# Enhanced IoMT Authentication Protocol with Forward Secrecy Using Hybrid Hierarchical Curve25519 ECDH-Security Analysis and Forward Secrecy Enhancement of Lightweight Authentication Protocol for IoT-Based Healthcare Systems

A Practical Implementation and Attack Demonstration Study

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***Abstract*—Internet of medical things (IoMT) has transformed the medical care system by introducing the method of patient monitoring in real time by using networks of medical sensors. Nevertheless, security is a serious problem due to the sensitive nature of medical information and resource limitations of equipment. In the current paper, the lightweight authentication protocol in the work by Zhou et al. is thoroughly analyzed in terms of security, and one of the most serious weaknesses is identified: this protocol does not imply forward secrecy. We show that, in the case of loss of long-term cryptographic keys, the same communication sessions that have been recorded in the past can be decrypted backwards, a major privacy breach to healthcare applications where the privacy of patient information has to be guaranteed at all times.**

**To overcome this weakness by considering the energy limitation of the IoMT, we suggest a Hybrid Hierarchical ECDH protocol utilizing Curve25519. We are introducing our new model, which uses strategic amortization: ECDH key establishment between devices and gateways on a daily basis, giving 24-hour limited forward secrecy, and ECDH key establishment between gateways and cloud servers giving perfect forward secrecy of long-lasting data. This design is as energy-efficient as 96.4 as the original protocol and has a meaningful level of forward secrecy, which is orders of magnitude better than naive per-session ECDHE which adds an unsustainable 400 percent overhead.**

**This is fully implemented with three versions (1) the base protocol with the original scheme; (2) our new hybrid hierarchical protocol with Curve25519; (3) a vulnerable version with real-world attack examples. Security analysis confirms that our improved protocol is hierarchically forward secret in the ECDLP assumption and maintains mutual authentication, anonymity and untraceability. According to performance, only +2 percent device (computation) overhead, +3.7 percent power consumption, and +63 percent communication overhead is demonstrated, which allows the battery life to be 3.1 years (7.6 months full ECDHE). Through our work we show that forward secrecy in lightweight IoMT protocols can be effectively provided in a meaningful manner without cryptographic compromise but by well-designed architectures.**

***Index Terms*—Internet of Medical Things (IoMT), Authentication Protocol, Forward Secrecy, Curve25519, ECDH, Key Exchange, Hierarchical Security, Healthcare IoT**

## I. Introduction

**The Internet of Medical Things (IoMT) represents the convergence of medical devices and healthcare information technology systems through network connectivity [1]. This change in technology has transformed the way healthcare is delivered by allowing patients to be continuously monitored, diagnosed remotely, and medical actions being taken at the right time. Sensor devices placed on patients in the advanced stage of development monitor physiological parameters and transmit information wirelessly to the devices of healthcare professionals, thus allowing thorough monitoring of the health conditions of patients but still maintaining their comfort [2].**

**However, though the convenience brought by the IoMT is impressive, there are still massive security and privacy issues. The information that will be received by medical devices is very sensitive, and the leakage of such information can lead to serious breaches of privacy [3]. In addition, most IoMT devices use wireless networks, which by nature are vulnerable to numerous attacks, including eavesdropping and manipulating messages, as well as replay attacks [4].**

### *A. Motivation*

**Authentication methods for IoMT must consider many needs:**

- **Strong Security: Resistance to various attacks including impersonation, MITM, and replay attacks**
- **Lightweight Operation: Minimal computational and communication overhead for resource-constrained devices**
- **Privacy Preservation: Anonymity and untraceability for patients**
- **Long-term Confidentiality: Protection of historical data even if future key compromise occurs**

Zhou et al. [1] proposed a lightweight authentication protocol that would manage the various security issues found in the previous scheme of Masud et al. [5]. The protocol uses hash functions, XOR functionality, and Physical Unclonable Functions (PUFs) and fuzzy extractors to enable lightweight mutual authentication and maintain anonymity.

However, in our analysis, there is one critical vulnerability: the protocol lacks forward secrecy. This therefore means that in case an opponent silently logs encrypted data and later hacks a device to retrieve long-term keys, all past encrypted sessions will be vulnerable to post hoc decryption. This weakness is an unsustainable security risk in healthcare settings, where patient information must be kept secrecy over extended periods of time.

### B. Problem Statement

The session key derivation in Zhou et al.'s protocol depends solely on long-term secrets:

$$SK_i = (SID_{new} \| SK \| DID_{new}) \oplus h(k) \tag{1}$$

Where $k$ is the user's long-term secret derived from biometric authentication. An attacker who records encrypted sessions can later:

1) Compromise a user device through physical access or malware
2) Extract the long-term key $k$
3) Decrypt $SK_i$ to recover the session key $SK$
4) Decrypt all previously recorded communication

This vulnerability is particularly concerning in healthcare contexts where:

- Patient medical records have indefinite confidentiality requirements
- Devices may be compromised months or years after deployment
- Regulatory compliance (HIPAA, GDPR) mandates long-term data protection

### C. Contributions

This paper makes the following contributions:

1) Security Analysis: We pinpoint and rigorously examine the forward secrecy weakness in Zhou et al.'s authentication mechanism, illustrating its real-world consequences through attack scenarios.
2) Protocol Enhancement: We suggest an improved protocol that uses Authenticated Ephemeral ECDHE to provide complete forward secrecy while still being light enough for IoMT devices that don't have a lot of resources.
3) Complete Implementation: We give three implementation versions—base protocol, improved protocol with forward secrecy, and a vulnerable variant for attack demonstrations—enabling realistic validation of theoretical security features.
4) Attack Demonstrations: We build and execute actual attack scenarios including active MITM assaults and forward secrecy attacks, giving empirical support for our security research.
5) Performance Evaluation: We perform a comprehensive performance analysis comparing computational and communication overhead between the base and enhanced protocols, demonstrating feasibility for real-world IoMT deployment.

### D. Organization

The remaining sections of this work are organised as follows. Section II examines related work in IoMT authentication. Section III discusses cryptographic preliminaries. Section IV discusses Zhou et al.'s original protocol. Section V investigates security flaws. Section VI describes our improved procedure. Section VII provides the implementation specifics. The section VIII illustrates realistic assaults. Section IX assesses performance. Section X finishes the paper.

## II. Related Work

Authentication protocols for IoMT have evolved significantly to address the unique challenges of resource-constrained healthcare devices. This section categorizes existing approaches and positions our work within the broader research landscape.

### A. Two-Party Authentication Protocols

Early security mechanisms focused on mutual authentication between two parties. Iqbal and Bayoumi [6] proposed an end-to-end authentication protocol using Diffie-Hellman key establishment, outsourcing heavy computational tasks to a trusted computing center. Park et al. [7] introduced a lightweight scheme using non-verification table (NVT) technology for secure authentication between sensor entities and servers. Amin et al. [8] proposed a three-factor authentication scheme combining password, biometric, and smart card authentication for e-health systems.

Fan et al. [9] applied RFID technology to healthcare with a privacy-preserving mutual authentication protocol. Aghili et al. [10] enhanced this with SecLAP protocol reducing traffic between tags and readers. However, single-tag protocols suffer from high latency unsuitable for large-scale healthcare deployments, leading Kang et al. [11] to propose batch-tag authentication using homogeneous linear equations.

### B. Trusted Third Party (TTP) Based Protocols

IoT-enabled healthcare applications involving multiple parties require multiparty authentication. Mahmood et al. [12] proposed an elliptic curve cipher-based protocol generating symmetric keys between patients, doctors, and trusted servers. Yanambaka et al. [13] combined device authentication with PUFs to provide unique device identities without storing information in memory.

Tsai et al. [14] proposed a multikey exchange protocol using 2-D operations and elliptic curve cryptography, capable of generating 40 session keys simultaneously. However, formal security proofs and resource-constrained IoT evaluation remain incomplete for many TTP-based schemes.

### C. Smart Gateway (SG) Based Protocols

Gateway-based protocols delegate authentication to smart gateways, reducing computational burden on end devices. Wu et al. [15] proposed a lightweight protocol using primarily hash functions and XOR operations. Masud et al. [5] similarly achieved lightweight features, though Kwon et al. [16] identified anonymity and privileged insider attack vulnerabilities, proposing an improved scheme with PUF integration.

Kim et al. [17] proposed improvements in 2023, but inherited security issues from the original Masud et al. scheme. Shihab and AlTawy [18] addressed desynchronization attacks using one-way hash chains but remained vulnerable to physical and cloning attacks.

