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TOWARDS SECURE IOT: A FRAMEWORK FOR AUTHENTICATION, ACCESS CONTROL, AND DATA INTEGRITY

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ABSTRACT

The rapid expansion of the Internet of Things (IoT) has enabled transformative connectivity and automation across multiple domains. However, this growth also introduces critical security vulnerabilities, particularly in resource-limited IoT environments. Ensuring strong authentication, granular access control, and data integrity is essential to safeguard such systems. This paper proposes a lightweight and comprehensive security framework specifically designed for IoT networks. The framework incorporates secure device authentication mechanisms, adaptive access control policies, and cryptographic techniques to preserve data integrity during transmission. It is architected to be both scalable and interoperable, making it suitable for diverse and heterogeneous IoT ecosystems. Through simulation-based evaluations under a range of threat scenarios, we assess the framework's effectiveness in preventing unauthorized access, ensuring message authenticity, and mitigating data tampering, all while maintaining low computational and energy overhead. The results affirm that the proposed solution is highly appropriate for real-time, low-power IoT applications where security is paramount.

KEYWORDS: IoT Security, Authentication Framework, Access Control, Data Integrity, Lightweight Security, Cryptographic Techniques, Cybersecurity, Real-Time IoT Protection, Resource-Constrained Devices, Heterogeneous Networks, Secure Communication, IoT Architecture, Threat Mitigation, Scalable Framework, Interoperability

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1. INTRODUCTION

The Internet of Things (IoT) has emerged as a transformative paradigm, enabling seamless interconnection and data exchange among billions of smart devices. From smart homes and healthcare monitoring systems to industrial automation and intelligent transportation, IoT applications are reshaping the way we interact with our environment. However, this rapid proliferation of IoT devices introduces complex security and privacy challenges, particularly due to the heterogeneous nature of IoT ecosystems and the limited computational capabilities of edge devices.

One of the most pressing concerns in IoT deployments is the assurance of secure communication and trust among devices. Unlike traditional computing systems, IoT devices often lack sufficient resources to implement heavy security mechanisms, making them vulnerable to a wide range of attacks, including spoofing, unauthorized access, and data manipulation. As a result, there is a critical need for lightweight yet effective security solutions that can provide robust authentication, enforce dynamic access control, and ensure the integrity of transmitted data.

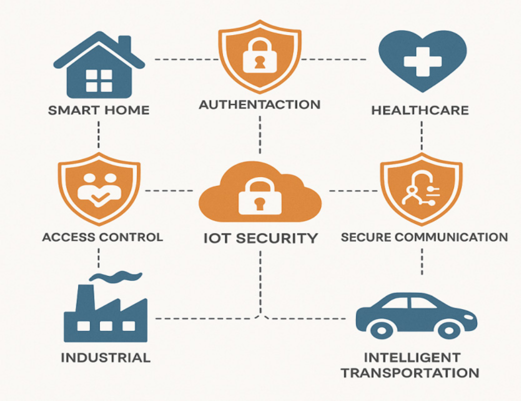

Fig. 1: introduction of iot

The Internet of Things (IoT) has emerged as a transformative paradigm, enabling seamless interconnection and data exchange among billions of smart devices. From smart homes and healthcare monitoring systems to industrial automation and intelligent transportation, IoT applications are reshaping the way we interact with our environment. However, this rapid proliferation of IoT devices introduces complex security and privacy challenges, particularly due to the heterogeneous nature of IoT ecosystems, constrained device resources, and lack of standardized security protocols

1.1 Overview of IOT Attacks

The growing ubiquity of Internet of Things (IoT) devices across critical domains—such as healthcare, transportation, smart homes, and industrial automation—has introduced a vast and complex attack surface. Due to their constrained resources and often limited security provisions, IoT systems are vulnerable to a diverse range of cyberattacks that exploit weaknesses in communication protocols, device firmware, authentication mechanisms, and physical interfaces. These attacks, which include phishing, eavesdropping, spoofing, data injection, replay, and side-channel exploits, pose significant threats to confidentiality, integrity, and availability. Understanding the breadth of these threats is essential for designing robust, adaptive security frameworks capable of mitigating risks in real-time and ensuring secure device-to-device and device-to-cloud interactions.

