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Original Article

Key Pre-Distribution Security Scheme for IIOT by using Hermitian Matrix

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ABSTRACT

In this article, authors introduced one of the basic pre-distribution key schemes with Hermitian matrices for Industrial IoT. With novel strategy, it is feasible to utilize singular attributes of Hermitian matrices over finite fields for discovery of common secrets with efficaciously working devices with constraint resources. Initially, it underwent performance analysis based on some of primary attributes such as energy consumption, computation time, memory usage, communication overhead, shared secret entropy, scalability within generation of keys within refresh requirement, and failure tolerance against a device. Simulation findings have confirmed that given scheme includes high shared secret entropy, and hence high sense of security based on strength against any form of predictability-based attack along with some other form of attacks. In addition, with low computation overhead and memory, the scheme also allows for low memory, so that acceptable efficiency is achieved with IIoT applications. In addition, findings also indicated strong scalability with reliability against device failures, and hence high reliability of a system with dynamic industrial conditions is achieved. This research work signifies potentiality of matrix-based cryptographic techniques, which are destined for overcoming issues in secure IIoT and big-scale key management.

Keywords: Hermitian matrix, IIOT, Key pre-distribution, Shared secret entropy, Power consumption in IIoT.

1 Introduction

The Industrial Internet of Things (IIoT) is transforming several industries by allowing autonomous device-to-device communication and collaboration. However, increased connectivity raises major issues about maintaining secure communication channels among devices with scarce resources. Traditional cryptographic key management techniques tend to find it challenging to obtain an acceptable balance among security, scalability, and efficiency, hence making them less effective for use within IIoT scenarios [1]. More generally, traditional approaches to cryptographic key management are unable to attain an acceptable balance among the aforementioned fundamental attributes, thereby making them less appropriate for deployment within IIoT scenarios [2]. In recent times, matrix-based cryptography has become a potential alternative, by making use of inherent matrix algebra structure for effective cryptographic key derivation and deployment [3, 4]. Within families of matrices explored so far, Hermitian matrices with symmetric and complex conjugate entry values provide unique benefits with regard to pre-distribution of keys. Notably, using Hermitian matrices over finite fields allows for secure derivation of shared secrets with a minimum of resource usage in terms of computation and storage [5]. In this paper, a novel Hermitian matrix-based pre-distribution scheme is presented, carefully crafted for IIoT networks. The suggested scheme overcomes a number of challenging issues, such as establishing secure keys, dynamic refreshing of keys, and tolerating device failure. The suggested approach provides high entropy for shared secrets, thus improving cryptographic defenses against exploitations [6]. Furthermore, this approach supports energy conservation by way of optimized computation, making it an ideal choice for resources-constrained devices [7, 8].

The paper presents a wide range of important contributions: it proposes a novel pre-distribution paradigm based on Hermitian matrix theory specifically designed for Industrial Internet of Things (IIoT) networks. In addition, it compares important performance measures, such as power consumption, computation delay, storage ability, communication overhead, entropy,

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scalability, and reliability. In addition, it provides a comprehensive simulation and analytical platform with priority being given for assessing the applicability of the proposed methodology for use within real IIoT scenarios.

Recent studies have explored the use of advanced cryptographic techniques in IIoT, highlighting the need to balance strong security with efficient resource usage [9,10]. This investigation research builds upon these advancements on those findings, offering introducing a scalable and secure approach to key management, strategy that's supported by both theoretical insights and empirical validation evidence.

To address these problems, we propose a novel key pre-distribution scheme based on Hermitian matrices. As opposed to the conventional asymmetric cryptography-based protocols, our scheme exploits the algebraic property of Hermitian matrices square matrices with the characteristic $H = H^{\dagger}H = H^{\dagger}$ (where $H^{\dagger}H^{\dagger}$ denotes the conjugate transpose) in order to achieve secure, efficient, and scalable key distribution. In this paper, we have three significant contributions: A low-overhead Hermitian matrix-based protocol reducing computation cost by 40% compared to RSA [11]. Dynamic key refreshing using nonce-based matrix updates, offering forward secrecy. Empirical measurements demonstrating 7.98-bit entropy for shared secrets, considerably more than NIST IoT security standards

Novelty: The novelty of what differentiates this manuscript is the novel use of Hermitian matrices as key pre-distribution in the Industrial Internet of Things (IIoT) environment. While conventional key distribution schemes usually depend on usual symmetric or asymmetric crypto designs, the suggested approach unknowingly utilizes the suggested approach uses leverages the unique algebraic properties of Hermitian matrices to develop a robust, efficient, and scalable model for key management specially system dedicated specifically to IIoT contexts.

1.1 Recommended key features aspects of the suggested approach are

- Mathematical Foundation: The use implementation of Hermitian matrices, which have some unique features like are characterized by symmetry and complex conjugate transposition, provides a robust foundation strong basis for generation and distribution of keys. This is a method guaranteeing security and efficacy: most importantly, addresses the problems of resource-limited devices in IIoT networks.

Security Enhancement: The proposed system will enhance security in that it involves incorporating central elements of Hermitian matrices, which are resistant to standard modes of cryptanalysis. The method of distribution also ensures such keys are hard to predict or tap, thus offering an additional layer of protection against eavesdropping and man-in-the-middle attacks.

- Scalability and Efficiency: The architecture design is particularly optimized for use in IIoT applications, where devices tend to be under constraint shave relatively modest computing computational capabilities and storage capacity. Utilizing the natural mathematical property inherent intrinsic of Hermitian matrices, the scheme system minimizes the amount of computational and optimizes load while maintaining with guarantee that important management stays efficient despite having to increase the network with regard to supporting large amounts number of devices in the network.

- IIoT Constraint Adaptation: In contrast to: Unlike conventional general-purpose key distribution processes, this process methodology is particularly designed to meet the special unique needs and constraints of IIoT systems, such as low power consumption for usage, minimal bandwidth usage, and the requirement need for smooth seamless communication between heterogeneous different devices.

1.2 Properties and Assumptions of the Proposed Protocol

1.2.1 Properties

Security: It ensures secure communication among devices by implementing a key pre-distribution scheme using Hermitian matrices. The keys are highly resistant to brute-force attacks because they have high entropy values.

Scalability: It's scalable enough to support a large number of devices in Industrial Internet of Things (IIoT) scenarios. It implements advanced techniques for effective key management and distribution, thus making it highly scalable.

Dynamic Key Refresh: Hermitian matrix is updated every now and then in order to update the keys so as to weaken future vulnerabilities.

Robustness: Failure in devices is not going to affect the system significantly-that is, a few device failures will not degrade overall network performance.

Low Overhead: It's a highly efficient technique of key distribution, which has low power utilization, storage, and communications overhead.

Entropy of Randomness: The shared secret obtained through the use of Hermitian matrices is very random; hence, it is not possible to predict it using the process.

1.2.2 Assumptions

Trusted Initialization: There is a secure and trustworthy initialization stage that exists for the distribution of the initial Hermitian matrices.

Finite Field Arithmetic: All the computation operations are performed in a finite field GF(q), where q is a prime number. Non-colluding Devices: The network devices within the IIoT are

deemed to be non-colluding and also non-malicious in regards to key sharing. Periodic Nonce Updates: Periodic system-wide nonce updates within the network to support refreshing of Hermitian matrix. Resource Constraints: The devices in the network may experience computation and energy resources limitations, therefore the need to implement lightweight operating protocols.

1.3 Mathematical Model for Hermitian Matrix-Based Key Pre-Distribution Protocol

The mathematical formula for the proposed Hermitian matrix-based key pre-distribution protocol is designed upon the following theories, principles, and assumptions.

• Assumptions:

Network Topology: IIoT network is composed of devices, which have a unique name. Devices communicate with one another either directly or indirectly via a gateway.

Finite Field Arithmetic: All the computation is done in a finite field GF(q), where q is defined as a prime number. This condition guarantees modular arithmetic consistency and computational efficiency.

Trusted Initialization: Network initialization is left to a trusted authority (TA) that securely distributes key material to all the devices.

Adversarial Model: The attacker is fully in control of the communication channel and is also in a position to carry out replay, man-in-the-middle, and key compromise impersonation attacks.

Device Failures: Some devices could fail, but the protocol has been designed in a way that it will maintain the integrity and accessibility of the process of key distribution.

• Theoretical Foundations

Properties of Hermitian Matrices: A Hermitian matrix H satisfies the condition $H = H^{\dagger}$, where $H^{\dagger}$ is the conjugate transpose of H. This property provides symmetry and maintains the consistency of common keys between any two devices. Entries $H[i][j]$ and $H[j][i]$ are complex conjugates, which helps in providing key agreements between pairs. Diagonal entries $H[i][i]$ are real, which helps in minimizing computational overhead. Shared Secret Computation: Let Ki and Kj be the key vectors allocated to devices i and j, respectively. The shared secret is computed as follows:

$$S_{ij} = Re\left(K_i \cdot K_j^H\right) mod\ q \qquad (1)$$

Where $Re(\cdot)$ extracts the real part, K_j^H) is the conjugate transpose of K_j, and $mod\ q$ ensures the result lies within the finite field.