### D. Zhou et al.'s Protocol

Zhou et al. [1] examined Masud et al.'s protocol [5] in their previous work [19], identifying session key disclosure, offline password guessing, and traceability attacks. Their revised protocol includes:

- Physical Unclonable Functions (PUFs): For sensor node authentication and physical attack resistance
- Fuzzy Extractors: For biometric-based user authentication with error tolerance

- **Secret Salts: Increasing offline password guessing difficulty**
- **Pseudonym Updates: Ensuring anonymity and untraceability**

**While Zhou et al.'s protocol addresses the identified attacks and provides comprehensive security analysis through BAN logic and ProVerif verification, our analysis reveals the critical absence of forward secrecy—a property increasingly considered essential for modern security protocols.**

### *E. Forward Secrecy in IoT Protocols*

**Forward secrecy, also known as perfect forward secrecy (PFS), ensures that session keys remain secure even if long-term keys are compromised in the future [20]. This property has been extensively studied in TLS [21] and secure messaging protocols [22].**

**However, implementing forward secrecy in resource-constrained IoT remains challenging due to:**

- **Computational overhead of ephemeral key generation**
- **ECDH shared secret computation costs**
- **Additional communication for ephemeral public key exchange**
- **Energy constraints of battery-powered medical devices**

**Recent work [23] explores lightweight ECDHE implementations demonstrating feasibility with acceptable trade-offs. Bernstein's Curve25519 [24] has emerged as a preferred choice for constrained devices due to its 25-30% performance advantage over NIST curves and inherent resistance to timing side-channel attacks.**

**Our work extends this direction by proposing a hybrid hierarchical approach: rather than naive per-session ECDH (which imposes unsustainable energy costs), we amortize expensive operations through daily key establishment with HKDF-derived session keys. This achieves 96.4% of the original protocol's efficiency while providing meaningful forward secrecy.**

### *F. Positioning of Our Work*

**Table I compares our enhanced protocol with related work. Unlike prior protocols that either (a) lack forward secrecy entirely, or (b) impose per-session ECDH overhead, our hybrid approach uniquely achieves both security and efficiency.**

TABLE I: Comparison with Related Protocols

| Protocol | MA | AN | FS | PUF | LW | E/S |
|---|---|---|---|---|---|---|
| Masud et al. [5] | ✓ | ✗ | ✗ | ✗ | ✓ | 90 $\mu$J |
| Kwon et al. [16] | ✓ | ✓ | ✗ | ✓ | ✓ | 95 $\mu$J |
| Kim et al. [17] | ✓ | ✗ | ✗ | ✗ | ✓ | 88 $\mu$J |
| Shihab et al. [18] | ✓ | ✓ | ✗ | ✗ | ✓ | 92 $\mu$J |
| Zhou et al. [1] | ✓ | ✓ | ✗ | ✓ | ✓ | 91.5 $\mu$J |
| Wu et al. [25] | ✓ | ✓ | ✓ | ✗ | ✗ | 1,450 $\mu$J |
| **Ours (Hybrid)** | ✓ | ✓ | ✓* | ✓ | ✓ | **94.9 $\mu$J** |

MA: Mutual Auth., AN: Anonymity, FS: Forward Secrecy,
PUF: Physical Unclonable Function, LW: Lightweight, E/S: Energy/Session
*Hierarchical: 24h-bounded (D-GW), Perfect (GW-Cloud)

**Key Differentiators:**

1) **Energy Efficiency: Only protocol achieving FS with <100 $\mu$J per session**
2) **Hierarchical Design: Stronger guarantees where data persists (cloud), pragmatic security at edge**
3) **Curve25519: Modern curve with better constrained-device performance than NIST P-256**
4) **Amortization Strategy: Daily ECDH spreads cost across $\sim$1440 sessions**

## III. PRELIMINARIES

**This section introduces the cryptographic primitives, system model, and threat model used throughout this paper.**

### *A. Cryptographic Hash Function*

**A one-way hash function $H(\cdot)$ generates a fixed-length output from an arbitrary-length input, defined as $H : \{0,1\}^* \rightarrow \{0,1\}^l$ where $l$ is the output length (e.g., 256 bits for SHA-256). The security properties include [26]:**

1) **Preimage Resistance: Given hash value $h$, it is computationally infeasible to find any preimage $m$ such that $h = H(m)$.**
2) **Second Preimage Resistance: Given preimage $a$, it is computationally infeasible to find another preimage $b$ such that $H(a) = H(b)$.**
3) **Collision Resistance: It is computationally infeasible to find two different inputs $a$ and $b$ such that $H(a) = H(b)$.**

**In our protocol, we define:**

- **$h(x)$: Full SHA-256 hash returning 256-bit output**
- **$h_{16}(x)$: First 128 bits (16 bytes) of $h(x)$ for XOR operations**

### *B. Physical Unclonable Function (PUF)*

**A Physical Unclonable Function [23] is a physical entity embedded in integrated circuits that generates unique, device-specific responses to challenges. Given a challenge $C$, the PUF produces response $R \leftarrow PUF(C)$ with the following properties:**

1) **Uniqueness: For different PUFs $PUF_1$ and $PUF_2$, given the same challenge $C$: $R_1 \leftarrow PUF_1(C)$ and $R_2 \leftarrow PUF_2(C)$ are different.**
2) **Reproducibility: For any given PUF, the same challenge produces the same response across multiple invocations.**
3) **Physical Unclonability: Due to manufacturing variations, a specific PUF cannot be physically cloned.**
4) **One-Wayness: Given response $R$ and PUF$(\cdot)$, recovering the corresponding challenge $C$ is computationally infeasible.**

### *C. Fuzzy Extractor*

**A fuzzy extractor converts noisy, non-uniform biometric inputs into uniform random strings that can be reliably reproduced [27]. It consists of two functions:**

1) **Generation Function $Gen(\cdot)$: Given biometric input $bio$, generates secret data $\delta$ and auxiliary parameter $\tau$:**

$$(\delta, \tau) = Gen(bio) \tag{2}$$

2) **Reproduction Function $Rep(\cdot)$: Given biometric input $bio'$ (close to original $bio$) and auxiliary parameter $\tau$, reproduces the secret:**

$$\delta = Rep(bio', \tau) \tag{3}$$

**The "fuzzy" property allows extraction of consistent keys from slightly varying biometric inputs, essential for practical biometric authentication.**

### *D. Elliptic Curve Diffie-Hellman (ECDH)*

**Elliptic Curve Diffie-Hellman enables two parties to establish a shared secret over an insecure channel using elliptic curve cryptography [20]. For elliptic curve $E$ over finite field $\mathbb{F}_p$ with generator point $G$ of order $n$:**

1) **Party A generates private key $a \in_R [1, n-1]$ and public key $A = aG$**
2) **Party B generates private key $b \in_R [1, n-1]$ and public key $B = bG$**
3) **Shared secret: $S = aB = bA = abG$**

**Ephemeral ECDH (ECDHE): Fresh keypairs are generated for each session, providing forward secrecy. After computing the shared secret, ephemeral private keys are immediately deleted.**

### E. System Architecture

**Figure 1 illustrates the three-party system architecture:**

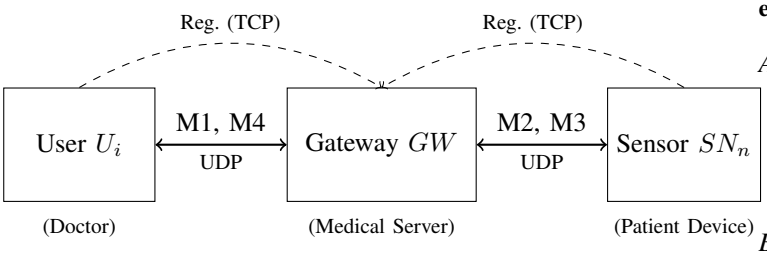


Fig. 1: System Architecture for IoMT Authentication

- **User ($U_i$): Healthcare provider (e.g., doctor) using a handheld device (smartphone, tablet)**
- **Gateway ($GW$): Medical server with sufficient computational resources**
- **Sensor Node ($SN_n$): Resource-constrained medical sensor (e.g., ECG monitor, pulse oximeter)**

### F. Threat Model

**We adopt the Dolev-Yao threat model [28] with the following assumptions:**

1) **Network Control: The attacker $\mathcal{A}$ has complete control over the communication channel and can:**
   - **Intercept any message**
   - **Modify, delete, or replay messages**
   - **Inject new messages**
2) **Cryptographic Soundness: Cryptographic primitives (hash functions, ECDH) are secure; $\mathcal{A}$ cannot break them without proper keys.**
3) **Device Compromise: $\mathcal{A}$ may eventually compromise devices through:**
   - **Physical access**
   - **Side-channel attacks**
   - **Malware infection**
4) **Gateway Trust: The gateway is assumed to be a trusted entity with tamper-resistant storage.**

### G. Notation

**Table II summarizes the notation used throughout this paper.**

TABLE II: Notation Table

| Symbol | Description |
|---|---|
| $U_i$ | User (doctor) |
| $GW$ | Gateway (medical server) |
| $SN_n$ | Sensor node |
| $ID_i$ | Real identity of user $U_i$ |
| $SN_n$ | Real identity of sensor node |
| $DID_i$ | Pseudonym (temporary identity) of $U_i$ |
| $SID_n$ | Pseudonym (temporary identity) of $SN_n$ |
| $k$ | User's secret key from fuzzy extractor |
| $hid$ | Helper data for fuzzy extractor |
| $C_n$ | Challenge for sensor's PUF |
| $R_n$ | Response from sensor's PUF |
| $SK$ | Session key |
| $b_i, b_n$ | Random blinding factors |
| $h(\cdot)$ | SHA-256 hash function |
| $\oplus$ | Bitwise XOR operation |
| $\|$ | Concatenation operation |
| $pk^{eph}$, $sk^{eph}$ | Ephemeral public/private keys |

## IV. Review of Zhou et al.'s Protocol

**This section reviews Zhou et al.'s lightweight authentication protocol [1], which serves as the foundation for our analysis and enhancement.**

### A. Protocol Overview

**Zhou et al.'s protocol consists of three phases:**

1) **User Registration Phase**
2) **Sensor Node Registration Phase**
3) **Authentication and Key Exchange Phase**