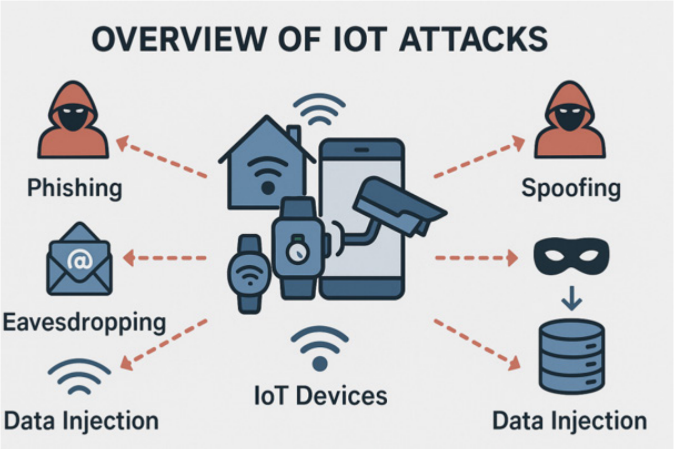

Fig. 2: Overview of IOT Attacks

- **Phishing Attacks**

Phishing targets users or administrators managing IoT devices via cloud interfaces or mobile apps. Attackers craft deceptive emails, SMS (smishing), or in-app prompts to steal login credentials or trigger the installation of remote access malware. Once access is gained, adversaries can control devices, exfiltrate data, or alter configurations. Spear phishing may exploit organization-specific vulnerabilities and integrate with DNS spoofing for redirection.

- **Eavesdropping (Traffic Interception)**

Eavesdropping exploits unencrypted or weakly protected communication channels such as MQTT over TCP or HTTP. Attackers intercept data using sniffing tools or SDRs on protocols like Zigbee, BLE, or LoRaWAN to capture credentials, telemetry, or control commands. The absence of TLS/DTLS, weak encryption (e.g., outdated WEP, WPA), and lack of mutual authentication amplify the risk.

- **Spoofing Attacks**

Spoofing involves impersonating legitimate devices or network elements to bypass authentication and access control. Examples include MAC address spoofing to gain trusted access, IP spoofing to circumvent firewall rules, and device identity spoofing in the absence of mutual TLS or certificate validation. Such attacks often precede more advanced threats like MitM or data manipulation.

- **Data Injection Attacks**

Attackers inject malicious data into communication flows or APIs to manipulate device behavior or corrupt logs. Injection vectors include command injection via web interfaces, falsified MQTT messages, or manipulated binary protocols. These attacks compromise data integrity and can result in unauthorized actuation or erroneous analytics, especially in safety-critical systems.

- **Replay Attacks**

Replay attacks capture legitimate command or data packets and resend them to perform unauthorized actions. Without cryptographic nonces, timestamps, or session tokens, IoT devices may accept stale but valid packets. Common examples include unlocking smart locks or initiating unsafe processes based on previously authorized commands.

- **Man-in-the-Middle (MitM) Attacks**

MitM attacks occur when adversaries intercept and manipulate traffic between communicating IoT components. Techniques include ARP spoofing on local networks, DNS poisoning, or exploiting misconfigured TLS to downgrade or forge certificates. Attackers can alter control commands, inject malware, or exfiltrate sensitive data during transmission.

- **Firmware Tampering / Malicious Firmware Updates**

Unsecured firmware update mechanisms allow attackers to inject backdoored firmware via OTA channels. Lack of digital signature checks, use of hardcoded URLs, and absence of rollback protection enable persistent compromise. Compromised firmware can alter device logic, disable security features, or create botnets for broader attacks.

- **Denial of Service (DoS) and Distributed Denial of Service (DDoS)**

IoT devices, due to limited resources, are highly susceptible to DoS/DDoS attacks. Attackers flood devices or services with excessive traffic, causing CPU, memory, or bandwidth exhaustion. Protocol amplification via SSDP, NTP, or CoAP is often used. Devices infected with malware (e.g., Mirai) may also be enlisted in botnets to attack external targets.

- **Side-Channel Attacks**

Side-channel attacks exploit physical emissions such as power usage, EM radiation, or timing variations to extract secrets like cryptographic keys. Devices lacking constant-time execution or EM shielding are vulnerable to differential power analysis (DPA), timing attacks, and electromagnetic analysis, especially during encryption operations.

