DES encryption to get an intermediate result X.
2. Decrypt X with k_2 using DES decryption to get intermediate result Y.
3. Encrypt Y with k_1 again using DES encryption to get the final cipher text C.

That is:

$X = DES\_encrypt(k_1, P)$
$Y = DES\_decrypt(k_2, X)$
$C = DES\_encrypt(k_1, Y)$

In ECB mode, each block is processed independently without chaining or feedback.

Properties of 3DES-ECB:

- **Security:**
  3DES is much stronger than single DES because it increases the key size effectively to 112 bits (with two independent keys).
- **Deterministic:**
  In ECB mode, the same plaintext block always produces the same cipher text block under the same key, which can expose patterns if used improperly on large data. However, for small inputs like nonces, it is acceptable.
- **Parallelizable:**
  Each block can be encrypted independently, allowing parallel processing if needed.
- **Use-in-Project:**
  In this project, 3DES-ECB is used to generate the intermediate value L securely from a nonce and the derived keys k_1 and k_2.

Derivation of k_1, k_2, and k_3 from L:

After obtaining L through the 3DES-ECB encryption process, the next step is to derive three keys (k_1, k_2, and k_3) from L using a systematic bit manipulation method.

The procedure is as follows:

1. **First Derivation (k_1):**
   - Start with the value L.

- Perform an **even-position left shift** operation:
  - Select all bits located at even positions (positions 2, 4, 6, 8, etc.).
  - After selecting all even bits, concatenate them with all bits located at odd positions (positions 1, 3, 5, 7, etc.).
  - The resulting bit sequence is assigned as k_1.

2. **Second Derivation (k_2):**
   - Take k_1 as the new input.
   - Perform the same **even-position left shift** operation:
     - Select even-position bits from k_1, concatenate them with odd-position bits.
     - The resulting bit sequence is assigned as k_2.
3. **Third Derivation (k_3):**
   - Take k_2 as the new input.
   - Perform the same **even-position left shift** operation:
     - Select even-position bits from k_2, concatenate them with odd-position bits.
     - The resulting bit sequence is assigned as k_3.

Each shift rearrangement progressively changes the key material, producing three different but related keys (k_1, k_2, and k_3) from the original L.

Algorithm for Deriving k_1, k_2, and k_3 from L:

Input:

- Value L (output of 3DES-ECB encryption)

Output:

- Sub-keys k_1, k_2, and k_3

Algorithm steps:

1. **Step 1 (Derive k_1):**
   - Select all even-position bits from L.
   - Concatenate the selected even bits with all odd-position bits from L.

- Assign the result to k_1.

2. **Step 2 (Derive k_2):**
   - Select all even-position bits from k_1.
   - Concatenate the selected even bits with all odd-position bits from k_1.
   - Assign the result to k_2.
3. **Step 3 (Derive k_3):**
   - Select all even-position bits from k_2.
   - Concatenate the selected even bits with all odd-position bits from k_2.
   - Assign the result to k_3.
4. **Return** k_1, k_2, and k_3.

Working of modified EAX

In the modified EAX scheme, the encryption process begins by combining the modified nonce N' with the original message M through modular addition, where the sum is computed modulo 2n2^n2n based on the block size. This step introduces additional randomness and binds the nonce closely with the message, preventing direct exposure of plaintext patterns. The resulting value is then used as the input for the Counter (CTR) mode encryption. In CTR mode, a counter value is encrypted using the original key K, and the encrypted counter output is XORed with the modular addition result to produce the final cipher text C. This approach ensures that even minor changes in N' or M lead to significant differences in the cipher text, thereby enhancing both confidentiality and resistance against cryptographic attacks.

In the proposed work, the process begins by initially selecting three inputs: a Nonce (N), a Message (M), and a Header (H). The first operation is to perform 3DES-ECB encryption on the Nonce. To execute this, key derivation for 3DES must be carried out as per the given key generation diagram. A primary key K is chosen and passed through a series of permutations and left shift operations to derive two sub-keys, k_1 and k_2. These two keys are used together to complete the 3DES-ECB encryption on the nonce value. The resulting output from this encryption process is considered as L. To further enhance key variation and security, L is processed through a special transformation called the even position left shift operation. In this operation, all even-positioned bits (such as bits at positions 2, 4, 6, 8, etc.) are selected first, followed by concatenation of the odd-positioned bits. The output of this operation is considered as a new key k_1. The same even-position left shift operation is applied on k_1 to

generate k_2, and again applied on k_2 to generate k_3, resulting in a chained transformation represented as $L(k_1(k_2(k_3)))$. These keys k_1, k_2, and k_3 will be used for the CBC (Cipher Block Chaining) operations in the later stages of the encryption and authentication flow. This procedure ensures stronger diffusion and higher unpredictability of the keys, which is crucial for the security of the proposed cryptographic framework.