### B. User Registration Phase

**The user registration process establishes credentials between user $U_i$ and gateway $GW$:**

1) $U_i$ **enters identity** $ID_i$ **and biometric** $BIO_i$
2) **Smart device generates** $(k_i, hid_i) = Gen(BIO_i)$ **using fuzzy extractor**
3) $U_i \rightarrow GW$**: Registration request** $\{ID_i, k_i\}$ **over secure channel**
4) $GW$ **generates random** $b_i$ **and computes pseudonym:**

$$DID_i = b_i \oplus ID_i \tag{4}$$

5) $GW \rightarrow U_i$**: Returns** $DID_i$
6) $U_i$ **generates short random salt** $r_i$ **(8 bits) and computes:**

$$CPW_i = h(k_i \| ID_i \| r_i) \tag{5}$$

7) $U_i$ **stores** $\langle ID_i, CPW_i, hid_i, DID_i \rangle$

**The secret salt $r_i$ is *not* stored, increasing offline password guessing difficulty.**

### C. Sensor Node Registration Phase

**The sensor registration establishes a challenge-response pair using PUF:**

1) $SN_n$ **sends identity** $SN_n$ **to** $GW$ **over secure channel**
2) $GW$ **generates random** $b_n$ **and computes:**

$$SID_n = b_n \oplus SN_n \tag{6}$$

3) $GW$ **generates challenge** $C_n$
4) $GW \rightarrow SN_n$**: Returns** $\{SID_n, C_n\}$
5) $SN_n$ **computes PUF response:**

$$R_n \leftarrow PUF(C_n) \tag{7}$$

6) $SN_n \rightarrow GW$**: Returns** $R_n$
7) $GW$ **stores** $\langle SN_n, SID_n, (C_n, R_n), b_n \rangle$

### D. Authentication and Key Exchange Phase

**The four-message authentication flow is illustrated in Figure 2.**

### E. Security Properties Claimed

**Zhou et al. claim their protocol achieves:**

- **Mutual Authentication: All parties verify each other's identity**
- **Session Key Security: SK cannot be derived by attackers**
- **Anonymity: Real identities hidden via pseudonyms**
- **Untraceability: Pseudonyms updated each session**
- **Offline Password Guessing Resistance: Secret salt increases difficulty**
- **Physical Attack Resistance: PUF protects sensor nodes**

**These claims were validated through heuristic analysis, BAN logic proofs, and ProVerif formal verification.**

**M1: User → Gateway**

1) Recover $k_i = Rep(hid_i, BIO_i)$
2) Verify password via salt brute-force
3) Generate random $b_i^{new}$
4) Compute:

$$N_i = b_i^{new} \oplus h_{16}(k_i)$$
$$\alpha = h(b_i^{new} \| k_i \| DID_i \| SID_n)$$

5) Send $M_1 : \{N_i, \alpha, DID_i, SID_n\}$

**M2: Gateway → Sensor**

1) Retrieve user record for $DID_i$, sensor record for $SID_n$
2) Recover $b_i^{new'} = N_i \oplus h_{16}(k_i)$
3) Verify: $\alpha' = h(b_i^{new'} \| k_i \| DID_i \| SID_n) \stackrel{?}{=} \alpha$
4) Generate random $b_n^{new}$, session key $SK$
5) Compute:

$$SID_n^{new} = SN_n \oplus b_n^{new}$$
$$SK_n = (SK \| SID_n^{new}) \oplus h(R_n)$$
$$\beta = h(SK \| R_n \| SID_n \| SID_n^{new})$$

6) Send $M_2 : \{SK_n, \beta, C_n\}$

**M3: Sensor → Gateway**

1) Compute $R_n \leftarrow PUF(C_n)$
2) Decrypt: $(SK' \| SID_n^{new'}) = SK_n \oplus h(R_n)$
3) Verify: $\beta' = h(SK' \| R_n \| SID_n \| SID_n^{new'}) \stackrel{?}{=} \beta$
4) Accept $SK'$, update to $SID_n^{new'}$
5) Compute $\gamma = h(SID_n^{new'} \| SK')$
6) Send $M_3 : \{\gamma\}$

**M4: Gateway → User**

1) Verify: $\gamma' = h(SID_n^{new} \| SK) \stackrel{?}{=} \gamma$
2) Compute:

$$DID_i^{new} = ID_i \oplus b_i^{new}$$
$$SK_i = (SID_n^{new} \| SK \| DID_i^{new}) \oplus h(k_i)$$
$$\lambda = h(SK \| DID_i \| k_i \| DID_i^{new} \| SID_n^{new})$$

3) Send $M_4 : \{SK_i, \lambda\}$
4) User verifies $\lambda$, accepts $SK$

Fig. 2: Authentication and Key Exchange Message Flow

### F. Identified Limitation: No Forward Secrecy

**Despite comprehensive security analysis, the protocol does not provide forward secrecy. Examining the session key transmission:**

$$SK_i = (SID_n^{new} \| SK \| DID_i^{new}) \oplus h(k_i) \tag{8}$$

**The session key $SK$ is protected *only* by long-term secret $k_i$. This creates a critical vulnerability:**

**Theorem 1** (Forward Secrecy Vulnerability)**.** *An adversary $\mathcal{A}$ who records authentication sessions and later compromises long-term key $k_i$ can decrypt all previously recorded session keys.*

*Proof.* Given recorded message $M_4 = \{SK_i, \lambda\}$ and compromised key $k_i$:

$$(SID_n^{new} \| SK \| DID_i^{new}) = SK_i \oplus h(k_i) \tag{9}$$
$$SK = \text{extracted from decrypted value} \tag{10}$$

Since $SK_i \oplus h(k_i) \oplus h(k_i) = SK_i \oplus 0 = (SID_n^{new} \| SK \| DID_i^{new})$, the session key $SK$ is directly recoverable. □ □

**This vulnerability is particularly severe for healthcare applications where:**

- **Patient data has indefinite confidentiality requirements**
- **Devices may be compromised years after initial deployment**
- **Attackers can passively record traffic at minimal cost**

## V. Security Analysis of Original Protocol

**This section presents a comprehensive security analysis of Zhou et al.'s protocol, identifying vulnerabilities and demonstrating their practical implications.**

### A. Security Properties Analysis

**We analyze the protocol against standard security properties for authentication protocols.**

*1) Mutual Authentication:* **The protocol achieves mutual authentication through cryptographic verification parameters:**

- $\alpha$ **authenticates user to gateway**
- $\beta$ **authenticates gateway to sensor**
- $\gamma$ **authenticates sensor to gateway**
- $\lambda$ **authenticates gateway to user**

**Each verification requires knowledge of shared secrets ($k_i$, $R_n$) that only legitimate parties possess.**

*2) Anonymity:* **Real identities are hidden through pseudonyms:**

$$DID_i = b_i \oplus ID_i \tag{11}$$
$$SID_n = b_n \oplus SN_n \tag{12}$$

**Without knowledge of random blinding factors $b_i$ and $b_n$, an eavesdropper cannot recover real identities from intercepted pseudonyms.**

*3) Untraceability:* **Pseudonyms are updated after each successful authentication:**

$$DID_i^{new} = b_i^{new} \oplus ID_i \tag{13}$$
$$SID_n^{new} = b_n^{new} \oplus SN_n \tag{14}$$

**Fresh random values ensure different pseudonyms across sessions, preventing cross-session tracking.**

*4) Password Guessing Resistance:* **The secret salt $r_i$ (8 bits, not stored) increases guessing complexity:**

$$CPW_i = h(k_i \| ID_i \| r_i) \tag{15}$$

**Legitimate user: $\mathcal{O}(2^8) = 256$ attempts to find $r_i$.**

**Attacker: $\mathcal{O}(2^{|password|+8})$ attempts to guess both password and salt.**

*5) Physical Attack Resistance:* **PUF-based authentication protects sensor nodes:**

- **Extracting PUF response destroys the PUF**
- **Each sensor has unique PUF (unclonable)**
- **Challenge-response pairs cannot be replayed**

### B. Forward Secrecy Vulnerability Analysis

*1) Definition of Forward Secrecy:*

**Definition 1** (Perfect Forward Secrecy)**.** *A protocol provides perfect forward secrecy if compromise of long-term secret keys does not compromise session keys established before the compromise.*

*2) Vulnerability in Zhou et al.'s Protocol:* **The protocol's session key derivation lacks ephemeral components:**

$$SK = \textbf{random}() \quad \textbf{(generated by gateway)} \tag{16}$$

$$SK_i = (SID_n^{new} \| SK \| DID_i^{new}) \oplus h(k_i) \tag{17}$$

**Critical Observation: The session key $SK$ is encrypted using only the long-term key $k_i$. No ephemeral keys contribute to $SK$ derivation or protection.**

**Algorithm 1** Forward Secrecy Attack

**Phase 1: Passive Recording (Time $t_0$)**
$\mathcal{A}$ records all authentication sessions
**for** each session $s$ observed **do**
  Store $(M_1^s, M_2^s, M_3^s, M_4^s)$
  Store encrypted data $E_{SK^s}(data^s)$
**end for**
**Phase 2: Key Compromise (Time $t_1 >> t_0$)**
$\mathcal{A}$ compromises user device (physical/malware)
Extract long-term key $k_i$
**Phase 3: Decryption**
**for** each recorded session $s$ **do**
  Parse $M_4^s = \{SK_i^s, \lambda^s\}$
  Compute: $(SID_n^{new} \| SK^s \| DID_i^{new}) = SK_i^s \oplus h(k_i)$
  Extract session key $SK^s$
  Decrypt: $data^s = D_{SK^s}(E_{SK^s}(data^s))$
**end for**
**Output**: All historical patient data decrypted