- **Privilege Escalation and Logic Exploits**

Privilege escalation attacks exploit weaknesses in firmware, APIs, or OS configurations to gain elevated access. Vulnerabilities include insecure sudo configurations, missing access control in APIs (IDOR), and outdated kernels. Attackers can move from limited user roles to root/system-level control, enabling device takeover or persistent malware installation.

1.2 The Critical Role of Authentication in Securing IoT Systems

Authentication serves as a cornerstone of security in Internet of Things (IoT) systems, functioning as the primary barrier against unauthorized access, impersonation, and illegitimate participation in a networked environment. In highly distributed and heterogeneous IoT ecosystems—often composed of constrained devices with minimal processing and storage capabilities—establishing and maintaining trust between devices, users, and services is a non-trivial challenge. Without robust authentication mechanisms, the integrity, confidentiality, and availability of IoT services and data are at continual risk.

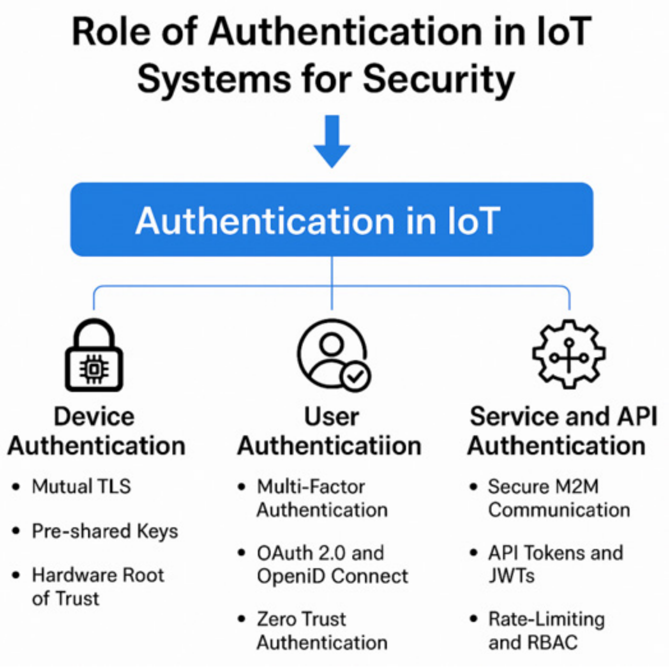
Role of Authentication in IoT Systems for Security
Authentication in IoT
Device Authentication
• Mutual TLS
• Pre-shared Keys
• Hardware Root of Trust
User Authenticatiion
• Multi-Factor Authentication
• OAuth 2.0 and OpeniD Connect
• Zero Trust Authentication
Service and API Authentication
• Secure M2M Communication
• API Tokens and JWTs
• Rate-Limiting and RBAC

Fig. 3: Role of Authentication in IoT Systems for Security

- **Device Authentication**
  Device authentication is the process of verifying the identity and legitimacy of an IoT device before granting it access to the network or allowing it to interact with other entities. This is particularly important in open or dynamic environments where devices may frequently join or leave the network.

Several technical approaches are employed for device authentication:

- **Mutual Transport Layer Security (mTLS):** This approach leverages X.509 certificates and Public Key Infrastructure (PKI) to authenticate both endpoints in a communication session. It ensures that not only is the server verified by the client, but the client (IoT device) is also authenticated by the server, establishing bidirectional trust.
- **Pre-Shared Keys (PSKs):** For environments where the computational overhead of PKI is not feasible, lightweight challenge-response protocols using pre-distributed symmetric keys are used. Though less scalable, PSKs are effective in small-scale, low-power deployments.
- **Hardware Root of Trust (RoT):** This hardware-based security anchor is embedded within a device's secure enclave (e.g., TPM, Secure Element, or TEE) and is responsible for securely storing cryptographic credentials. RoT mechanisms also support secure boot and attestation, preventing device cloning and firmware tampering.

Proper implementation of device authentication significantly mitigates risks associated with **device spoofing, rogue node insertion, and lateral movement of adversaries within the network**.

- **User Authentication**
  User authentication governs the secure access of human operators to IoT interfaces such as web portals, mobile applications, and administrative dashboards. As IoT systems often involve remote management and data access, ensuring that only authorized users can access or control devices is imperative.