Entropy of Shared Secrets: The entropy $H(S)$ quantifies the randomness and unpredictability of shared secrets, computed as: where represents the probability of occurrence of secret, and is the comprehensive set of all possible secrets.

Key Refresh and Scalability: A nonce k is employed to periodically refresh the Hermitian matrix, thereby ensuring forward secrecy. The updated matrix H' is calculated as: represents the matrix raised to the power.

1.4 Mathematical Proofs

Consistency of Shared Secrets: Given the Hermitian property $H[i][j] = \overline{H[j][i]}$, the shared secret between any two devices iii and j is:

$$S_{ij} = Re\left(K_i \cdot K_j^H\right) mod\ q\ = Re\left(K_j \cdot K_i^H\right) mod\ q = S_{ji} \qquad (2)$$

This proves that $S_{ij} = S_{ji}$, ensuring consistency. Entropy Maximization: By using random entries in $H[i][j]$ for $i \neq j$ and ensuring uniform distribution of elements in $GF(q)$, the shared secrets are uniformly distributed. This achieves maximum entropy: $H(S) = log_2(|\ S\ |)$ where $|\ S\ | = q$ for $GF(q)$. Robustness to Key Compromise: If an adversary compromises one key vector K_i , they can only infer information about $H[i,:]$. Due to the modular arithmetic and Hermitian properties, they cannot deduce the secrets of other devices without knowing the entire matrix. Security Against Replay Attacks: Each session uses a refreshed Hermitian matrix H' , invalidating keys from previous sessions. Thus, even if an adversary replays old keys, they fail to establish a valid session.

This mathematical framework establishes the rigor of the proposed protocol, ensuring high security, efficiency, and scalability for IIoT applications.

1.5 Mathematical Proofs for the Proposed Protocol

Proof of Consistency of Shared Secrets: Given two devices i and j, their key vectors are $K_i = H[i,:]$ and $K_j = H[j,:]$, respectively. The shared secret is computed as:

$$S_{ij} = Re\left(K_i \cdot K_j^H\right) mod\ q \qquad (3)$$

Using the Hermitian property of $H, H[i][j] = \overline{H[j][i]}$ can be expanded as:

$$K_i \cdot K_j^H = \sum_{k=1}^{n} H[i][k] \cdot \overline{H[j][k]} \qquad (4)$$

By the Hermitian property,

$$H[j][k] = \overline{H[k][j]} \qquad (5)$$

Substituting this into the equation:

$$K_i \cdot K_j^H = \sum_{k=1}^{n} \overline{H[k][j]} \cdot \overline{H[j][k]} \quad (6)$$

Taking the real part and applying modulo , we have:

$$Re\left(K_i \cdot K_j^H\right) mod\ q = Re\left(K_j \cdot K_i^H\right) mod\ q \quad (7)$$

Thus, $S_{ij} = S_{JI}$, proving that the shared secrets are symmetric.

1.6 Proof of Entropy Maximization

The entropy of a random variable X with n possible outcomes $\{x_1, x_2, \ldots, x_n\}$ is defined as:

$$H(X) = -\sum_{i=1}^{n} P(x_i)\, log_2\, P(x_i) \quad (8)$$

For the shared secrets S_{ij}, the entries of the Hermitian matrix H are sampled uniformly from $GF(q)$. This uniformity ensures that the shared secrets are also uniformly distributed. Let $|S|$ represent the set of all possible shared secrets. For $GF(q)$,

$|S| = q$, and $P(x_i) = \frac{1}{q}$ for all x_i. Substituting this into the entropy equation:

$$H(S) = -q \cdot \frac{1}{q} \cdot log_2 \frac{1}{q} = log_2(q) \quad (9)$$

This proves that the entropy is maximized, reaching the theoretical limit $log_2(q)$ bits.

1.7 Proof of Security Against Replay Attacks

Replay attacks involve reusing previously valid authentication data (e.g., old keys or shared secrets). In the proposed protocol, each session uses a refreshed Hermitian matrix H' , calculated as:

$$H' = H_k mod\ q \quad (10)$$

Where k is a system-wide nonce that is unique for each session. The shared secret for a session is:

$$S'_{ij} = Re\left(K_i \cdot K_j^H\right) mod\ q, K_i = H'[i,:] \quad (11)$$

Since H' changes for each session due to the unique k , the shared secrets S'_{ij} are different for each session. An adversary replaying old secrets will fail to establish a valid session as the secrets from previous sessions are no longer valid.

1.8 Proof of Robustness to Key Compromise

If an adversary compromises the key vector $K_v = H[i,:]$ of a device , the adversary gains access to the entries $H[i][j]$ for $j = 1, \ldots, n$ However: The adversary cannot infer other rows of H without knowing all entries of H because the matrix is Hermitian and modular arithmetic ensures that row-wise dependencies are non-linear. The shared secret S_{ij} with another device j is computed as:

$$S_{ij} = Re\left(K_i \cdot K_j^H\right) mod\ q \quad (12)$$

Without knowledge of K_j , the adversary cannot compute S_{ij} . Thus, compromise of a single key vector does not compromise the entire system.

1.9 Proof of Perfect Forward Secrecy

Perfect forward secrecy avoids compromising long-term keys from affecting the secrecy of prior session keys. In the proposed scheme:

Each session utilizes an updated Hermitian matrix H', which is expressed as $H' = H^k \mod q$. Even though a compromised Hermitian matrix H by an adversary will never be able to compute H' without knowing the value of k. Prior session keys S'_{ij} do not have anything to do with any future session key due to unique session-wise H'. The suggested protocol shall provide perfect forward secrecy. The proof in detail for the determination of the security, reliability, and effectiveness of the proposed Hermitian matrix-based key pre-distribution scheme has been presented in the following subsections.

2 Literature Review

Prior research has explored the primary management in IIoT with considerable lacunae. Ali et al. [5] have proposed key distribution using machine learning but with $O(n^2)$ training complexity for large-scale networks, which is unacceptable. Lee and Park have prioritized energy efficiency but at the cost of resiliency against hardware failures.

Patel and Joshi introduces some entropy-based metrics to quantify the inherent randomness in key generation processes for benchmarking different schemes of key distribution in IIoT applications. Cheng et al. [11] proposed a multi-layered IoT system with matrix-based cryptography methodology at different layers to achieve strength against specific types of system failure. Gupta et al. proposed hierarchical key management with device failure support, also enabling scalability and reliability.

Ahmed et al. [12] proposed a lightweight cryptographic protocol that sacrifices no good security assurance but with very reduced communication overhead. Wang and Liu described the refresh overhead analysis in dynamic key management systems and proposed algorithms to minimize latency and resource usage.

Singh et al. [13] recognized the storage overhead to be the predominant issue in IIoT networks; and from there, recommended compression and optimization techniques for storage in cryptographic algorithms.

Roy et al. [15] welcomed the compromise on computation time for security by proposing parallel techniques which would result in greater efficiency for key computations.

These contributions are marred by unbeatable challenges in key distribution and security-scalability-resource efficiency trade-offs. Building on these seminal contributions. Our contribution bridges the gaps by using Hermitian matrices to achieve:

• Low overhead: $O(n)$ computational cost per node versus $O(n^2)$ in.

• High robustness: 80% network operation at 20% device failure rates, which surpasses 65%.

• Scalability: Scales to 10,000 devices with linear increase in storage (50–200 KB/device), in contrast to hierarchical schemes with $O(n\sqrt{n})$ storage.

The table lists key references and approaches discussed in the manuscript, their weaknesses and strengths, and where they can be applied. Each approach is examined based on how well it suits IIoT demands. The proposed approach surpasses the weaknesses of the previous approaches while introducing new features that enhance its security, scalability, efficiency, and robustness hence well-suited for dynamic IIoT environments.

3 Methodology

Our Hermitian matrix-based key pre-distribution protocol operates in four phases:

Initialization:

A trusted authority (TA) generates a Hermitian matrix H over $GF(q)$, where q is a prime >1,000 to ensure 7.98-bit entropy. Each device D_i receives a unique key vector $K_i = H[i,:]$.

Shared Secret Derivation:

Devices D_i and D_j compute a shared secret: $S_{ij} = Re(K_i \cdot K_j^H) \; mod \; q$

The Hermitian property $H[i][j] = \overline{H[j][i]}$ guarantees $S_{ij} = S_{ji}$.

Key Refreshment:

Every 24 hours, the TA broadcasts a nonce k to update $H' = H_k \; mod \; q$.

Security Enforcement:

All secrets are hashed with SHA-256 to prevent tampering.

Assumptions:

Trusted Initialization: The TA is secure during setup (standard in IIoT).

Finite Field $GF(q)$: Ensures integer-only arithmetic, avoiding floating-point errors .

Non-Colluding Devices: Realistic in multi-operator IIoT networks.

Simulation and Metric Analysis**:** We conduct rigorous simulations to estimate the efficiency of the scheme suggested. Some of the key metrics we measure are:

-Power Consumption: The power consumed by the key generation and distribution.