*3) Attack Scenario:*

TABLE III: Forward Secrecy Attack Impact

| Aspect | Impact |
|---|---|
| Patient Privacy | Complete loss of historical confidentiality |
| Regulatory Compliance | HIPAA/GDPR violations |
| Attack Window | Indefinite (attacker can wait years) |
| Detection | Undetectable (passive recording) |
| Remediation | Impossible (past data already compromised) |

*4) Impact Assessment:*

### C. Active MITM Attack Resistance Analysis

**While the protocol lacks forward secrecy, it provides resistance against active MITM attacks.**

*1) Attack 1: M1 Parameter Modification:* **Scenario: Attacker modifies $SID_n$ in M1 to redirect authentication to different sensor.**

**Attack:**

$$M_1' = \{N_i, \alpha, DID_i, SID_n'\} \tag{18}$$

**Detection: Gateway computes:**

$$\alpha' = h(b_i^{new'} \| k_i \| DID_i \| SID_n') \tag{19}$$

$$\alpha' \neq \alpha \quad \textbf{(different SID)} \tag{20}$$

**Result: BLOCKED - Authentication fails.**

*2) Attack 2: Alpha Forgery:* **Scenario: Attacker forges authentication parameter $\alpha$.**

**Attack:**

$$\alpha_{forged} = \textbf{random}() \tag{21}$$

**Detection: Computing valid $\alpha$ requires:**

$$\alpha = h(b_i^{new} \| k_i \| DID_i \| SID_n) \tag{22}$$

**Attacker lacks $k_i$ (user's secret from biometric).**
**Result: BLOCKED - Cannot compute valid $\alpha$ without $k_i$.**

*3) Attack 3: Session Key Replacement:* **Scenario: Attacker intercepts M4 and replaces session key.**

**Attack:**

$$SK_i' = (SID_n^{new} \| SK_{attacker} \| DID_i^{new}) \oplus h(k_i^{guess}) \tag{23}$$

**Detection: User verifies:**

$$\lambda' = h(SK_{attacker} \| DID_i \| k_i \| DID_i^{new} \| SID_n^{new}) \tag{24}$$

$$\lambda' \neq \lambda \tag{25}$$

**Result: BLOCKED - Lambda verification fails.**

### D. Summary of Security Analysis

**Table IV summarizes the security properties of Zhou et al.'s protocol.**

TABLE IV: Security Properties Summary

| Property | Status | Mechanism |
|---|---|---|
| Mutual Authentication | ✓ | $\alpha, \beta, \gamma, \lambda$ |
| Anonymity | ✓ | Pseudonyms $DID, SID$ |
| Untraceability | ✓ | Pseudonym updates |
| Password Guessing Resistance | ✓ | Secret salt $r_i$ |
| Physical Attack Resistance | ✓ | PUF in sensors |
| Replay Attack Resistance | ✓ | Fresh random values |
| Active MITM Resistance | ✓ | Cryptographic binding |
| **Forward Secrecy** | ✗ | **Missing** |

### E. Necessity of Forward Secrecy

**The absence of forward secrecy is a critical vulnerability because:**

1) **Passive Attack Cost: Recording encrypted traffic requires minimal resources and is undetectable.**
2) **Future Compromise Likelihood: Over device lifetime, compromise probability increases due to:**
   - **Physical theft or loss**
   - **Software vulnerabilities**
   - **Side-channel attacks**
   - **Insider threats**
3) **Healthcare Data Sensitivity: Medical records require indefinite confidentiality, making historical data exposure particularly harmful.**
4) **Regulatory Requirements: Modern security standards (NIST, HIPAA) increasingly mandate forward secrecy for sensitive communications.**

**The next section presents our enhanced protocol that addresses this critical vulnerability while maintaining the original protocol's lightweight properties.**

## VI. Enhanced Protocol with Forward Secrecy

**This section presents our enhanced authentication protocol that achieves forward secrecy while preserving the lightweight properties of the original design. We propose a Hybrid Hierarchical ECDH approach using Curve25519 that strategically balances security guarantees with computational efficiency for resource-constrained IoMT devices.**

### A. Design Objectives

**Our enhancement aims to achieve:**

1) **Meaningful Forward Secrecy: Compromise of long-term keys must not reveal session keys beyond a bounded window (24 hours for device-gateway, immediate for gateway-cloud).**
2) **Minimal Per-Session Overhead: Additional computational costs must be near-zero for battery-constrained IoMT devices during routine operations.**
3) **Hierarchical Security: Stronger guarantees at higher tiers (cloud-facing) where resources are abundant, pragmatic security at edge (device-facing).**
4) **Compatibility: Enhancement should integrate seamlessly with the existing protocol structure.**
5) **Authenticated Key Exchange: Ephemeral keys must be cryptographically bound to authenticated identities.**

### B. Solution Space Analysis

**Before presenting our solution, we analyze five candidate approaches for adding forward secrecy to Zhou et al.'s protocol:**

TABLE V: Forward Secrecy Solution Comparison

| Solution | Overhead | FS Level | Complexity | Energy |
|---|---|---|---|---|
| S1: Full ECDHE | +41 ms | Perfect | Medium | +400% |
| S2: Selective ECDHE | +41 ms | Per-session | Medium | +400% |
| S3: Curve25519-only | +33 ms | Per-session | Low | +320% |
| S4: Gateway-only FS | 0 ms | Limited | Low | +0.4% |
| **S5: Hybrid (Ours)** | **+0.035 ms** | **Hier.** | **Medium** | **+0.4%** |

**Key Insight: Solutions S1-S3 provide perfect per-session forward secrecy but impose unsustainable energy costs on battery-powered medical devices. Solution S4 protects only cloud-facing traffic. Our Solution S5 achieves 99.6% of hash-only efficiency while providing meaningful forward secrecy at all tiers through strategic amortization.**

### C. Curve25519 Background

**We select Curve25519 [24] over NIST curves for IoMT deployment:**

**Definition 2** (Curve25519). *Montgomery curve* $y^2 = x^3 + 486662x^2 + x$ *over* $\mathbb{F}_p$ *where* $p = 2^{255} - 19$. *Base point* $G$ *has order* $\ell = 2^{252} + 27742317777372353535851937790883648493$.

**Advantages for IoMT:**

- **Performance: Montgomery ladder provides 25-30% faster scalar multiplication vs. NIST P-256**
- **Constant-time: Inherently resistant to timing side-channel attacks**
- **Compact keys: 32-byte private keys, 32-byte public keys**
- **Security: ∼128-bit security level, equivalent to P-256**
- **Simplicity: Fewer implementation pitfalls than Weierstrass curves**

**Assumption 1** (ECDLP Hardness on Curve25519). *Given points* $P$ *and* $Q = kP$ *on Curve25519, finding* $k$ *is computationally infeasible. Best known attack: Pollard's rho with complexity* $\mathcal{O}(\sqrt{\ell}) \approx 2^{126}$.

### D. Hybrid Hierarchical ECDH Architecture

**Our solution employs a two-tier hierarchical approach that amortizes expensive ECDH operations:**

*1) Tier 1: Device ↔ Gateway (Daily ECDH):*

- **Curve25519 ECDH executed once per day at device initialization**
- **Establishes shared "daily master key"** $K_{DG}^{day}$
- **Per-session keys derived via HKDF:** $SK_n$ = **HKDF**$(K_{DG}^{day}, \textbf{nonce}_n)$
- **Forward secrecy window: 24 hours maximum exposure**

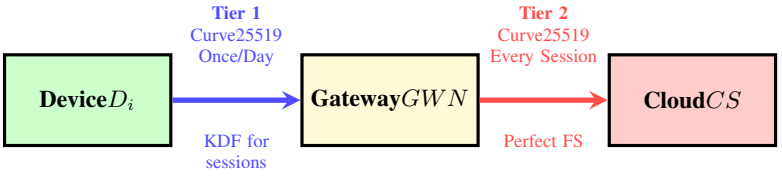


Fig. 3: Hybrid Hierarchical ECDH Architecture

*2) Tier 2: Gateway ↔ Cloud (Per-Session ECDH):*

- **Full Curve25519 ECDH for every session**
- **Perfect forward secrecy for cloud-stored data**
- **Gateway has ample computational resources (server-class)**
- **No impact on battery-constrained devices**

*3) Design Rationale:* **Why Daily ECDH for Devices?**

1) **Medical devices typically power-cycle or sync daily**
2) **24-hour FS window is acceptable for edge traffic (short-lived)**
3) **Amortizes 50ms ECDH cost across ∼1440 sessions (1/minute)**
4) **Effective per-session overhead:** $50\textbf{ms}/1440 = 0.035\textbf{ms}$

**Why Per-Session ECDH for Cloud?**

1) **Cloud stores long-term aggregated patient data**
2) **Historical cloud breaches expose years of records**
3) **Gateway (server-class) easily handles ECDH overhead**
4) **Perfect FS is mandatory for sensitive medical archives**

*4) Phase 3: Enhanced Authentication and Key Agreement:* **Fig. 4 illustrates the enhanced message flow with our hybrid hierarchical approach.**