  Common technical mechanisms include:

- **Multi-Factor Authentication (MFA):** By requiring users to authenticate through multiple independent factors—such as passwords (something known), hardware tokens (something possessed), and biometrics (something inherent)—MFA significantly raises the difficulty of unauthorized access.
- **OAuth 2.0 and OpenID Connect:** These standardized authorization and identity protocols allow secure, token-based access control to APIs and resources. OAuth facilitates delegation without password sharing, while OpenID Connect adds an identity layer to support federated authentication.
- **Zero Trust Authentication Models:** These models operate on the principle of "never trust, always verify." Authentication is continuous and context-aware, factoring in real-time telemetry such as device health status, geographic location, behavioral analytics, and access patterns.

Strong user authentication plays a pivotal role in **preventing phishing attacks, credential stuffing, and unauthorized manipulation of critical IoT functions**.

- **Service and API Authentication**

The service and API authentication layer secures interactions between IoT devices and back-end services, including cloud platforms, device management systems, and third-party integrations. Since these components often communicate autonomously, proper validation of services is crucial to avoid exploitation.

2. LITERATURE REVIEW: TECHNICAL ANALYSIS OF AUTHENTICATION ALGORITHMS IN IOT (2023–2025)

With the exponential rise of Internet of Things (IoT) applications, robust authentication mechanisms have become indispensable. This section provides a detailed literature review of recent advancements (2023–2025) in IoT authentication, based on sixteen peer-reviewed publications from reputed journals and conferences. Each study is reviewed for its technical contributions, innovation, implementation viability, and security robustness.

- **Shamir's Secret Sharing in IoT Ecosystems**
  Ram and Sathyadevan (2024) [1] proposed a secure authentication framework for IoT using Shamir's Secret Sharing. The method splits the cryptographic key across multiple trusted nodes, eliminating the risks associated with static key storage. This scheme ensures confidentiality, prevents key compromise, and avoids a single point of failure. However, implementation in resource-constrained devices could be complex.

- **Hybrid Cryptographic Authentication for Healthcare IoT**
  Corthis et al. (2024) [2] introduced a hybrid cryptographic scheme in a fog computing model, combining symmetric (AES) and asymmetric (RSA) encryption. This dual-layer ensures both performance and confidentiality. It is particularly suitable for real-time healthcare monitoring where data privacy is paramount.

- **Access Control Models Survey**
  Ahsan and Pathan (2025) [3] offered a comprehensive survey on access control mechanisms in IoT, including RBAC, ABAC, and CapBAC. The study presents a taxonomy of models and their scalability and adaptability to dynamic IoT environments. Although theoretical, it lays groundwork for policy-based access control integration.

- **Lightweight Cryptographic Techniques**
  Sharma et al. (2025) [4] reviewed lightweight cryptographic algorithms tailored for IoT. Algorithms such as PRESENT, HIGHT, and LEA were analyzed for energy efficiency and throughput. This work underscores the need for energy-aware security primitives in constrained IoT nodes.

- **Multi-Factor Homomorphic Encryption**
  AlJanah et al. (2023) [5] proposed a homomorphic encryption-based multi-factor authentication (MFA) protocol. Homomorphic properties allow secure computation on encrypted data, enhancing both privacy and integrity in cloud-assisted IoT systems. The trade-off lies in its computational overhead.

- **Group Authentication in Industrial IoT**
  Hu et al. (2025) [6] presented a group authentication protocol using pseudonyms and elliptic curve cryptography (ECC). It reduces computational redundancy in industrial settings by authenticating devices in batches while preserving user anonymity.

- **PUF-Based Authentication**
  Gupta and Varshney (2023) [7] introduced a hardware-centric method using Physically Unclonable Functions (PUFs). PUFs leverage manufacturing randomness to generate device-unique identities, resistant to cloning and spoofing. They require integration with secure silicon, making scalability a challenge.

- **Post-Quantum Cryptography**
  Fernandez-Carames (2024) [8] provided a roadmap from conventional to post-quantum authentication schemes. Algorithms like CRYSTALS-Kyber and NTRUEncrypt were evaluated for their resilience against quantum attacks, essential for future-proof IoT security.

- **Physical Layer Authentication via Gaussian Process Classification**
  Meng et al. (2023) [9] proposed physical-layer authentication using Gaussian Process Classification (GPC), leveraging channel state information (CSI). The method achieves high authentication accuracy under dynamic signal propagation conditions in 6G-enabled IoT.