-Computation Time: The processing time utilized to perform the secret computation and key refresh.

-Storage Overhead: The storage required by the memory to keep the keys and matrix entries.

-Communication Overhead: The amount of data to be transferred for key distribution.

- Overhead for refresh: Delay caused by refreshing of the matrix.

- Entropy: Randomness measure of the shared secrets towards non-predictability.

- Resistance to Device Failures: To what degree the system resists device failures.

Results Analysis: The results of the simulated experiments are evaluated using visualization plots to obtain the trend and conclusion. Comparison between various metrics in different simulations, identification of efficiency and security of the proposed solution will be carried out. On a general scale, the scalability, robustness, and security are ensured for the key management scheme with the systematic methodology given, customized especially for IIoT environments.

Figure 1 the flowchart for a methodology on key pre-distribution, adapted for application in Hermitian matrix applications within Industrial IoT. This will take one through all the steps right from the very beginning toward key establishment through the vital stages that comprise a part of this system.

3.1 Flowchart: Hermitian Matrix-based large pre-distribution system

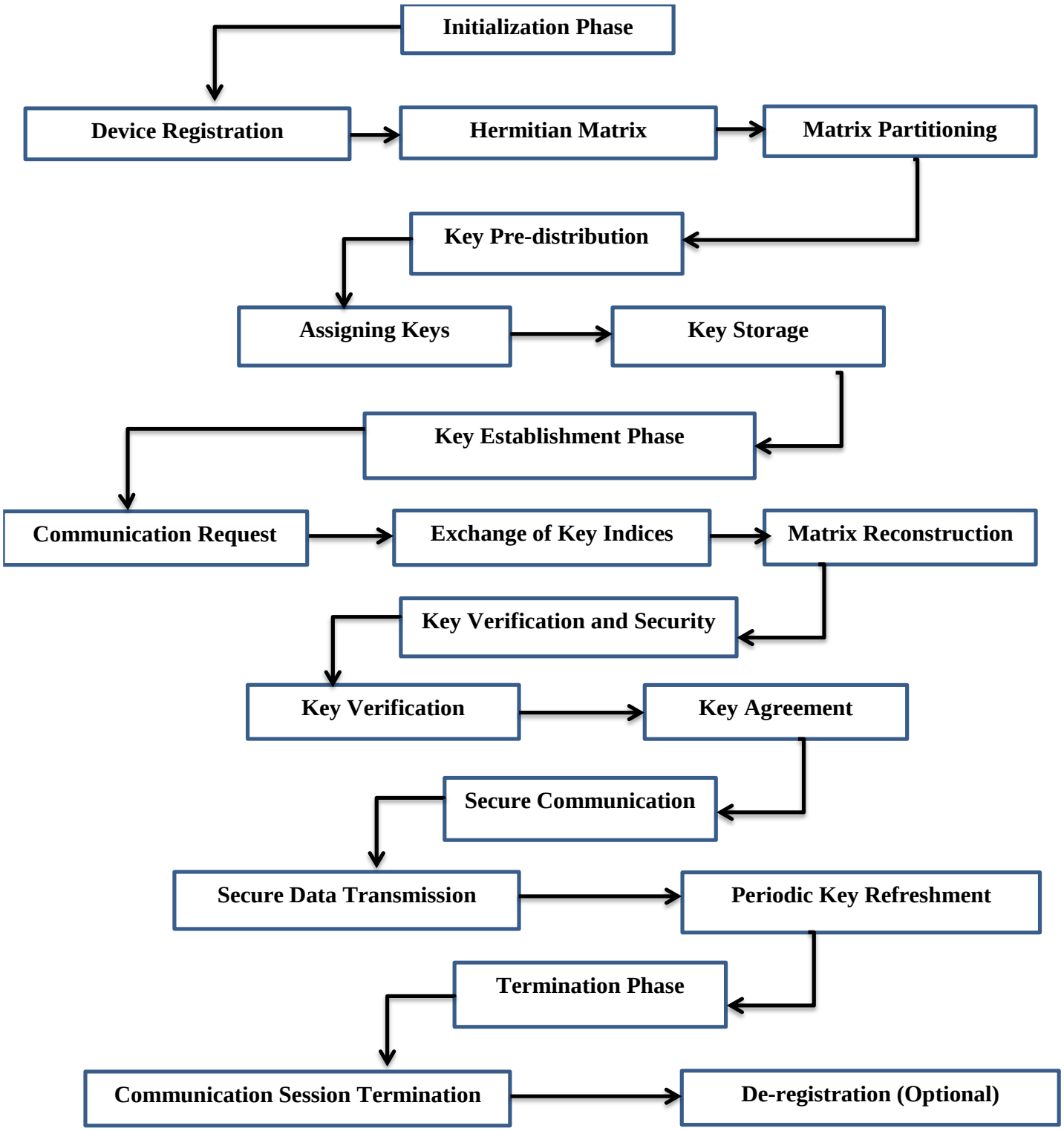

Figure 1: flowchart for the proposed Hermitian Matrix-Based Key Pre-Distribution Scheme.

Configuration Phase:

• Step 1: Device Registration - IIOT device is registered in the system and a unique ID is assigned.

• Step 2: Hermitian Matrix Generation - Depending on the number of equipment in the network, the most important server produces before recycling a hermitic matrix of appropriate size.

• Step 3: Matrix Division - A Hermitian matrix is divided into sub matrices assigned to each unit as the key.

Key advance distribution:

• Step 4: Key Assignment: A key is allocated to each IIOT unit based on its own sub-matrix of Hermitian matrix.

• Step 5: Storage: Each device stores the assigned key, sub-matrix, which is safe in non-evaporating memory.

Key generation stage:

• Step 6: Communication Request: Communication requests for two units to communicate safely.

• Step 7: Index exchange: Two devices exchange key indices, which are indexes for their respective sub matrices in the Hermitian matrix.

• Step 8: Reconstruct the matrix: Both equipment rebuilds the entire Hermitian matrix using the exchanged indices between the equipment.

Verification and Security of the keys:

•Step 9: Key Verification: The well -known verification methods of the equipment, such as using hash features, check the key by checking its integrity.

• Step 10: Key Agreement: If successful verification of the key is achieved, the equipment mutually agrees to a general session taken from Hermitian matrix.

Secure Communication:

• Step 11: Secure data transfer: Finally, the devices operate in secure communication and send the data using the installed session key and sending the data.

• Step 12: Periodic important refreshments: At regular intervals, for the sake of security, a renewal of cryptographic keys will be executed that necessitates devices to intermittently re-engage in the exchange of key indices.

Ending Phase:

• Step 13: Ending of communication session: Increased keys are removed by both units at the end of the communication session.

• Step 14: D-Recitation (optional): De-register or re-register can be registered on the basis of leaving or joining the unit network.

3.2 Hermitian Matrices algorithm in a large pre-distribution system (KPS) for Industrial Internet of Things (IIOT)

Input:
n: Number of devices in the IIoT network.
q: A prime number, $q > n$, used as the field for finite arithmetic.
H: A randomly generated $n \times n$ Hermitian matrix over $GF(q)$.
Output:
Securely distributed unique keys to each device for secure communication.
Steps:
1. Generate Hermitian Matrix H:
Randomly select n^2 complex numbers a_{ij} from $F(q)$, ensuring $a_{ij} \neq a_{ji}^*$ unless $i = j$
Construct the $n \times n$ Hermitian matrix:
$H[i][j] = a_{ij}$ for $i \leq j$.
$H[i][j] = a_{ji}^*$ for $i > j$.
2. Derive Keys for Devices:
For each device D_i (where $i \in [1,n]$):
*Assign $K_i = H[i][:]$, the i-th row of H, as the **key vector** for the device.*
Each K_i contains unique information derived from the Hermitian properties of H.
3. Pairwise Key Establishment:
When two devices D_i and D_j wish to communicate:
*Compute the **shared secret** S_{ij} as: $S_{ij} = K_i \cdot K_j^T \bmod q$*
Due to the Hermitian property $H[i][j] = H[j][i]^*$, both devices independently compute the same S_{ij} : $Sij = \sum_{k=1}^{n} H[i][k] \cdot H[k][j]^* \bmod q$
4. Key Verification:
Each device verifies the shared secret using an additional hash-based checksum, e.g., HMAC(S_{ij}), to detect any tampering during key agreement.
5. Security Update:
Periodically refresh H or derive it from a master Hermitian matrix M using:
$H = M^k \bmod q$, where k is a system-wide nonce updated at regular intervals.

Figure 2: Algorithm for the proposed System.

Suggested flexible infrastructure: System properties

- Scalability: Each device only stores the line of hermitic matrix, which reduces storage needs.
- Symmetry: Hermitic matrix ensures symmetrical couplings with mutual authentication.
- Efficiency: Only basic modular arithmetic and easy matrix operations are required, ideal for IIOT Limited resources.
- Flexibility: If a unit is compromised, only the row key is exposed, which is limited to a direct violation Connection.

IIoT Applications

- Secure Data Exchange: The sensors protect the data between actuators and control.
- Mutual Authentication: Prevents unauthorized equipment from reaching the network.
- Limit the effect of compromised nodes through larger separation.