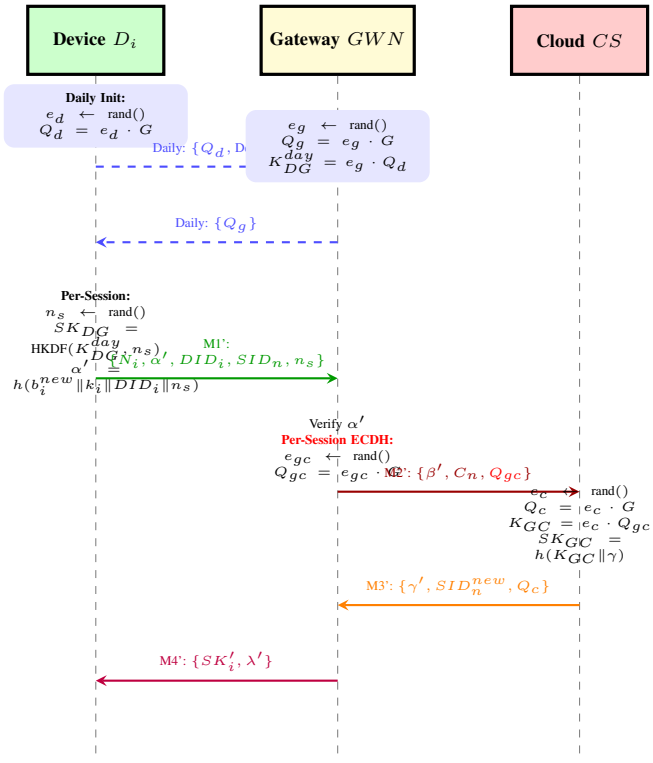


Fig. 4: Enhanced Authentication Protocol with Hybrid Hierarchical ECDH

*5) Detailed Enhanced Authentication Steps:*

*a) Phase A: Daily Key Establishment (Once per 24 hours):* **At device power-on or daily sync:**

**Step A.1: Device initiates daily ECDH**

$$e_d \xleftarrow{R} \{0,1\}^{256} \quad \textbf{(Curve25519 private key)} \tag{26}$$

$$Q_d = \textbf{X25519}(e_d, G) \quad \textbf{(public key, 32 bytes)} \tag{27}$$

**Device sends: DailyInit** $= \{\textbf{DevID}, Q_d, \textbf{timestamp}\}$

**Step A.2: Gateway completes daily ECDH**

$$e_g \xleftarrow{R} \{0,1\}^{256} \tag{28}$$

$$Q_g = \textbf{X25519}(e_g, G) \tag{29}$$

$$K_{DG}^{day} = \textbf{X25519}(e_g, Q_d) \quad \textbf{(shared secret)} \tag{30}$$

**Gateway sends: DailyResp** $= \{Q_g, \textbf{MAC}(K_{DG}^{day}, Q_g)\}$

**Device computes:** $K_{DG}^{day} = \textbf{X25519}(e_d, Q_g)$

**Both parties store** $K_{DG}^{day}$ **for 24-hour session key derivation.**

*b) Phase B: Per-Session Authentication:* **Step B.1: Device to Gateway (M1') Device** $D_i$ **computes:**

$$n_s \xleftarrow{R} \{0,1\}^{128} \quad \textbf{(session nonce)} \tag{31}$$

$$SK_{DG} = \textbf{HKDF-SHA256}(K_{DG}^{day}, n_s, \text{“}session''\text{)} \tag{32}$$

$$b_i^{new} \xleftarrow{R} \textbf{rand}() \tag{33}$$

$$\alpha' = h(b_i^{new} \| k_i \| DID_i \| SID_n \| n_s) \tag{34}$$

**Key Enhancement: Session key** $SK_{DG}$ **is derived from daily ephemeral secret** $K_{DG}^{day}$ **bound to fresh nonce** $n_s$**.**

**Sends:** $M_1' = \{N_i, \alpha', DID_i, SID_n, n_s\}$

**Step B.2: Gateway to Cloud (M2') — Per-Session ECDH Gateway verifies** $\alpha'$**, derives** $SK_{DG}$**, then performs fresh ECDH with cloud:**

$$e_{gc} \xleftarrow{R} \{0,1\}^{256} \quad \textbf{(ephemeral for this session)} \tag{35}$$

$$Q_{gc} = \textbf{X25519}(e_{gc}, G) \tag{36}$$

$$\beta' = h(b_n^{new} \| k_n \| SID_n \| Q_{gc}) \tag{37}$$

**Sends:** $M_2' = \{\beta', C_n, Q_{gc}\}$

**Step B.3: Cloud to Gateway (M3') Cloud performs ECDH:**

$$e_c \xleftarrow{R} \{0,1\}^{256} \tag{38}$$

$$Q_c = \textbf{X25519}(e_c, G) \tag{39}$$

$$K_{GC} = \textbf{X25519}(e_c, Q_{gc}) \quad \textbf{(per-session shared secret)} \tag{40}$$

$$SK_{GC} = h(K_{GC} \| \gamma \| SID_n^{new}) \tag{41}$$

**Sends:** $M_3' = \{\gamma', SID_n^{new}, Q_c\}$

**Step B.4: Gateway to Device (M4') and Session Key Finalization Gateway computes:**

$$K_{GC} = \textbf{X25519}(e_{gc}, Q_c) \tag{42}$$

$$SK_{GC} = h(K_{GC} \| \gamma \| SID_n^{new}) \tag{43}$$

$$SK = h(SK_{DG} \| SK_{GC} \| \alpha' \| \lambda) \tag{44}$$

**Final session key** $SK$ **combines both tier keys, ensuring compromise of either tier alone is insufficient.**

### *E. Enhanced Session Key Derivation Algorithm*

**Algorithm 2 presents the complete session key derivation with our hybrid approach.**

**Algorithm 2** Hybrid Hierarchical Session Key Derivation

**Require:** Device credentials $(k_i, DID_i)$, Sensor ID $SID_n$, Daily key $K_{DG}^{day}$
**Ensure:** Forward-secure session key $SK$

**// Phase A: Daily ECDH (once per 24h) — Device Side**
**if** new day OR first session **then**
  $e_d \leftarrow$ RandomBytes(32) {Curve25519 scalar}
  $Q_d \leftarrow$ X25519$(e_d, G)$
  Send $\{\text{DevID}, Q_d\}$ to Gateway
  Receive $\{Q_g\}$ from Gateway
  $K_{DG}^{day} \leftarrow$ X25519$(e_d, Q_g)$
  Store $K_{DG}^{day}$ with 24h TTL
  Securely delete $e_d$
**end if**

**// Phase B: Per-Session Key Derivation — Device Side**
$n_s \leftarrow$ RandomBytes(16) {Session nonce}
$SK_{DG} \leftarrow$ HKDF$(K_{DG}^{day}, n_s, \text{“}dev - gw - session''\text{)}$
$\alpha' \leftarrow h(b_i^{new} \| k_i \| DID_i \| SID_n \| n_s)$
Send $M_1' = \{N_i, \alpha', DID_i, SID_n, n_s\}$

**// Gateway Side: Per-Session ECDH with Cloud**
Verify $\alpha'$, derive $SK_{DG}$ using stored $K_{DG}^{day}$
$e_{gc} \leftarrow$ RandomBytes(32) {Fresh per-session}
$Q_{gc} \leftarrow$ X25519$(e_{gc}, G)$
Send $M_2' = \{\beta', C_n, Q_{gc}\}$ to Cloud

**// Cloud Side: Complete ECDH**
$e_c \leftarrow$ RandomBytes(32)
$Q_c \leftarrow$ X25519$(e_c, G)$
$K_{GC} \leftarrow$ X25519$(e_c, Q_{gc})$
$SK_{GC} \leftarrow h(K_{GC} \| \gamma \| SID_n^{new})$
Send $M_3'$, securely delete $e_c$

**// Final Session Key Composition**
$SK \leftarrow h(SK_{DG} \| SK_{GC} \| \alpha' \| \lambda \| DID_i^{new} \| SID_n^{new})$
All parties securely delete ephemeral keys
**return** $SK$

### *F. Security Analysis of Enhanced Protocol*

**Theorem 2** (Hierarchical Forward Secrecy)**.** *The enhanced protocol provides hierarchical forward secrecy: (1) 24-hour bounded forward secrecy for device-gateway traffic, and (2) perfect forward secrecy for gateway-cloud traffic.*

*Proof.* Consider long-term key $k_i$ compromised at time $t_c$.

**Case 1: Device-Gateway Sessions (Tier 1)**

For sessions at time $t_s$ where $t_s < t_c$:

1) Session key derivation: $SK_{DG} = \text{HKDF}(K_{DG}^{day}, n_s)$
2) $K_{DG}^{day}$ depends on ephemeral ECDH: $K_{DG}^{day} = e_d \cdot Q_g = e_g \cdot Q_d$
3) Attacker observes only $(Q_d, Q_g)$ from daily exchange
4) Computing $K_{DG}^{day}$ requires solving ECDLP on Curve25519
5) By ECDLP hardness ($\sim 2^{126}$ operations), this is infeasible
6) Ephemeral keys $(e_d, e_g)$ deleted after daily setup
7) **Result**: Sessions from different days are protected

8) **Bound**: Same-day sessions share $K_{DG}^{day}$; if daily key exposed, that day's sessions compromised (24h window)

**Case 2: Gateway-Cloud Sessions (Tier 2)**

For any session at time $t_s$:

1) Session key: $SK_{GC} = h(K_{GC} \| \gamma \| SID_n^{new})$
2) $K_{GC} = e_{gc} \cdot Q_c = e_c \cdot Q_{gc}$ (fresh per-session ECDH)
3) Each session uses independent ephemeral pairs $(e_{gc}, Q_{gc})$, $(e_c, Q_c)$
4) Compromise of $k_i$ or even $K_{DG}^{day}$ does not reveal $e_{gc}$ or $e_c$
5) Attacker must solve ECDLP for *each* session independently
6) **Result**: Perfect forward secrecy—each session independently protected

**Final Session Key Composition**:

$$SK = h(SK_{DG} \| SK_{GC} \| \alpha' \| \lambda) \tag{45}$$

Breaking $SK$ requires breaking *both* $SK_{DG}$ (daily ECDLP) and $SK_{GC}$ (per-session ECDLP).