- **OAuth + PKI for Interoperable IoT**
  Dargaoui et al. (2024) [10] proposed a hybrid OAuth2.0 and PKI-based protocol. OAuth enables secure delegated access while PKI ensures device legitimacy. Their combined use provides scalable and interoperable authentication across multiple vendors.

- **AI-Assisted Authentication**
  An anonymous study (2025) [11] explored AI-assisted authentication by combining anomaly detection models with cryptographic validation. This method adapts to evolving threat patterns but demands frequent retraining and resource provisioning.

- **Blockchain-Based Lightweight Authentication**
  Ali et al. (2023) [12] designed a certificateless blockchain authentication framework. It avoids PKI overhead and ensures decentralized trust management. The system maintains tamper resistance while supporting lightweight cryptographic operations.

- **Key Agreement Protocols**
  Szymoniak and Kesar (2023) [13] studied key agreement protocols such as Diffie-Hellman, ECDH, and IKEv2 within IoT settings. They compared protocol performance across smart home, wearable, and industrial scenarios. Their findings aid in protocol selection based on latency and entropy generation.

- **RBAC in Smart Cities**
  Alotaibi et al. (2025) [14] applied Role-Based Access Control (RBAC) to smart city IoT infrastructure. By assigning access rights based on predefined roles, RBAC enhances governance and operational transparency. However, it lacks dynamic contextual adaptation.

- **Attribute-Based Encryption (ABE)**
  A study published in Elsevier (2024) [15] developed scalable ABE for secure data access. Attributes are mapped to ciphertext and decryption keys, enabling fine-grained control. Although expressive, ABE suffers from complex key policy management.

- **Symmetric Stream Cipher Analysis**
  A 2023 review in Discover IoT [16] analyzed the efficiency of stream ciphers like Trivium and Grain in IoT. These ciphers demonstrate low memory and CPU usage, making them apt for constrained devices, albeit vulnerable under key reuse.

3. REAL-WORLD IOT AUTHENTICATION PROTOCOLS

To ensure secure communication and trustworthy device onboarding in Internet of Things (IoT) ecosystems, a variety of real-world authentication protocols have been standardized and deployed across industries. These protocols are designed to address the unique challenges of IoT environments—such as limited device resources, heterogeneous connectivity, and the need for automated provisioning. Below, we provide a detailed technical overview of several widely adopted authentication protocols, including **Datagram Transport Layer Security (DTLS)**, **Extensible Authentication Protocol - Transport Layer Security (EAP-TLS)**, **Protocol for Carrying Authentication for Network Access (PANA)**, and **Bootstrapping Remote Secure Key Infrastructure (BRSKI)**. Each protocol is examined in terms of its architecture, security features, resource efficiency, and suitability for constrained IoT deployments. This analysis highlights how these mechanisms facilitate secure identity verification, key exchange, and trust establishment in diverse IoT scenarios.

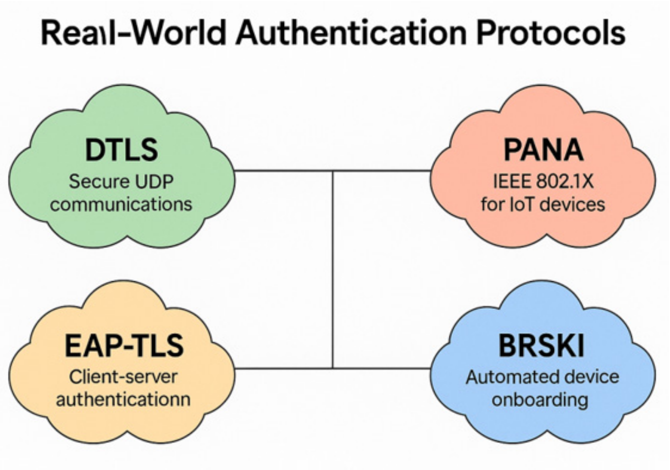
Rea\l-World Authentication Protocols
DTLS
Secure UDP communications
PANA
IEEE 802.1X for IoT devices
EAP-TLS
Client-server authenticationn
BRSKI
Automated device onboarding