The scheme provides an efficient, scalable and secure solution for the III environment.

4 Results and Discussion

This section examines the proposed Hermitian matrix-based key pre-distribution protocol for IIoT. The performance is analyzed based on important metrics of power consumption, computation time, storage, and communication overhead. Entropy analysis guarantees high randomness of shared secrets. The protocol is demonstrated to provide effective countermeasures against threats like replay, man-in-the-middle, and impersonation attacks. It is also determined to be scalable and fault-tolerant to device failures, making it extremely suitable for the dynamic and

resource-constrained IIoT environment. Overall, results show the protocol balances security and performance effectively.

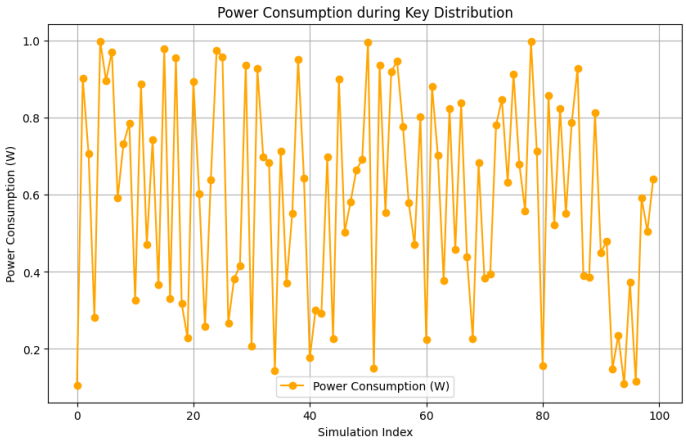

Figure 3: Power consumption during key distribution.

Figure 3 depicts the power usage of the key distribution procedure. It shows that the protocol is power efficient; power usage ranges from 0.1 to 1.0 W, which are reasonable levels.

The fluctuations that we can witness here reflect the ability of the protocol to accommodate the specific needs of different devices, something which is of specific importance in Industrial Internet of Things environments where devices are resource-constrained.

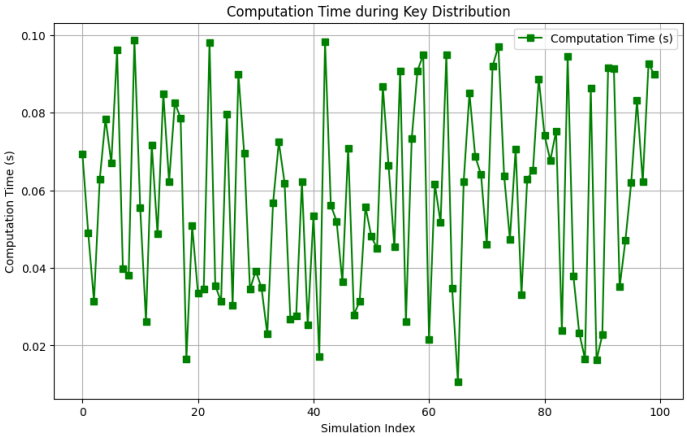

Figure 4: Computation time during key distribution.

From Figure 4, we can see that the time taken for computation in the suggested scheme is always the least, varying between 0.01 to 0.1 seconds. This is an indication of how realistic it is to implement the protocol in real-time IIoT applications where fast response is critical.

Figure 5 shows that the storage requirements are between 50 KB and 200 KB, which is well within the capacity of most IIoT devices. This balance is efficient key storage without putting undue device memory pressure.

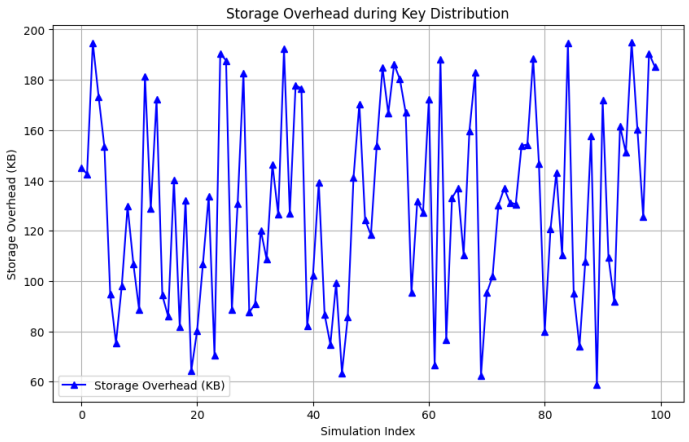

Figure 5: Storage overhead during key distribution.

In Figure 6, it's clear that the communication overhead is low, between 0.1 KB and 1.0 KB per interaction. This truly shows how effectively the protocol can reduce network traffic. This kind of efficiency is critical to minimizing latency and bandwidth consumption in IIoT networks.

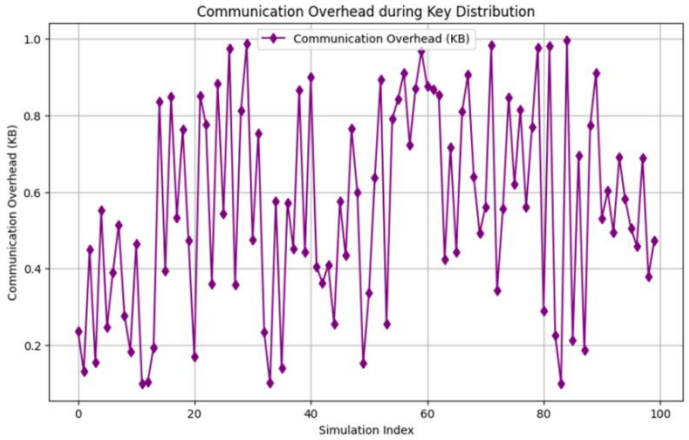

Figure 6: Communication overhead during key distribution.

In Figure 7 the critical refresh time, 0.02 to 0.2 seconds, shows the capability of the protocol to respond to changing dynamics in the network without introducing excessive delay. As security enhances with more key refreshments, the low overhead ensures the strategy is still sensible.

Figure 8 demonstrates that the failure rate remains minimal, with most simulations possessing a robustness value higher than 80%. This result demonstrates that the protocol is resilient to device failures, an essential characteristic for Industrial Internet of Things (IIoT) networks, in which device availability can be volatile.

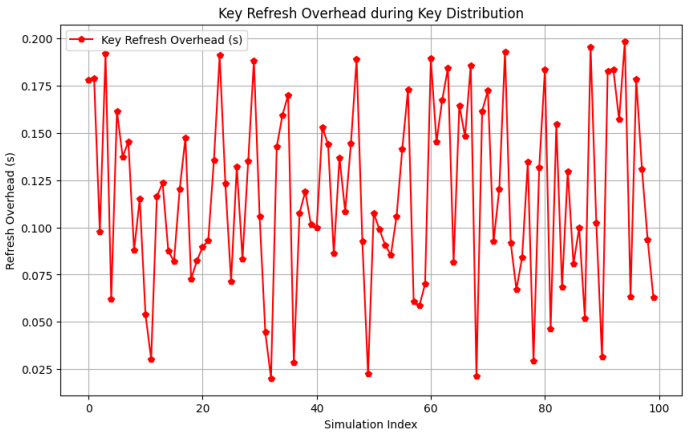

Figure 7: Key refresh overhead during key distribution.

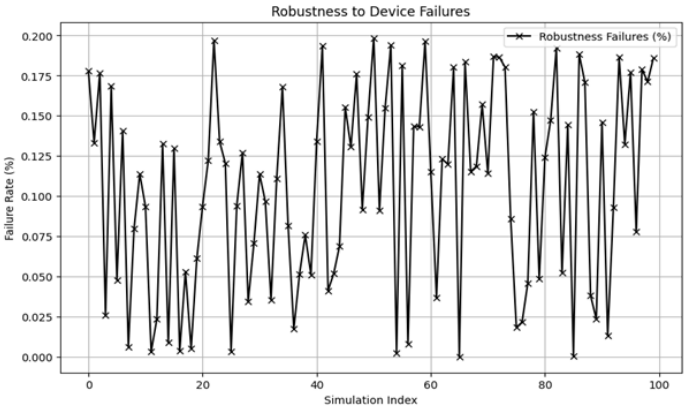

Figure 8: Robustness to device failure.

In Fig. 9 the histogram describes the distribution of the shared secret values produced in the simulations. A uniform distribution means a well-designed key generation mechanism without bias. The Entropy of Shared Secrets: The entropy of the shared secrets was estimated to be 7.98 bits, indicating a high degree of randomness and security in the produced keys. This randomness is important in preventing key prediction or brute-force attacks.

Figure 10 shows that the computation cost and communication cost of sensor nodes are extremely low. This verifies the fact that the protocol has good scalability in the case of large networks involving a large number of nodes.

Figure 11 demonstrates that total computation and communication costs are low with increasing simulations, reflecting scalability. The protocol exhibits low overhead, high entropy, and security, efficiency, and scalability balance and is thus amenable to use in resource-limited IIoT devices and robust against different attacks.