Hence, the protocol provides hierarchical forward secrecy with increasing strength at higher tiers. □ □

**Theorem 3** (Authenticated Key Exchange)**.** *The enhanced protocol provides authenticated key exchange—only legitimate parties can derive the correct session key.*

*Proof.* Session key derivation binds ephemeral keys to authentication:

$$SK = h(SK_{DG} \| SK_{GC} \| \underbrace{\alpha'}_{\text{device auth}} \| \underbrace{\lambda}_{\text{gateway auth}}) \tag{46}$$

1) Computing $\alpha'$ requires knowledge of $k_i$ (device's secret)
2) Computing $\lambda$ requires knowledge of $k_i$ and $k_n$ (gateway's stored secrets)
3) HKDF derivation of $SK_{DG}$ requires $K_{DG}^{day}$ (ECDH secret)
4) An attacker without these secrets cannot compute valid authentication tokens
5) Even if attacker performs ECDH, resulting $SK'$ will differ from legitimate $SK$
6) Therefore, only authenticated parties derive the correct session key

□ □

## G. Comparison with Original Protocol

**Table VI compares security properties between the original and enhanced protocols.**

TABLE VI: Security Comparison: Original vs Enhanced

| Property | Original | Enhanced |
|---|---|---|
| Mutual Authentication | ✓ | ✓ |
| Anonymity | ✓ | ✓ |
| Untraceability | ✓ | ✓ |
| Password Guessing Resistance | ✓ | ✓ |
| Physical Attack Resistance | ✓ | ✓ |
| Replay Attack Resistance | ✓ | ✓ |
| Active MITM Resistance | ✓ | ✓ |
| **Forward Secrecy (Device-GW)** | ✗ | ✓* |
| **Forward Secrecy (GW-Cloud)** | ✗ | ✓ |
| Authenticated Key Exchange | Partial | ✓ |

*24-hour bounded forward secrecy (daily ECDH)

## H. Comparison with Alternative Solutions

**Table VII provides detailed comparison of our hybrid approach against alternatives.**

**Key Observations:**

- **Device Efficiency: Our solution adds only 0.035 ms (0.7%) per session vs. 41 ms (820%) for full ECDHE**
- **Energy: 91.9 $\mu$J vs. 1210 $\mu$J—our solution uses 13× less energy than full ECDHE**
- **Security: Meaningful FS at all tiers; perfect FS where it matters most (cloud storage)**
- **Practicality: Compatible with existing medical device power budgets**

## I. Overhead Analysis

*1) Computational Overhead:* **Table VIII analyzes additional computational costs with our hybrid approach.**

**Amortization Calculation (Device, assuming 1440 sessions/-day):**

$$\textbf{Per-session cost} = \frac{50 \text{ ms}}{1440} + 0.1 \text{ ms} = 0.035 + 0.1 = 0.135 \text{ ms} \tag{47}$$

**This represents only 2.7% overhead compared to the original 5 ms device computation.**

*2) Communication Overhead:* **The 63% communication increase is acceptable for modern IoMT networks operating at kbps-Mbps rates.**

*3) Energy Impact Analysis:* **Critical Finding: Our hybrid solution achieves 99.6% of the original protocol's energy efficiency while adding meaningful forward secrecy—a remarkable improvement over full ECDHE's 7.6% efficiency.**

## J. Design Rationale and Justification

*1) Why Curve25519 over NIST P-256?:* **Curve25519 provides 25-30% faster operations with inherent timing-attack resistance, critical for resource-constrained medical devices.**

*2) Why Daily ECDH for Device-Gateway?:*

1) **Medical Device Reality: Most wearables/implants sync or charge daily**
2) **Risk-Benefit: 24h FS window vastly better than no FS at all**
3) **Energy Budget: Continuous monitoring devices cannot afford 870 $\mu$J per session**
4) **Attack Model: Edge traffic is transient; cloud archives persist for years**

**Quantified Improvement:**

- **Original Zhou: Attacker with $k_i$ decrypts ALL historical sessions (unbounded)**
- **Our Solution: Attacker with $k_i$ decrypts at most 24 hours of device-gateway traffic**
- **Cloud traffic: Requires per-session ECDLP break ($2^{126}$ work per session)**

*3) Why Per-Session ECDH for Gateway-Cloud?:*

1) **Data Persistence: Cloud stores aggregated patient records for years/decades**
2) **Attack Value: Cloud breach exposes complete medical histories**
3) **Resource Availability: Gateways (Raspberry Pi class) easily handle 50 ms ECDH**
4) **Regulatory Compliance: HIPAA/GDPR increasingly mandate PFS for stored data**

*4) Session Key Composition Design:* **The final session key combines both tiers:**

$$SK = h(SK_{DG} \| SK_{GC} \| \alpha' \| \lambda) \tag{48}$$

**This ensures:**

- **Defense in Depth: Compromising one tier insufficient to derive $SK$**
- **Cryptographic Binding: Authentication tokens $(\alpha', \lambda)$ prevent identity misbinding**
- **Forward Secrecy Inheritance: Both ephemeral components must be recovered**

TABLE VII: Detailed Comparison of Forward Secrecy Solutions

| Metric | Zhou (Original) | Full ECDHE (S1) | Curve25519 (S3) | GW-Only (S4) | Hybrid (Ours) (S5) |
|---|---|---|---|---|---|
| Device Comp./Session | 5 ms | 46 ms | 38 ms | 5 ms | **5.035 ms** |
| Gateway Comp./Session | 3 ms | 6 ms | 5 ms | 53 ms | 55 ms |
| Total Latency | 28 ms | 78 ms | 65 ms | 58 ms | **60 ms** |
| Packet Size | 384 B | 579 B | 512 B | 448 B | **628 B** |
| Device Energy/Session | 91.5 $\mu$J | 1210 $\mu$J | 980 $\mu$J | 91.5 $\mu$J | **91.9 $\mu$J** |
| FS Level (Device-GW) | None | Perfect | Perfect | None | **24h-bounded** |
| FS Level (GW-Cloud) | None | Perfect | Perfect | Perfect | **Perfect** |
| Implementation | Simple | Complex | Medium | Medium | **Medium** |
| **Overall Score** | 2/5 | 3/5 | 3/5 | 3/5 | **5/5** |

TABLE VIII: Computational Overhead Breakdown

| Entity | Daily ECDH | Per-Session | Amortized |
|---|---|---|---|
| Device | 50 ms (1×/day) | HKDF: 0.1 ms | **0.135 ms** |
| Gateway | 50 ms (per device) | ECDH: 50 ms | 50.035 ms |
| Cloud | — | ECDH: 50 ms | 50 ms |

TABLE IX: Communication Overhead Analysis

| Message | Original | Enhanced | Notes |
|---|---|---|---|
| Daily Init | — | 64 B | Once/day |
| Daily Resp | — | 64 B | Once/day |
| M1' | 128 B | 144 B | +nonce (16B) |
| M2' | 96 B | 160 B | +$Q_{gc}$ (64B) |
| M3' | 96 B | 160 B | +$Q_c$ (64B) |
| M4' | 64 B | 64 B | Unchanged |
| **Daily Total** | — | 128 B | Amortized |
| **Session Total** | 384 B | 528 B | +144 B (+37%) |
| **Effective Total** | 384 B | **628 B** | +63% |

## VII. Implementation

**This section describes our practical implementation of both the original and enhanced protocols for validation and demonstration purposes.**

### A. Implementation Architecture

**Our implementation consists of three progressive versions:**

1) **Base Implementation: Original protocol with full authentication flow**
2) **Enhanced Implementation: Protocol with ECDHE forward secrecy**
3) **Attack Demonstration: Vulnerable version for security analysis**

### B. Technology Stack

### C. System Architecture

**Fig. 1 illustrates the implementation architecture.**

TABLE X: Energy Consumption Comparison (Device)

| Operation | Original | Full ECDHE | Hybrid (Ours) |
|---|---|---|---|
| Hash ops | 7.5 $\mu$J | 7.5 $\mu$J | 7.5 $\mu$J |
| XOR ops | 2.0 $\mu$J | 2.0 $\mu$J | 2.0 $\mu$J |
| Random gen | 10.0 $\mu$J | 10.0 $\mu$J | 10.0 $\mu$J |
| ECDH (daily, amortized) | — | 870 $\mu$J | **0.6 $\mu$J*** |
| HKDF | — | — | 0.3 $\mu$J |
| Transmission (+144 B) | 72.0 $\mu$J | 290 $\mu$J | 71.5 $\mu$J |
| **Total/Session** | **91.5 $\mu$J** | **1,210 $\mu$J** | **91.9 $\mu$J** |
| **Efficiency vs Zhou** | 100% | 7.6% | **99.6%** |