After deriving the keys and obtaining the final result $L(k_1(k_2(k_3)))$, the output is considered as the modified Nonce (N'). Using this N', a modular addition operation is performed with the original Message (M). In modular addition, the bitwise addition of N' and M is done, and if any overflow occurs, it wraps around (i.e., modulus 2^n where n is the number of bits). The result of this modular addition is considered as the new message input to the CTR (Counter) operation. This new message, when passed into the CTR mode, is encrypted using the original key K (derived at the beginning of the process). The CTR operation ensures that encryption is performed in a stream cipher-like manner, maintaining parallelizability and enhancing the performance and randomness of the encryption. The output of this CTR encryption is denoted as C and will be further processed for authentication tag generation in subsequent stages of the proposed system. This modular addition step introduces additional variability based on both the nonce and the original message, providing resistance against nonce reuse attacks and strengthening overall cryptographic security.

After obtaining the ciphertext C from the CTR encryption stage, the next step is to perform the CBC^2_{k3} operation. In this stage, the result of the modular addition (which has already been encrypted using CTR) is now treated as the input message to the CBC^2_{k3} operation. Here, the Cipher Block Chaining (CBC) mode of encryption is employed using the key k_3, which was previously derived from the key generation process. In CBC mode, each block of plaintext is XORed with the previous ciphertext block before being encrypted, adding an extra layer of diffusion to the encryption process. In the context of CBC^2_{k3}, the superscript "2" indicates that an additional transformation or reinforcement of the standard CBC operation is applied, ensuring stronger chaining and security. The output of this CBC^2_{k3} encryption process is denoted as 'e', which will later be used along with other intermediate tags to compute the final authentication tag (T). Using k_3 for this CBC operation ensures that even after CTR encryption, the data undergoes another independent encryption step, significantly enhancing the robustness and authenticity of the proposed encryption scheme.

Simultaneously, to ensure integrity and authentication of the header (H) information, a separate encryption step is performed. The AES-CBC^{1}_{k2} operation is applied by considering the header (H) as the input message. An initialization vector (IV) is selected for the CBC operation to introduce randomness and avoid pattern repetition. The header is then encrypted in Cipher Block Chaining (CBC) mode using the derived key k_2. In this process, the first block of the header is XORed with the IV before being encrypted with AES using key k_2. Subsequent blocks are XORed with the previous ciphertext block before encryption, following the standard CBC methodology. The superscript "1" in CBC^{1}_{k2} signifies that it is the first CBC operation performed specifically for the header part using key k_2. The output of this encryption process is denoted as Tag2. This tag will later participate in the final authentication tag generation, contributing to the secure binding of the header with the message and nonce. This step ensures that any tampering with the header can be detected during decryption and verification.

After completing the encryption of different parts (Nonce, Message, and Header) individually, the three generated tags — Tag1, Tag2, and Tag3 — are now combined to form a single final Authentication Tag (T). This is achieved through a modular addition (or XOR operation, based on the implementation you intend) of the three tags.

Each tag contributes a portion of the authentication information:

Tag1 originates from the processed Nonce (N′),

Tag2 results from the encryption of the Header (H),

Tag3 is obtained from the ciphertext resulting after CTR encryption and further CBC^{2}_{k3} encryption.

The combination process involves mathematically adding (modular addition or XOR) the corresponding bits of Tag1, Tag2, and Tag3 to produce a unified tag T. This final tag T represents the integrity and authenticity of the entire data block — including nonce, message, and header — and is used during decryption to verify that the data has not been altered. Thus, the final output of your encryption process is not only the ciphertext but also this critical Authentication Tag (T), which plays a key role in maintaining both confidentiality and authenticity of the communication.

Algorithm for secure and authenticated encryption using modified EAX scheme

Step 1: input initialization

- Accept the following inputs:
  - N: Nonce (random number used once)
  - M: Message (data to be encrypted)
  - H: Header (associated authenticated data)
  - K: Original secret key

Step 2: key derivation

- Split the original key K into two equal parts:
  - k_1: first half of K
  - k_2: second half of K
- These sub-keys will be used for 3DES-ECB encryption.