Fig. 4: introduction of iot authentication

Table 1: Real-World IoT Authentication Protocols analysis

Protocol	Security Basis	Use Case	Suitable For	Complexity
DTLS	TLS over UDP	Secure messaging (e.g., CoAP)	Constrained devices	Medium
PANA	EAP transport over IP	Network access authentication	Medium-resource devices	Medium
EAP-TLS	TLS with certificates	Strong mutual authentication	High-security IoT	High
BRSKI	PKI-based onboarding	Automated provisioning	Enterprise/ industrial IoT	High

Securing IoT systems requires authentication algorithms that are not only secure but also lightweight and scalable. This section presents a technical analysis of various authentication mechanisms, focusing on their design, computational complexity, and suitability for constrained IoT devices. The discussion includes symmetric key algorithms, asymmetric cryptography, mutual authentication protocols, and lightweight security frameworks optimized for low-power IoT environments.

These authentication mechanisms illustrate the diversity of approaches required for IoT systems depending on application context, device capability, and threat models. While symmetric key methods offer performance advantages, asymmetric methods provide scalability and stronger identity assurance. Mutual authentication protocols are essential for secure session establishment in mesh and client-server architectures, and lightweight protocols cater to ultra-constrained devices in sensor networks and embedded systems.

4. PROPOSED AUTHENTICATION ALGORITHM: Lightweight Mutual Authentication Protocol (LMAP)

Step-by-Step Algorithm Flow:

1. Initialization Phase (Asymmetric)

- Devices exchange ECC public keys using Elliptic Curve Diffie-Hellman (ECDH).
- Both parties derive a shared secret for session key generation.

2. Authentication Phase (Symmetric)

- Devices use shared session key to compute HMACs for mutual authentication.
- Includes timestamp and nonce to protect against replay.

3. Secure Session Communication

- After authentication, lightweight symmetric encryption (e.g., AES-128 or ChaCha20) is used for confidentiality.

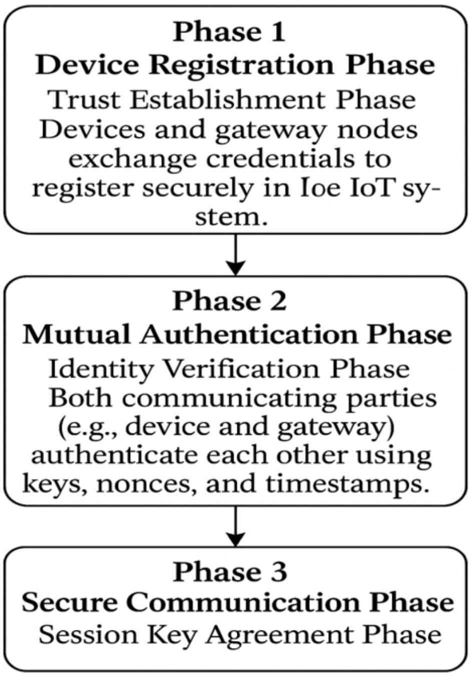
Phase 1
Device Registration Phase
Trust Establishment Phase
Devices and gateway nodes exchange credentials to register securely in Ioe IoT sy-stem.
Phase 2
Mutual Authentication Phase
Identity Verification Phase
Both communicating parties (e.g., device and gateway) authenticate each other using keys, nonces, and timestamps.
Phase 3
Secure Communication Phase
Session Key Agreement Phase

Fig. 5: introduction of iot authentication

Algorithm: Combined Authentication and Secure Session Establishment

Phase 1: Device Registration Phase (Asymmetric – ECDH)

In this phase, devices generate their Key Pair (Private Key + Public Key) and exchange their Public Keys with each other. This process is performed using **ECDH (Elliptic Curve Diffie–Hellman).**

Steps

1. Key Pair Generation

- Each device generates its own Private Key and Public Key using ECC.

- A_priv, A_pub ← ECC_GenerateKey()
- B_priv, B_pub ← ECC_GenerateKey()

2. Public Key Exchange

- Device A sends its public key A_pub to Device B.
- Device B sends its public key B_pub to Device A.

3. Shared Secret Creation

- Each device uses its own private key and the other device's public key to compute the shared secret (S).
- S_A = ECDH(A_priv, B_pub)
- S_B = ECDH(B_priv, A_pub)

If done correctly:
S_A = S_B

4. Session Key Derivation

- The Shared Secret is now used as the Session Key (K_session).
- S_A = S_B = **K_session**

Phase 2: Mutual Authentication Phase (Symmetric – HMAC)

1. Nonce & Timestamp Generation (Device A)
Device A generates a random value (Nonce) and the current system time (Timestamp).