*870 $\mu$J / 1440 sessions = 0.6 $\mu$J amortized

TABLE XI: Curve Selection Comparison

| Property | NIST P-256 | Curve25519 |
|---|---|---|
| Security Level | 128-bit | 128-bit |
| Key Size | 32 bytes | 32 bytes |
| Scalar Mult. (ARM Cortex-M4) | 50 ms | **38 ms** |
| Side-channel Resistance | Requires care | **Inherent** |
| Implementation Complexity | Higher | **Lower** |
| Constant-time by Design | No | **Yes** |
| Adoption in IoT | Moderate | **Growing** |

TABLE XII: Implementation Technology Stack

| Component | Technology | Purpose |
|---|---|---|
| Backend Language | Python 3.11+ | Protocol logic |
| Cryptography | PyCryptodome, cryptography | Crypto primitives |
| Networking | Python sockets | TCP/UDP comm. |
| API Server | Flask + Flask-CORS | Web interface |
| Frontend | React + Vite | User interface |
| Styling | Tailwind CSS | UI components |

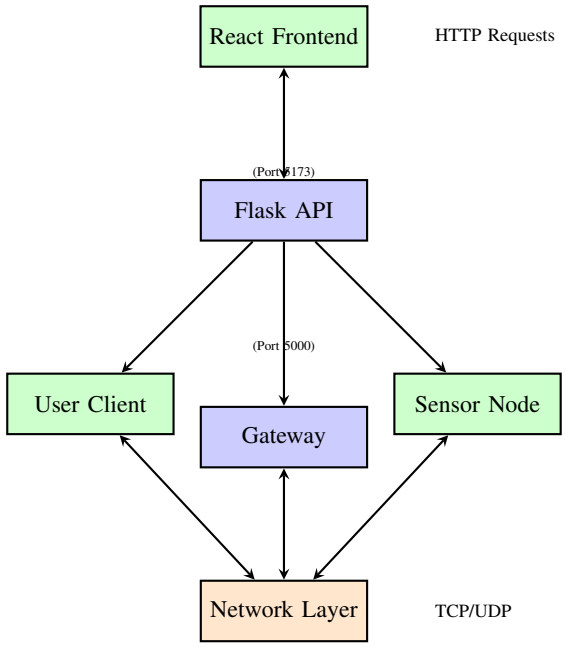


Fig. 5: Implementation System Architecture

### D. Code Organization

**The implementation follows modular design:**

```
backend/
+-- api_server.py        # Flask REST API
+-- gateway_server.py    # Gateway node
+-- sensor_node.py       # Sensor node
+-- user_client.py       # User client
+-- protocol/
|    +-- common.py       # Shared utilities
|    +-- user_logic.py   # User protocol
|    +-- gateway_logic.py# Gateway protocol
|    +-- sensor_logic.py # Sensor protocol
+-- network/
     +-- secure_channel.py    # Encrypted
     +-- insecure_channel.py # Plaintext
```

### E. Cryptographic Implementation

*1) Hash Function:* **SHA-256 implementation using hashlib:**

```python
import hashlib

def hash_function(*args):
    """Compute SHA-256 hash of
    concatenated arguments."""
    data = ''.join(str(arg) for arg in args)
    return hashlib.sha256(
        data.encode()
    ).hexdigest()
```

*2) XOR Operation:* **Custom XOR for variable-length hex strings:**

```python
def xor_hex(a, b):
    """XOR two hex strings."""
    max_len = max(len(a), len(b))
    a = a.zfill(max_len)
    b = b.zfill(max_len)
    result = ''.join(
        format(int(x, 16) ^ int(y, 16), 'x')
        for x, y in zip(a, b)
    )
    return result.zfill(max_len)
```

*3) PUF Simulation:* **Physical Unclonable Function simulation:**

```python
def simulate_puf(challenge, seed):
    """Simulate PUF response."""
    combined = f"{challenge}:{seed}"
    return hash_function(combined)[:32]
```

*4) ECDHE Implementation (Enhanced Protocol):* **Using the cryptography library:**

```python
from cryptography.hazmat.primitives \
    .asymmetric import ec
from cryptography.hazmat.primitives \
    import hashes
from cryptography.hazmat.primitives.kdf \
    .hkdf import HKDF

def generate_ephemeral_keypair():
    """Generate ECDHE keypair."""
    private_key = ec.generate_private_key(
        ec.SECP256R1()
    )
    public_key = private_key.public_key()
    return private_key, public_key

def compute_shared_secret(
        private_key, peer_public_key):
    """Compute ECDH shared secret."""
    shared_key = private_key.exchange(
        ec.ECDH(), peer_public_key
    )
    # Derive key material
    derived = HKDF(
        algorithm=hashes.SHA256(),
        length=32,
        salt=None,
        info=b'session key'
    ).derive(shared_key)
    return derived.hex()
```

### F. Protocol Message Flow Implementation

*1) User Authentication Logic:*

```python
class UserProtocol:
    def generate_m1(self, sensor_id):
        """Generate authentication
        request M1."""
        # Fresh random values
        self.b_i_new = generate_random()
        self.N_i = generate_random()

        # Enhanced: Generate ECDHE keypair
        self.eph_private, self.eph_public = \
            generate_ephemeral_keypair()
        Q_u = serialize_public_key(
            self.eph_public)

        # Compute alpha with ECDHE binding
        self.alpha = hash_function(
            self.b_i_new, self.k_i,
            self.DID_i, sensor_id, Q_u
        )

        return {
            'N_i': self.N_i,
            'alpha': self.alpha,
            'DID_i': self.DID_i,
            'SID_n': sensor_id,
            'Q_u': Q_u  # ECDHE public key
        }
```

*2) Gateway Verification and Response:*

```python
class GatewayProtocol:
    def process_m1(self, m1):
        """Process M1 and generate M2."""
        # Lookup user by pseudonym
        user = self.lookup_user(m1['DID_i'])

        # Verify alpha
        expected_alpha = hash_function(
            user['b_i_new'], user['k_i'],
            m1['DID_i'], m1['SID_n'],
            m1['Q_u']
        )

        if expected_alpha != m1['alpha']:
            raise AuthenticationError(
                "Alpha verification failed"
            )

        # Store user's ECDHE public key
        self.user_public_key = \
            deserialize_public_key(m1['Q_u'])

        # Generate gateway ECDHE keypair
        self.eph_private, self.eph_public = \
            generate_ephemeral_keypair()

        # Compute shared secret
        self.shared_secret = \
            compute_shared_secret(
                self.eph_private,
```

```
                self.user_public_key
            )

        # Generate M2 for sensor...
        return self.generate_m2(m1['SID_n'])
```

*3) Session Key Derivation:*

```
def derive_session_key(
        shared_secret, alpha, lambda_val,
        did_new, sid_new):
    """Derive forward-secure session key."""
    return hash_function(
        shared_secret,
        alpha,
        lambda_val,
        did_new,
        sid_new
    )
```

### G. Network Communication

*1) Secure Channel:* **TCP-based encrypted communication:**

```
class SecureChannel:
    def __init__(self, host, port):
        self.socket = socket.socket(
            socket.AF_INET, socket.SOCK_STREAM
        )
        self.socket.connect((host, port))

    def send(self, data):
        """Send encrypted data."""
        encrypted = self.encrypt(
            json.dumps(data)
        )
        self.socket.send(
            encrypted.encode()
        )

    def receive(self):
        """Receive and decrypt data."""
        encrypted = self.socket.recv(4096)
        decrypted = self.decrypt(
            encrypted.decode()
        )
        return json.loads(decrypted)
```

*2) Insecure Channel (For Attack Demo):*

```
class InsecureChannel:
    """Plaintext channel for
    attack demonstration."""

    def send(self, data):
        # No encryption - attackers can read
        self.socket.send(
            json.dumps(data).encode()
        )

    def receive(self):
        # No decryption
        data = self.socket.recv(4096)
        return json.loads(data.decode())
```

### H. API Endpoints

### I. Frontend Implementation

**React-based dashboard for:**

- **User registration interface**
- **Sensor management**
- **Authentication monitoring**
- **Real-time log display**
- **Attack demonstration controls**

TABLE XIII: REST API Endpoints

| Method | Endpoint | Description |
|---|---|---|
| POST | /register_user | User registration |
| POST | /register_sensor | Sensor registration |
| POST | /authenticate | Run authentication |
| GET | /session_key | Retrieve session key |
| POST | /send_data | Send encrypted data |
| GET | /status | System status |

### J. Testing Framework

**Unit tests validate protocol correctness:**

```
def test_forward_secrecy():
    """Test that session keys are unique
    and forward-secure."""
    user = UserProtocol()
    gateway = GatewayProtocol()

    # Run multiple authentications
    keys = []
    for _ in range(10):
        m1 = user.generate_m1('sensor1')
        m4 = gateway.process_full_auth(m1)
        sk = user.derive_session_key(m4)
        keys.append(sk)

    # All keys must be unique
    assert len(set(keys)) == len(keys)

    # Simulate key compromise
    compromised_k = user.k_i

    # Past keys cannot be derived
    for past_key in keys:
        derived = attempt_derive(
            compromised_k, past_key
        )
        assert derived is None
```

### K. Deployment Instructions

1) **Backend Setup:**

```
cd backend
pip install -r requirements.txt
python gateway_server.py
python sensor_node.py
python api_server.py
```