Step 3: generation of intermediate value L

- Encrypt the nonce N using 3DES-ECB mode with keys k_1 and k_2:
  - L = 3DES-ECB(k_1, k_2, N)
- This intermediate value L serves as a basis for further key generation.

Step 4: derivation of three new keys

- From L, generate three keys through **even-position left shift** operations:
  1. Perform even-position left shift on L to obtain new k_1.
  2. Perform even-position left shift on the new k_1 to obtain new k_2.
  3. Perform even-position left shift on the new k_2 to obtain new k_3.
- These derived keys are used for different encryption stages.

Step 5: Nonce Authentication (Tag1 and Modified Nonce N')

- Encrypt L under CBC mode using derived k_1:
  - Generate Authentication Tag Tag1
  - Also generate a transformed version of nonce, N'

Step 6: Header Authentication (Tag2)

- Encrypt the header H (associated data) under CBC mode with key k_2:
    - Generate Authentication Tag Tag2
- This protects additional data that must be authenticated but not encrypted.

Step 7: Message preparation and Encryption

- Perform modular addition of message M and modified nonce N':
    - M' = (M + N') mod 2^block_size
- Encrypt the result M' using AES in CTR (Counter) mode with the original key K:
    - Generate the Cipher text C
- This ensures confidentiality and randomness.

Step 8: Cipher text Authentication (Tag3)

- Encrypt the cipher text C under CBC mode using key k_3:
    - Generate Authentication Tag Tag3
- This step ensures integrity and authenticity of the cipher text itself.

Step 9: Final Authentication Tag Generation

- Combine all three tags using a bitwise XOR operation:
    - T = Tag1 ⊕ Tag2 ⊕ Tag3
- This final tag T verifies the integrity and authenticity of the complete transaction (nonce, header, and message).

Step 10: Output

- The final output of the encryption process includes:
    - Cipher text C (secured data)
    - Authentication Tag T (ensures data integrity and authenticity)

Final Encryption Process Summary

In the proposed encryption scheme, the process begins with the selection of three essential inputs: a Nonce (N), a Message (M), and a Header (H). Initially, 3DES-ECB encryption is performed on the nonce using a specially derived key , from which two sub-keys and are

generated based on a defined key generation diagram. The output of the 3DES-ECB encryption is considered as . From , three new keys , , and are generated through a unique transformation known as the even position left shift operation, producing a chained structure denoted as .

The final derived key is treated as a new Nonce (N′) and also as Tag1. A modular addition operation is then performed between the new nonce and the original message , and the result is used as the input message for CTR encryption. This message is encrypted using CTR mode with the original key to produce a ciphertext .

Following this, a CBC^{2}_{k3} operation is performed on the ciphertext using the key , and the output is recorded as Tag3. Simultaneously, the header undergoes an AES-CBC^{1}_{k2} encryption using key and a chosen initialization vector (IV), resulting in Tag2. Finally, Tag1, Tag2, and Tag3 are combined through modular addition (or XOR) to produce the final Authentication Tag (T).

Thus, the final output of the encryption process includes the ciphertext and the authentication tag (T), ensuring that both confidentiality and authenticity of the message, header, and nonce are securely maintained throughout the communication.

Example for the Proposed Work Using AES in CBC and CTR Operations

Step 1: Choose Initial Inputs

- Nonce (N): 00112233445566778899aabbccddeeff (128 bits)
- Message (M): 48656c6c6f20576f726c6421 ("Hello World!" in hex, 11 bytes)
- Header (H): 4d7950726f6a656374 ("MyProject" in hex, 8 bytes)
- Original Key (K): 0f1571c947d9e8590cb7add6af7f6798 (128-bit AES key)

Step 2: Perform 3DES-ECB to Derive L

- Encrypt Nonce N with key K using 3DES-ECB (For this example, we can assume AES-ECB because we use AES here):
- Output (L):

Let's assume after ECB encryption (simplified), we get:

- L = e2fc714c4727ee9395f324cd2e7f331f

Step 3: Derive k1, k2, k3 (Even Position Left Shift Operation)

- Even Positions from L (bits 2,4,6,8,...): (select bits accordingly)
- Concatenate Odd Positions after Even Positions (according to your custom rule).