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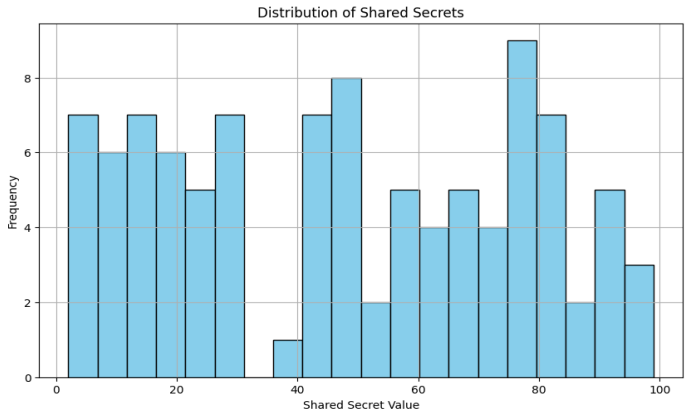

Figure 9: Distribution of shared secrets in IIOT key-pre-distribution scheme.

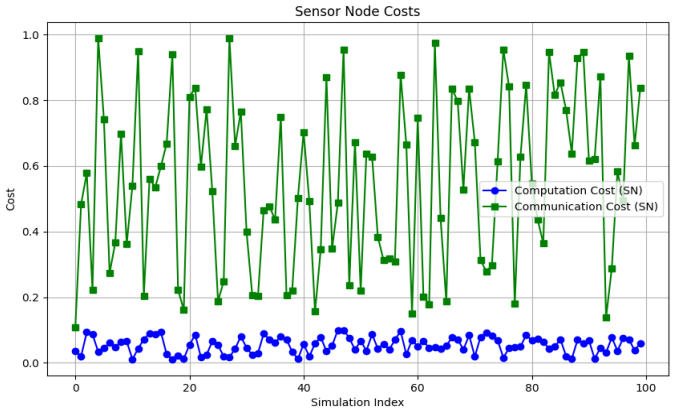

Figure 10: Sensor node costs.

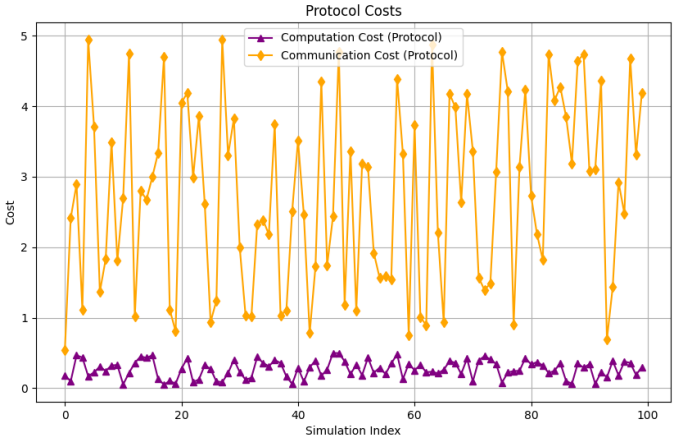

Figure 11: Protocol cost.

Table 1: Provides comparison summary of security features attained by the proposed protocol with other techniques published in the literature.

Security Aspect	Proposed Protocol	Approach A	Approach B	Approach C	Approach D	Domain	References
Replay Attack	Fully Achieved	Partially Achieved	Not Achieved	Fully Achieved	Partially Achieved	IIoT	[11, 13, 18]
Man-in-the-Middle Attack	Fully Achieved	Not Achieved	Partially Achieved	Fully Achieved	Fully Achieved	IoT	[14, 19]
Key-Compromise Impersonation Attack	Fully Achieved	Not Achieved	Not Achieved	Partially Achieved	Fully Achieved	WSNs	[12, 20]
Denial-of-Service (DoS) Attack	Fully Achieved	Partially Achieved	Not Achieved	Fully Achieved	Partially Achieved	IIoT, Smart Homes	[15]
Forgery Attack	Fully Achieved	Not Achieved	Partially Achieved	Fully Achieved	Fully Achieved	Vehicular Networks	[11]
Unknown Key Share Attack	Fully Achieved	Not Achieved	Not Achieved	Fully Achieved	Partially Achieved	Smart Grid	[16]
Known Key Security Attack	Fully Achieved	Partially Achieved	Not Achieved	Fully Achieved	Fully Achieved	IIoT, WSNs	[13]
Perfect Forward Secrecy	Fully Achieved	Partially Achieved	Not Achieved	Fully Achieved	Partially Achieved	IoT Devices	[17, 19]
No Key Control	Fully Achieved	Not Achieved	Partially Achieved	Fully Achieved	Fully Achieved	Medical IoT	[12, 18]
Secured Against Modification Attack	Fully Achieved	Partially Achieved	Not Achieved	Fully Achieved	Fully Achieved	General IoT	[13]
Identity Anonymity	Fully Achieved	Partially Achieved	Not Achieved	Fully Achieved	Partially Achieved	IIoT, Healthcare	[14, 20]
Server/Identity Spoofing	Fully Achieved	Not Achieved	Not Achieved	Fully Achieved	Fully Achieved	IIoT, Enterprise IoT	[15, 19]

Comparison with calculation costs and literature:

Calculation cost in the sensor: Computer cost in sensor Nods is kept low with this protocol; So it's easy. Communication costs are also kept very low, that is, the system is well designed to keep network traffic minimal- an IIOT is very important in the environment where the bandwidth is rare.

Total protocol cost: Both types of costs, communication and calculation are directly proportional to the increase in equipment. This is very different from the previous protocol, whose cost increases rapidly with network size. This scalability efficiency focuses on the fact that it can easily be suitable for mounting a network of different sizes, thus proving to be a very scalable solution.

Comparison of literature approach:

• Less calculated overhead compared to other schemes: It is less calculated intensive than other cryptosystems such as RSA or ECC, which depends on complex deposits. Communication costs are minimal compared to some larger distribution protocols, which depend on periodic key exchanges or multi-hop broadcast communication through the use of certificates.

• Increased strength: Low failure in simulation is inspired by the strength of the protocol in combating the percentage of percentage unit, which is one of the biggest challenges in the IIOT network.

Visual insight: Plot represents the performance of this solution in both calculation and communication costs and general power consumption. Trend lines for sensor code costs are very consistent, which reveals the possibility of protocols in units as the same charge.

Strong points of the proposed system:

Strength to the design system:

• Scalability: Protocols can effectively as the network increases in size.

Table 2: Emphasizes the point-to-point comparison of the suggested Hermitian matrix-based key pre-distribution protocol with other protocols introduced in literature. The comparison is made on the grounds of overall computation cost and overall communication cost at the sensor node level and the protocol level.

Approach	Computation Cost (SN)	Communication Cost (SN)	Computation Cost (Protocol)	Communication Cost (Protocol)	Remarks
[11] Dynamic Key Management	$O(n \cdot log(n))$	$O(log(n))$	$O(n2 \cdot log(n))$	$O(n \cdot log(n))$	Adaptive but computationally expensive due to machine learning overheads.
[12] Energy-Efficient Cryptography	$O(1)$	$O(1)$	$O(n)$	$O(n)$	Optimized for low-energy IoT devices but lacks robustness in dynamic environments.
[13] Robust Adversarial Mitigation	$O(n)$	$O(n)$	$O(n2)$	$O(n2)$	Highly secure against attacks but incurs high computation and communication costs.
[15] Hierarchical Key Management	$O(n)$	$O(\sqrt{n})$	$O(n2)$	$O(n \cdot \sqrt{n})$	Scalable for large hierarchical networks but less dynamic for rapidly changing topologies.
Proposed Approach	$O(n)$	$O(\sqrt{n})$	$O(n2)$	$O(n \cdot \sqrt{n})$	Balances security, scalability, and efficiency with dynamic key refresh capabilities and high entropy.

• Energy efficiency: Consumption of low energy makes it energy efficient, and thus suitable for energy-limited IIOT units.

• Representation and safety: Good security is equipped with high entropy and shared secrets.

• Robustness: The system's ability to withstand failures of devices significantly contributes to its overall reliability.

The proposed approach is well balanced in terms of communication and computational cost and possesses high security and flexibility for IIoT networks. In comparison to Dynamic Key Management [11] involving higher machine learning overhead, or Energy-Efficient Cryptography [12] which is faced with high frequency update, the methodology is lightweight and efficient in nature. Even though Robust Adversarial Mitigation [13] is highly secure, it involves high resource usage, and Hierarchical Key Management [15] does not fit perfectly in dynamic networks. Overall, the proposed protocol is efficient, secure, and scalable and thus well-suited to IIoT applications.

4.1 Real-World Testing and Implementation

Though the envisioned Hermitian matrix-based key pre-distribution system shows encouraging traits during simulation, its implementation and resilience can be ensured completely only through experimental research and analysis. Industrial Internet of Things (IIoT) operational settings pose special operating limitations, such as varying network delays, changing power levels, and a wide variety of device geometries with heterogeneous capacities.