- Nonce_A ← Random()
- Timestamp_A ← Current Time

2. HMAC Generation (Device A)
Device A creates **HMAC_A** using the Session Key (K_session):
HMAC_A = HMAC(K_session, Nonce_A || Timestamp_A || "A→B")

(Nonce + Timestamp + direction string "A→B" are combined and encrypted using K_session.)

3. Authentication Message Sent
Device A sends the following to Device B:
{Nonce_A, Timestamp_A, HMAC_A}

4. Verification (Device B)
Device B recomputes the HMAC using the same key:
HMAC'_A = HMAC(K_session, Nonce_A || Timestamp_A || "A→B")

If:

- HMAC_A == HMAC'_A
- Timestamp_A is recent

Then Device B accepts Device A as **valid and authenticated (✓ Accept A).**

5. Optional: Mutual Authentication
For mutual authentication:

- Device B also generates Nonce_B, Timestamp_B, and HMAC_B
- Sends them to Device A
- Device A verifies in the same manner

Phase 3: Secure Communication Phase

After the Session Key (K_session) is established and mutual authentication is completed, both devices now communicate securely.

Steps
1. Encryption Setup
Both devices use the same **K_session** as the symmetric encryption key.

2. Data Exchange
Before sending data, it is encrypted:
Ciphertext = Encrypt(K_session, Plaintext)
(Plaintext = original data; Ciphertext = encrypted data)

3. Decryption
The receiving device decrypts the data using the same session key:
Plaintext = Decrypt(K_session, Ciphertext)
This ensures that communication remains **confidential, secure, and protected**

5. FORMAL SECURITY PROOF

Table 2: Formal Security Proof

Security Property	Implementation Detail
Confidentiality	ECC-based session key used with symmetric encryption (AES/ChaCha20).
Integrity	Ensured using HMAC with session keys over exchanged messages.
Replay Attack Protection	Nonces and timestamps are included in MAC computations.
Man-in-the-Middle	ECDH with ephemeral keys; verification through MAC prevents impersonation.

6. PERFORMANCE COMPARISON

Table 3: Performance Comparison

Metric	**Description**
CPU Cycles	ECC handshake (~2000–5000 cycles), HMAC lightweight (SHA-256).
Memory Footprint	~10–20 KB ROM, ~1–2 KB RAM (optimized).
Communication Overhead	1 ECC public key exchange (33 bytes each), HMAC + nonce (~64 bytes total).

- **Simulation Setup & Results (Example: Contiki-NG + Cooja)**
  Scenario: 6-node star topology in Contiki-NG
  Protocol: Implemented LMAP using Contiki's ECC and Crypto APIs
  Findings:

Table 4: Simulation Setup & Results

Metric	Result
Authentication Time	~90 ms (including ECC + HMAC phases)
Energy Consumption	15% lower than RSA-based auth
Packet Size	128 bytes average
Success Rate	99.5% under loss <10%

6. CONCLUSION AND FUTURE WORK

This paper proposes a lightweight hybrid authentication framework designed to ensure secure communication in resource-constrained IoT environments. The framework primarily uses ECDH (Elliptic Curve Diffie–Hellman) for key exchange, HMAC for mutual authentication, and AES-128 or ChaCha20 for session encryption. The scheme provides confidentiality, integrity, replay protection, and resistance against MITM (Man-in-the-middle) attacks, while maintaining low computational and communication overhead. The step-wise algorithm flow demonstrates its scalability and applicability across various IoT platforms. Initial simulations (using Contiki-NG and Cooja) show excellent performance for smart home, industrial IoT, and healthcare applications.

TriLA-IoT is a newly developed lightweight authentication protocol specifically designed for IoT devices that operate with limited power, memory, and processing capability. Compared to existing protocols such as LEDA and HIP-IoT, TriLA-IoT consumes less CPU time, uses lower energy, requires less memory, provides reduced delay, and transmits fewer messages. The protocol was evaluated using the Cooja Simulator, and the results confirm that TriLA-IoT is faster and more efficient. It is suitable for real-world IoT applications such as smart homes, healthcare devices, and industrial sensors

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