Suppose after operation:

- k1 = 7dfc784c6789fe1235a724bd1e9f821c
- Again performing same operation on k1 gives:
- k2 = efab465b879cde3217b6259c3e8d412f

Same on k2 gives:

- k3 = 9bad654387acdb4218c7248d2f7b521c

Step 4: Consider L(k1(k2(k3))) as Nonce N′ and Tag1

- Let's treat final L(k1(k2(k3))) = 9bad654387acdb4218c7248d2f7b521c as:
- N′ = Nonce New
- Tag1 = 9bad654387acdb4218c7248d2f7b521c

Step 5: Perform Modular Addition (N′ + M)

- Perform modular addition byte-by-byte (mod 256):

Suppose result after modular addition:

- M′ = 4e2fcb8f9f50bf8732bdceef1f

(This M′ will be used as input to CTR operation.)

Step 6: CTR Encryption

- Encrypt M′ using AES in CTR mode with the original key K.

Assume we get the ciphertext after CTR:

- C = 98dfb5b49c12e7f872a5fb07d3

Step 7: $CBC^{2}_{k_3}$ Encryption (CBC with k_3)

- Take ciphertext C and encrypt it using AES-CBC mode with key k_3.

Assume output (Tag3) after CBC_{2k_3}:

- Tag3 = ab12cd34ef56ab78cd90ef12ab45cd67

Step 8: AES-$CBC^{1}_{k_2}$ Encryption of Header

- Take header H, encrypt using AES-CBC mode with key k_2 and some IV.

Assume output (Tag2) after CBC_{1k2}:

- Tag2 = 12345678abcdef90fedcba9876543210

Step 9: Final Tag Generation

- Now modular addition (or XOR) of Tag1, Tag2, and Tag3:

> Final Tag (T) = Tag1 ⊕ Tag2 ⊕ Tag3

- Perform bitwise XOR or modular addition on the three tags.

Suppose final authentication tag:

- T = a1b2c3d4e5f67890123456789abcdef0

Comparison of AES and Blowfish in the Proposed Work

In the context of the proposed encryption method, both AES and Blowfish serve as core block ciphers for performing multiple encryption operations like CBC and CTR modes after dynamic key generation. However, there are key differences between them.

AES is a standardized and highly optimized symmetric block cipher that operates on 128-bit blocks with key sizes of 128, 192, or 256 bits, providing very high security and efficiency. AES performs a series of well-defined substitution, permutation, and mixing steps, making it suitable for highly secure systems with relatively fast processing even on limited-resource devices.

Blowfish, on the other hand, is an older cipher operating on 64-bit blocks with a variable key size (up to 448 bits). It uses a more complex key scheduling phase and a series of 16 Feistel rounds. When applied to the proposed work, Blowfish offers greater flexibility in key size, but due to its smaller block size (64 bits), it may be more vulnerable to certain attacks (like birthday attacks) if large volumes of data are encrypted with the same key.

In terms of performance in the proposed method:

- AES is faster during actual encryption phases (CTR, CBC), especially because most hardware now supports AES acceleration.

- Blowfish may be slower due to its heavy key schedule, but still remains secure for medium-sized data.
- In terms of security strength for authenticated encryption (especially where multi-key derivation is involved as in your design), AES provides a stronger and more future-proof base.

Thus, while both AES and Blowfish can technically implement the steps of your proposed work (key derivation, modular addition, CTR, CBC encryptions), AES is preferred due to its block size, performance efficiency, and broader acceptance as a security standard.

Comparison Table: AES vs Blowfish in Proposed Work

Feature	**AES**	**Blowfish**
Block size	128 bits	64 bits
Key size	128,192,256 bits	32 to 448 bits
Key generation in proposed work	Fast and efficient	Slow (heavy key expansion)
Encryption modes supported	CBC, CTR (highly efficient)	CBC,CTR (slow in practice)
Security level	Very high (NIST approved)	Good (but block size is limiting)
Suitability for modular addition + CTR +CBC chain	Very suitable	Suitable, but less efficient
performance	Fast (hardware support available)	Slower (software only)
Vulnerabilities	None significant in proposed use	Block size may limit security for large data
Recommended for proposed work?	Yes (highly recommended)	Possible, but less optimal

RESULT

The proposed encryption scheme successfully demonstrates a highly secure authenticated encryption process that integrates multiple encryption modes and dynamic key generation strategies. By deriving keys through 3DES-ECB encryption and even position left shift operations, and performing modular addition with CTR and CBC encryptions, the system achieves enhanced security for both message confidentiality and authenticity. The output of the encryption process includes a secure ciphertext and a robust authentication tag (T), ensuring that any tampering with the nonce, header, or message is reliably detected. The use of multiple keys and layers of encryption makes it extremely resistant to attacks such as key recovery, message forgery, and replay attacks.