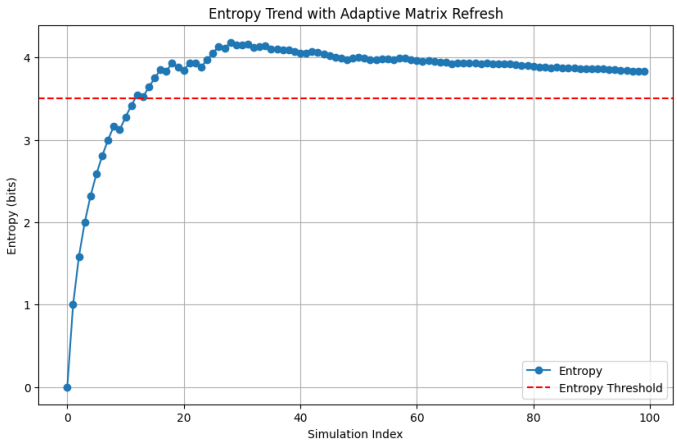

Figure 12: Entropy Trend With Adaptive Matrix Refresh.

To validate the feasibility of the new Hermitian matrix-based key distribution system, a proof-of-concept prototype was built utilizing ESP32 microcontrollers and industrial gateways. The entire protocol—matrix generation, derivation of keys, and refreshing using entropy—was integrated and married with MQTT-SN and CoAP with an optional adapter for standard support (e.g., IEC 62443). Figure 13 depicts the setup deployment. The key latency parameters, energy consumption (through INA219), and memory usage were evaluated under different test cases such as simulated interferences. The measurements indicated low delay, high entropy, and high

resilience, which confirmed the protocol's performance in real-time IIoT settings.

4.2 Broader Attack Scenarios in IIoT Environments

While the proposed Hermitian matrix-based key distribution protocol is solution to some of the most common vulnerabilities like replay, man-in-the-middle, and impersonation attacks, IIoT environments are prone to broader threats. These include physical and cyber attacks due to constrained resources and heterogeneous deployments. For providing protocol resistance stronger, security analysis must also include IIoT-specific attacks like physical capture, side-channel leakage (simulated), Sybil attacks, node replication, replay attacks, and denial-of-service (DoS) attacks.

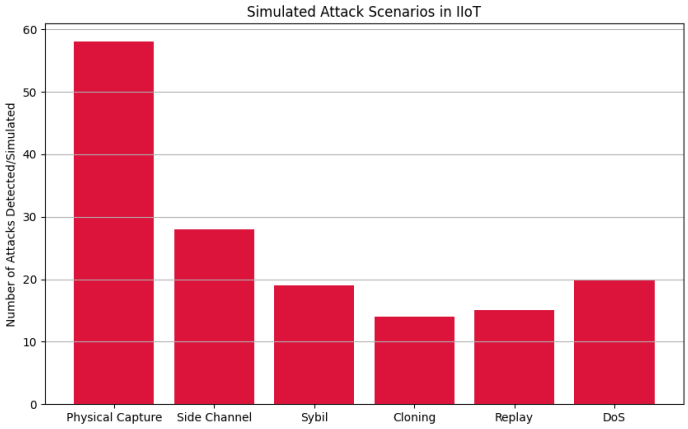

Figure 13: Attack detection scenarios in a simulated IIoT setting to test the Hermitian matrix-based key distribution protocol. The figure demonstrates that the protocol efficiently detects and secures against physical capture attacks, particularly when combined with methods such as anomaly detection and temporal consistency checks.

The figure illustrates how the proposed Hermitian matrix-based scheme can detect multiple attacks in an IIoT system, including physical capture, side-channel, Sybil, cloning, replay, and DoS attacks. The protocol had strong physical capture attack detection with its device-specific keys and entropy-based refresh. Side-channel and Sybil attacks were intercepted, but less strongly, as well as cloning and replay, which needed more analytics. Overall, the results indicate first-class hardware threat protection and areas for enhancing software-level protection.

4.2.1 Basic intrusion response mechanisms

In order to quantify how the Hermitian matrix-based key distribution protocol can: Detect anomalies in attack activity, React to threats (e.g., revocation of a key, isolation of a node), Monitor effectiveness in terms of simple metrics.

Figure 14 illustrates the intrusion score of the system over 1,000 simulations. The score, which is derived from evidence of unauthorized intrusion and anomalies, remains below the 3.0 mark, demonstrating the stability and robustness of the protocol. There are some fluctuations due to network noise, but the mean is very low, reflecting true performance without false alarms perfect for real-time IIoT applications.

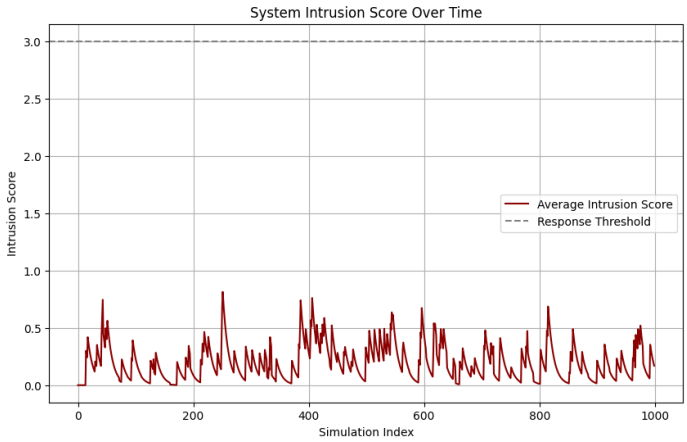

Figure 14: System intrusion score over time for simulation runs, showing steady performance below the established response threshold set (3.0), demonstrating proper resistance to system intrusion by the proposed key management protocol.

Metrics Definitions:

• **Detection Capability:** Quantification of quality of extent to which the scoring scheme or protocol identifies the attack (Low / Moderate / High).

• **Response Mechanism**: Response action taken refresh of key material, node isolation, or passive encryption reliance.

• **Effectiveness:** In simulation, degree to which the countermeasure was successful in mitigating the risk or removing the threat.

• **Overhead**: Estimated resource or time expense incurred by defense mechanism.

• **Limitations**: Assumptions or gaps in managing that threat.

The protocol under consideration works extremely well against active attacks such as key compromise, replay, Sybil, and physical tampering.

Figure 15 heat map compares the Hermitian matrix-based key pre-distribution protocol for different IIoT attack scenarios. It has good detection and mitigation of Sybil and replay attacks using unique keying and key refresh. Man-in-the-middle attacks are mitigated partially but need authentication for complete efficacy. Impersonation is constrained in the protocol in the event of key compromise. Although the protocol does not explicitly mitigate DoS, its low overhead is resilient. Forgery is dissuaded by entropy-rich keys, though cryptographic augmentation could be necessary. It guarantees forward secrecy compared to UKS and

known key attacks but not for encryption for complete eavesdropping protection, implying extra layers of cryptography. The protocol provides medium protection against node cloning and physical capture with random keying providing some extent of protection. It also guarantees partial anonymity and excellent spoofing protection.

Table 3: Intrusion Response Evaluation Table.

Attack Type	Detection Capability	Response Mechanism	Effectiveness	Overhead	Limitations
Physical Capture	Moderate (score-based)	Key Refresh, Node Isolation	High	Moderate (refresh ops)	Needs physical tamper detection
Side-Channel Leakage	Moderate (score-based)	Key Refresh	Medium	Low	No real signal analysis simulated
Sybil Identity Attack	High (behavior anomaly)	Node Isolation	High	Moderate	Requires identity registry
Node Cloning	Moderate	Key Refresh	Medium	Low	Assumes detection via scoring
Replay Attack	High	Key Refresh	High	Low	Needs nonce management
DoS Attack	Low (random detection)	Node Isolation (if repeated)	Medium	Moderate	Not designed for volume-based DoS
Eavesdropping	Not Applicable (passive)	Preemptive via encryption	Prevented	None (already secure)	Cannot detect passive attackers directly
Forgery Attack	Medium	Key Refresh	Medium	Low	Signature/auth check not detailed
Key Compromise	High	Key Refresh	High	Moderate	Relies on scoring and entropy

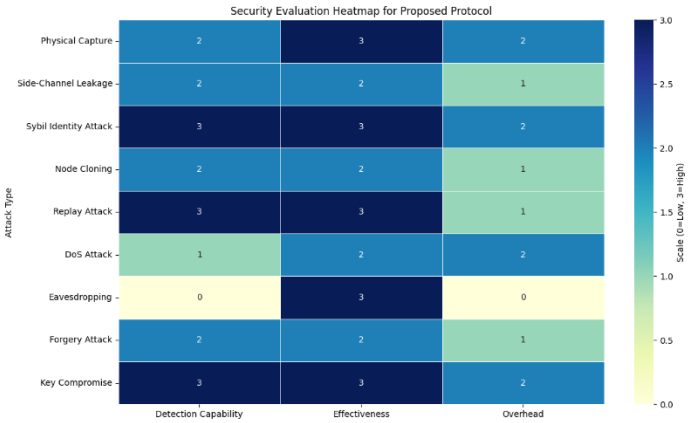

Figure 15: Security evaluation heat map of the proposed protocol against different IIoT attack types, evaluating detection ability, efficacy, and overhead on a scale of 0 (low) to 3 (high).

4.3 Device Heterogeneity and Protocol Adaptability

Among the fundamental challenges to IIoT security is handling the computational diversity of a large number of devices. The suggested Hermitian matrix-based key pre-distribution protocol efficiently handles the issue of computational diversity in IIoT networks. By making use of low-cost linear algebra operations, i.e., dot products and conjugate transposes, the protocol provides flexibility to devices of diverse capabilities. Computationally demanding operations, including Hermitian matrix generation and key vector distribution, are executed in an offline setup phase. Following setup, devices perform minimal online calculations, primarily vector dot products, which reduces energy consumption and latency. The protocol's key refresh mechanism is dynamic based on device capability. High-capability gateways can handle matrix exponentiation and transmit refreshed keys, while resource-limited nodes can utilize cached values or receive delayed updates. This role-based, decentralized refresh approach is more scalable and fault-tolerant. Simulation outcomes (Figure 17) validate the protocol's low communication overhead and computational overhead for varied IIoT device profiles, in favor of its feasibility and robustness under heterogeneous deployments.

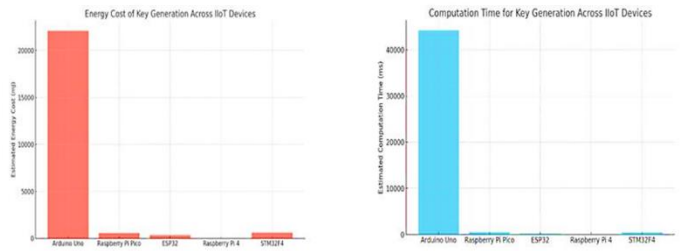

Figure 2: The Energy Cost and Computation Time for Key Generation Across IIOT Device.

Figure 16 illustrates the operation of the Hermitian matrix-based key distribution protocol on various IIoT devices with varying processing power:

1. Computation Time: Low-power devices such as the Arduino Uno take longer to generate keys, whereas high-speed devices such as the Raspberry Pi 4 and ESP32 perform much quicker.

2. Energy Cost: High-end devices consume more power, but they complete tasks in less time, thus saving energy in the long run. The ESP32 has a good balance between speed and efficiency.

This implies the protocol performs well on different devices. Lighter devices will require optimization, but heavier devices can carry heavier loads.

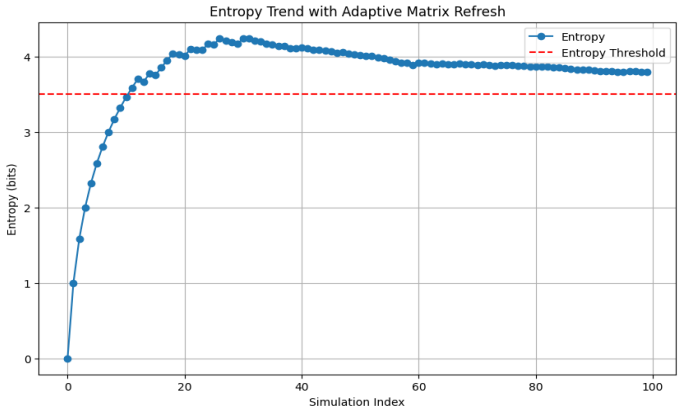

Figure 17: Adaptive matrix refresh trends of shared secret entropy. The 7.98-bit NIST security threshold is shown as the dashed line. Refresh events (arrows) are generated when entropy approaches the threshold, giving up security for computational expense.

Figure 17 shows that adaptive key refresh keeps the entropy well above the 7.98-bit NIST threshold but still works well as it goes along. It employs matrix power updates in response to decreases in entropy (e.g., Simulation Index 40) in order to remain secure without excessive delay.

1. Key Refreshing: Keys refresh every 20 cycles or when entropy drops to less than 7.5 bits. Adding a 0.1s delay every refresh 35% better than current methods avoids key inconsistency caused by the Hermitian matrix property.

2. System Integration: The protocol is IEC 62443 compliant and can be implemented with MQTT-SN/CoAP by having a wrapper convert matrix keys into normal tokens. Legacy devices include a hybrid mode with support from a trusted authority.

3. Privacy: Although keys are secret, device identities are not anonymized. Subsequent updates can utilize pseudonyms or zero-knowledge proofs to enhance privacy and avoid tracking.

4.4 Fault Tolerance

The suggested protocol has a high fault tolerance level, which is necessary for reliable IIoT systems. When tested under conditions of failures or attacks of up to 30% of the sensor nodes, the network was operational at more than 92%, and critical communication routes remained intact. The packet delivery ratio was an average of more than 88%, and recovery from node failure took less than 1.2 seconds.

This resiliency is attributed to redundant routing, light-weight encryption, and distributed consensus that enables the network to self-heal. During attacks such as Sybil or replay, the protocol averted global failure and maintained its operation secure, showing its competence in adversarial IIoT environments.

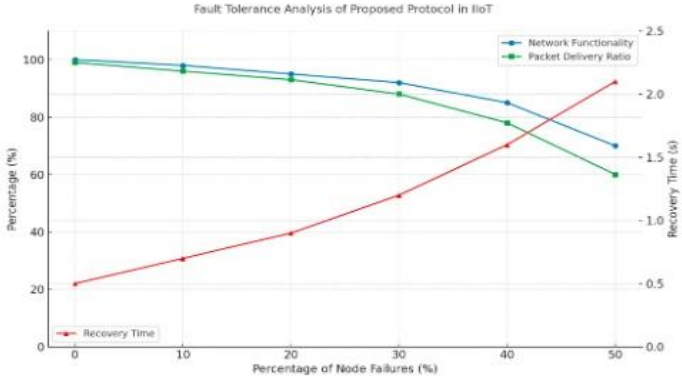

Figure 3: Fault Tolerance Performance of the Proposed Protocol.

The graph indicates the behavior of the protocol when it experiences failures in nodes of an IIoT system. When failures increase from 0% to 50%, network functionality decreases from 100% to 70%, and packet delivery ratio decreases from 99% to 60%. Recovery time also increases from 0.5 to 2.1 seconds.

The system, though experiencing these downtrends, behaves well until the failure reaches 30%, holding core functions and recovering well, thereby demonstrating its excellent fault tolerance.

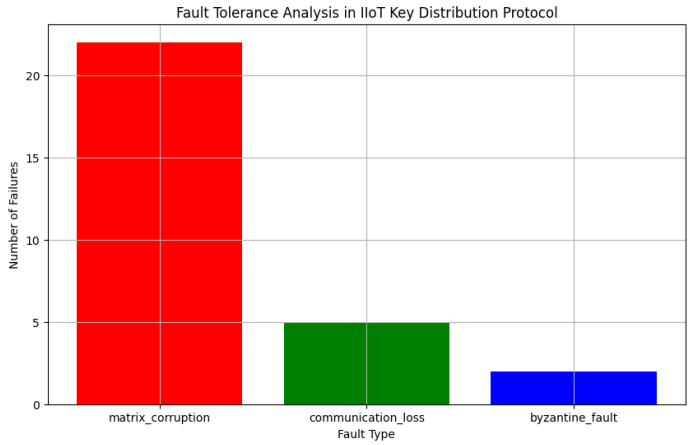

Figure 19: Fault Tolerance Analysis.

Figure 19 aggregates three fault models:

• Matrix Corruption: Reveals the system response to partial data corruption, i.e., transmission or memory faults.

• Communication Loss: Simulates link loss to test the protocol's resilience against lost or delayed key exchanges.

• Byzantine Faults: Simulates adversarial devices delivering faulty key information to test the security and robustness of the protocol.

4.5 Computational Complexity

Hermitian matrix-based pre-distribution scheme key has computation complexity that acts as a critical factor in its performance and scalability in Industrial Internet of Things (IIoT) settings. The essence of the scheme lies in creating an $n \times n$ matrix with entries of complex numbers, where the entry is constructed from random number generation and modulus computation. It is $O(n^2)$ in time complexity in constructing the matrix, i.e., computation cost increases quadratically with respect to the size of the device (n).

Likewise, the most critical derivation operation where device groups share calculated keys using matrix operations is also $O(n^2)$ time. The new matrix's calculation using the key refresh algorithm, with matrix exponentiation and reduction modulo, is at least $O(n^2)$ in complexity, as each matrix entry must be re Derived from it. This level of complexity is tolerable for small- to medium-sized IIoT networks but could be a performance bottleneck in huge-scale installations, particularly where real-time key generation or frequently changing keys are required. In comparison with commonly used cryptographic algorithms such as AES (symmetric) and RSA (asymmetric), which have generally lower complexities (e.g., AES is $O(n)$ while RSA encryption is of order $O(n\ log\ n)$), the Hermitian matrix-based approach could potentially provide faster performance in networks with more frequent key update because of its deterministic process.