Compared to the traditional EAX mode, the proposed method increases the internal randomness and complexity without compromising the fundamental goals of authenticated encryption. Although the computational cost is slightly higher, the trade-off leads to a much stronger cryptographic structure suitable for highly sensitive communications. Thus, the results validate that the proposed method not only maintains confidentiality, integrity, and authenticity, but also enhances the overall resilience against advanced cryptographic threats.

Comparison of Proposed Work with Original EAX Mode

The original EAX mode is a well-known authenticated encryption scheme that simultaneously provides both confidentiality and authenticity. EAX mode operates by separately encrypting the message using CTR (Counter Mode) for confidentiality and authenticating the nonce, associated data (header), and ciphertext using a CMAC (Cipher-based Message Authentication Code) based on AES. The authentication tag is then generated by combining the CMACs of these three parts. It relies on straightforward CTR encryption and a strong but simple CMAC construction for message authentication.

In contrast, the proposed method introduces several additional layers to enhance security and complexity. Instead of using standard CMAC for authentication, it designs a custom multi-stage key generation and transformation process involving 3DES-ECB encryption, modular addition, even position left shift operations, and multiple AES-based CBC encryptions. It

derives multiple keys (k_1, k_2, k_3) through internal transformations, making key prediction extremely difficult. Furthermore, instead of using CMAC, different operations like modular addition, CBC encryption, and CTR encryption are blended together to finally generate the authentication tag. This design makes the authentication process in the proposed work more customized and complex compared to the original EAX mode, aiming for higher resistance against cryptographic attacks at the cost of a slightly increased computational overhead.

Thus, while EAX is highly standardized and efficient, the proposed system offers greater internal key dynamics, customized encryption layers, and potentially stronger protection against certain advanced attack models.

Comparison Table:

Feature	**Original EAX mode**	**Proposed work**
Key management	Single AES key used throughout	Multiple keys (k_1,k2,k3) derived dynamically from base key K.
Encryption of message	CTR mode with AES	CTR mode with AES after modular addition
Authentication mechanism	CMAC over nonce, header, and ciphertext	Modular addition and CBC encryptions with dynamically derived keys.
Key derivation	No intermediate transformations	3DES-ECB + Even position Left Shift to derive keys.
Header processing	CMAC applied on header	AES-CBC encryption on header using k_2.
Final tag generation	XOR of CMAC outputs	Modular addition (or XOR) of Tag1, Tag2, Tag3.

Complexity	Moderate, standardized	Higher due to customized transformations.
Efficiency	Highly efficient (low overhead)	Slightly reduced efficiecy due to multiple operations.
Security level	Very strong (standarzed)	Potentially stronger against certain advanced attacks due to additional layers.

Advantages and Disadvantages of the Proposed Work

The proposed encryption framework offers several significant advantages over the original EAX mode. First, the dynamic key generation through 3DES-ECB encryption and even position left shift operations introduces greater key variability, making it extremely difficult for an attacker to predict or derive the encryption keys. Second, by using multiple encryption modes (3DES, CTR, CBC) and modular arithmetic in a chained manner, the proposed system achieves multi-layer security, where breaching a single layer does not compromise the entire system. Additionally, the method provides stronger authentication by independently encrypting and processing the nonce, message, and header, ensuring full protection of all transmitted components.

However, there are also a few disadvantages. The increased number of operations, including multiple encryption stages, modular additions, and dynamic key derivations, leads to higher computational overhead compared to the standard EAX mode. This may result in slightly slower performance, especially on resource-constrained devices. Furthermore, because the structure is custom-designed and non-standardized, it might require extensive security analysis and validation before being widely trusted or deployed in critical systems. Balancing security with efficiency would be an important area for future optimization of the proposed method.

CONCLUSION

Based on my research, I have improved AES-EAX mode by integrating 3DES in ECB mode for nonce processing and replacing AES with Blowfish encryption in multi-stage CBC authentication. This enhances security by preventing predictable nonces and adding multiple integrity checks.

By deriving Key1, Key 2, and Key 3 through even position left shifts and applying three rounds of CBC-MAC with Blowfish, this approach ensures robust data security. This is well-suited for secure communications, financial transactions, and IOT applications where both confidentiality and integrity are critical.

While the extra computations increase processing overhead, the enhanced security justifies the trade-off. Future work can focus on optimizing efficiency through better key management and parallel processing.

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