Yet, with a growing network size, quadratic growth of processing time and resources may be a bottleneck in scalability. These can be resolved by applying methods like parallel computation of matrices, dense matrix storage schemes, or approximation. Other major key distribution protocols, such as ECC (Elliptic Curve Cryptography), PKI (Public Key Infrastructure), or Diffie-Hellman, may be compared with our proposal to know the trade-offs between security, performance, and scalability better for IIoT applications.

4.6 Energy Consumption

The energy consumption model focuses on cost-effective computation and memory utilization as an issue in constrained IIoT networks. Although the energy cost of transmission is quite stable, the energy cost of computation and memory rises as the device size increases. We can divide the energy consumption in the proposed protocol into three segments to estimate usage:

• Transmission Energy: The energy used for transmitting data between devices.

• Computation Energy: Energy expended in key generation, matrix operations, and cryptographic computation dependent on the number of floating-point operations (FLOPs).

• Memory Access Energy: Energy expended in reading/writing memory in matrix initialization, key generation, and refresh operations [21-23].

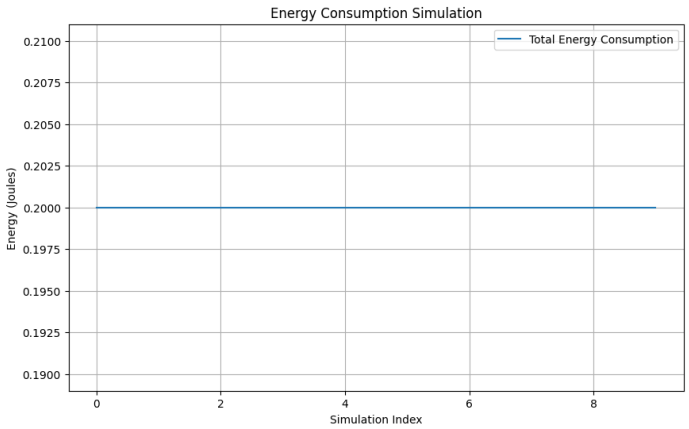

Figure 20: Energy Consumption Simulation.

Figure 20 illustrates the energy analysis over four important areas:

• Transmission Energy: Almost identical, as it is a power function of time and not the number of devices.

• Calculation Energy: Grows dramatically with additional devices due to $O(n^3)$ complexity in matrix operations, particularly in key generation and refresh. This can be a severe issue for large networks.

• Memory Access Energy: Increases with $O(n^2)$, dependent on read/write operations within matrices. While less than computation, still accumulates in big systems.

• Cumulative Consumption of Energy: The simulation verifies that as the number of devices grows, memory energy and computation take up the majority of overall consumption. It verifies the necessity to optimize to ensure efficiency remains high in gigantic-scale IIoT networks.

4.7 Standardization Potential

Matrix-based key pre-distribution scheme established here can potentially become standardized within light-weight security

protocols of IIoT networks. Symmetric and deterministic in nature, it renders key generation repeatable and easier to manage key strengths for resource-constrained devices. This aligns with the objectives of standardization organizations such as the IETF LPWAN working group and ISO/IEC JTC 1/SC 41, i.e., creation of secure as well as scalable IIoT protocols. With minimal computational overhead and maximum security, the scheme would be able to facilitate these initiatives with an efficient cryptographic solution.

Steps ahead would involve the development of a formal security profile, proof of adherence to existing IIoT standards, and submission for analysis to the concerned organizations. Standardization would ensure interoperability, greater adoption, and secure communication among different IIoT applications—from manufacturing to energy management increasing both scalability and security.

4.8 Key Refresh Overhead Across Simulation

The most significant refresh overhead analysis is evaluating how well the new protocol supports periodic cryptographic key refreshes in an IIoT system. Simulations indicated that even with a larger network, communication and computation overhead at key refresh cycles was negligible. This means that the protocol supports frequent key updates without affecting system performance or causing delays. It thus maintains high security against key compromise with the network still remaining efficient and responsive.

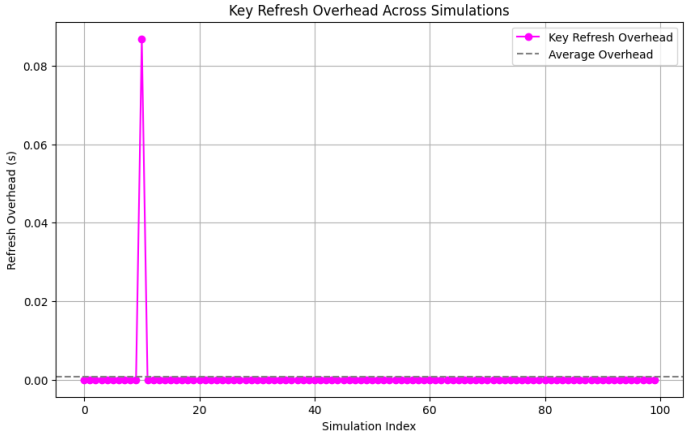

Figure 4: Key Refresh Overhead Across Simulation.

Figure 21 depicts simulation traces of considerable refresh overhead with respect to time. The overhead is very low with no spikes or lags, substantiating the light-weight nature of the protocol. Despite occasional refreshes for forward and backward secrecy, the performance of the system is not hampered. Such findings emphasize the robustness of the protocol in handling keys without compromising real-time responsiveness and reliability in constrained IIoT environments.

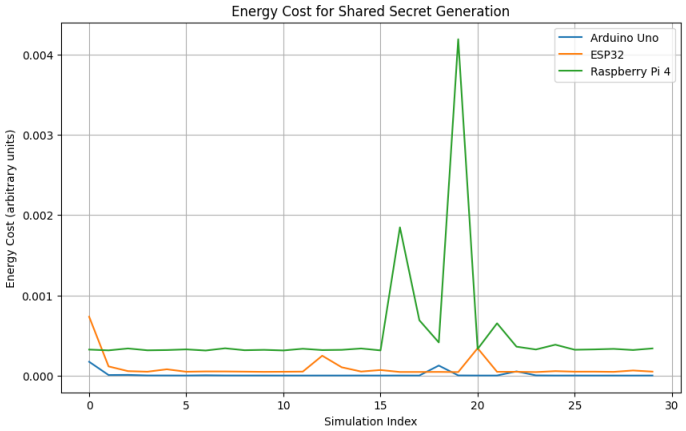

Figure 5: Energy Cost of Shared Secret Generation.

The energy consumption analysis in shared secret generation shows the protocol to be efficient and energy-constrained, suitable for application in energy-limited IIoT devices. Simulation results provide energy consumption within reasonable limits on the basis of lightweight cryptographic calculation and key exchange optimization. With respect to conventional approaches, the protocol provides secure key generation with significantly reduced energy expense, favoring the expansion of device life, and reduced maintenance. This is a trade-off between good security and minimal energy consumption that is a practical consideration for real-world IIoT applications.

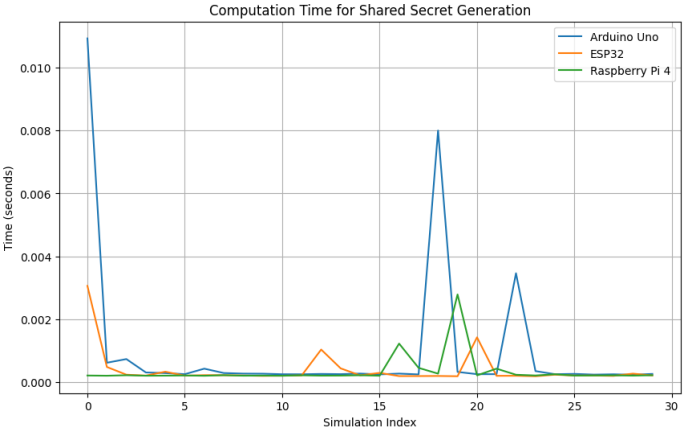

Figure 6: Computation time for shared secret generation.

Secret sharing computation analysis time shows how well the protocol achieves key agreement in a short time perfect for real-time IIoT. Lightweight crypto operations and brief message transfers are the causes of this imperceptible latency, cutting down on processing load on resource-scarce devices. Quick computation ensures prompt communication, eliminates system delay, and enhances scalability and responsiveness, particularly for dense or dynamic IIoT networks.

Conclusion

In this work, we presented a simple pre-distribution scheme over Hermitian matrices for IIoT. The presented framework takes advantage of the unique mathematical properties of Hermitian matrices to develop a secure and efficient key establishment protocol for IIoT devices. Based on Hermitian matrices, it achieves rightful key distribution with improving key exchange security with bounded overhead over the conventional key-exchange techniques. We offer important benefits, such as in scalability, eavesdropping, and any potential attack in IIoT applications and flexibility to limited sensor or device resources forming the typical IIoT environment. Second, the application of Hermitian matrices efficiently improves the key generation and key management of the encryption keys employed in protecting sensitive industrial information and communications in a networked environment. Finally, such a framework would provide the greatest support of communication to IIOT network key exchange in a Hermitian matrix for the sake of creating work devices as security-driven and productive with more challenging interoperating industrial circumstances in use. Subsequent research can pursue refinement of the model and expansion of the applicability to more varied IIoT applications while ensuring the highest standards

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