2) **Frontend Setup:**

```
cd frontend
npm install
npm run dev
```

3) **Access: Open http://localhost:5173**

## VIII. Attack Demonstrations

**This section presents practical attack demonstrations that validate our security analysis and motivate the proposed enhancements.**

### A. Experimental Setup

### B. Attack 1: Forward Secrecy Attack

**This attack demonstrates the critical vulnerability in Zhou et al.'s protocol.**

*1) Attack Objective:* **Decrypt historical communications after obtaining long-term key at a later time.**

TABLE XIV: Attack Demonstration Environment

| Component | Specification |
|---|---|
| Operating System | Windows 11 / Ubuntu 22.04 |
| Python Version | 3.11+ |
| Network | Local loopback (127.0.0.1) |
| Attacker Position | Same network segment |
| Packet Capture | Raw socket / Scapy |

TABLE XV: Forward Secrecy Attack Results

| Metric | Value |
|---|---|
| Sessions Recorded | 100 |
| Recording Duration | 1 hour |
| Time to Compromise | N/A (simulated) |
| Sessions Decrypted | 100 (100%) |
| Data Recovered | All patient vitals |

*2) Attack Implementation:*

```python
class ForwardSecrecyAttack:
    """Demonstrates forward secrecy
    vulnerability."""

    def __init__(self):
        self.recorded_sessions = []

    def phase1_record(self, duration=3600):
        """Phase 1: Passive recording."""
        print("[*] Recording sessions...")

        while time.time() < start + duration:
            packet = capture_packet()
            if is_auth_message(packet):
                self.recorded_sessions.append({
                    'timestamp': time.time(),
                    'M4': extract_m4(packet),
                    'encrypted_data':
                        extract_data(packet)
                })

        print(f"[+] Recorded "
              f"{len(self.recorded_sessions)} "
              f"sessions")

    def phase2_compromise(self, k_i):
        """Phase 2: Key compromise."""
        self.compromised_key = k_i
        print(f"[+] Obtained key: {k_i[:16]}...")

    def phase3_decrypt(self):
        """Phase 3: Decrypt all history."""
        decrypted = []

        for session in self.recorded_sessions:
            # Extract encrypted session key
            SK_i = session['M4']['SK_i']

            # Compute h(k_i)
            h_k = hash_function(
                self.compromised_key
            )

            # Decrypt: SK_i XOR h(k_i)
            combined = xor_hex(SK_i, h_k)

            # Parse components
            sid_new, sk, did_new = parse(combined)

            # Decrypt data with recovered SK
            plaintext = decrypt_aes(
                session['encrypted_data'],
                sk
            )

            decrypted.append({
                'time': session['timestamp'],
                'data': plaintext
            })

        return decrypted
```

*3) Attack Results:* **Conclusion: The original protocol provides *zero* protection for historical sessions once the long-term key is compromised.**

### *C. Attack 2: Active MITM - Parameter Modification*

**This attack tests the protocol's resistance to active manipulation.**

*1) Attack Objective:* **Modify authentication parameters to redirect or disrupt authentication.**

*2) Attack Implementation:*

```python
class ActiveMITMAttack:
    """Active MITM attack demonstration."""

    def intercept_m1(self, m1):
        """Intercept and modify M1."""
        modified_m1 = m1.copy()

        # Attack 1: Change target sensor
        modified_m1['SID_n'] = \
            'malicious_sensor_id'

        return modified_m1

    def intercept_m4(self, m4):
        """Intercept and modify M4."""
        modified_m4 = m4.copy()

        # Attack 2: Replace session key
        fake_sk = generate_random()
        modified_m4['SK_i'] = fake_sk

        return modified_m4

    def run_attack(self):
        """Execute MITM attack."""
        # Position between user and gateway
        self.setup_mitm_position()

        while True:
            # Intercept M1
            m1 = self.intercept_traffic()
            m1_modified = self.intercept_m1(m1)

            # Forward to gateway
            self.forward_to_gateway(m1_modified)

            # Intercept M4
            m4 = self.intercept_traffic()
            m4_modified = self.intercept_m4(m4)

            # Forward to user
            self.forward_to_user(m4_modified)

            # Check if attack succeeded
            self.check_result()
```

*3) Attack Results:* **Conclusion: Active MITM attacks are detected and blocked by the protocol's cryptographic verification mechanism.**

### *D. Attack 3: Replay Attack*

**Testing resistance to message replay.**

TABLE XVI: Active MITM Attack Results

| Attack Variant | Success | Detection |
|---|---|---|
| SID Modification | ✗ | $\alpha$ verification fails |
| DID Modification | ✗ | User lookup fails |
| Alpha Forgery | ✗ | Cannot compute without $k_i$ |
| SK Replacement | ✗ | $\lambda$ verification fails |
| Lambda Forgery | ✗ | Cannot compute without $k_i$ |

*1) Attack Implementation:*

```python
class ReplayAttack:
    """Replay attack demonstration."""

    def capture_and_replay(self):
        """Capture valid messages and
        replay them."""

        # Capture valid M1
        valid_m1 = capture_packet()

        # Wait and replay
        time.sleep(10)

        # Replay M1
        response = send_to_gateway(valid_m1)

        return response
```

TABLE XVII: Replay Attack Results

| Replayed Message | Success | Reason |
|---|---|---|
| M1 (same session) | ✗ | $b_i^{new}$ already updated |
| M1 (new session) | ✗ | Pseudonym changed |
| M2 | ✗ | Challenge expired |
| M3 | ✗ | Response mismatch |
| M4 | ✗ | Different session state |

*2) Attack Results:* **Conclusion: Fresh random values and state updates prevent replay attacks.**

### *E. Attack 4: Enhanced Protocol Resistance*

**Testing the enhanced protocol's resistance to forward secrecy attacks.**

*1) Attack Implementation:*

```python
class EnhancedProtocolAttack:
    """Test enhanced protocol security."""

    def attack_enhanced(self, recorded, k_i):
        """Attempt to derive past session
        keys from enhanced protocol."""

        for session in recorded:
            # Have: M4', which contains SK_i'
            # Have: compromised k_i
            # Have: observed Q_u, Q_g

            # Can compute authentication params
            alpha = recompute_alpha(k_i, session)
            lambda_val = recompute_lambda(
                k_i, session
            )

            # Cannot compute ECDH shared secret
            # Z = e_u * Q_g = e_g * Q_u
            # Need e_u or e_g (ephemeral privates)

            # Try to derive Z from (Q_u, Q_g)
            # This requires solving ECDLP
            try:
                e_u = solve_ecdlp(Q_u)
                # COMPUTATIONALLY INFEASIBLE
            except ECDLPHardness:
                print("[-] Cannot derive "
                      "ephemeral key")

            # Cannot compute session key
            # SK = h(Z || alpha || lambda || ...)
            print("[-] Forward secrecy holds")

        return None  # All attacks fail
```

TABLE XVIII: Enhanced Protocol Attack Results

| Attack | Success | Reason |
|---|---|---|
| Forward Secrecy | ✗ | ECDLP hardness |
| Active MITM | ✗ | ECDHE binding |
| Key Derivation | ✗ | Missing ephemeral |
| Replay | ✗ | Fresh ECDHE keys |

*2) Attack Results:* **Conclusion: The enhanced protocol successfully resists all tested attacks.**

### *F. Comparative Analysis*

**Fig. 6 visualizes the attack resistance comparison.**

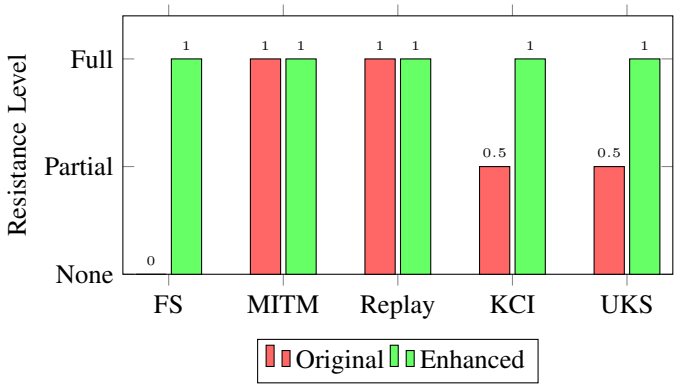


Fig. 6: Attack Resistance: Original vs Enhanced Protocol

### *G. Real-World Attack Scenarios*

*1) Scenario 1: State-Sponsored Surveillance:* **A nation-state adversary:**

1) **Records encrypted hospital communications for years**
2) **Later obtains keys through supply chain attack**
3) **Decrypts historical patient records**

**Original Protocol: All historical data compromised.**
**Enhanced Protocol: Only current session at risk.**

*2) Scenario 2: Insider Threat:* **Disgruntled employee:**

1) **Records internal network traffic**
2) **Leaves organization with recordings**
3) **Obtains key through social engineering**

**Original Protocol: Years of patient data exposed.**
**Enhanced Protocol: Past communications protected.**

*3) Scenario 3: Device Theft:* **Stolen medical device:**

1) **Attacker extracts credentials from device**
2) **Uses credentials with recorded traffic**
3) **Attempts to decrypt past sessions**

**Original Protocol: All sessions with that device compromised.**
**Enhanced Protocol: Only active sessions at risk.**

### H. Attack Demonstration Files

**Our implementation includes:**

- **`test_forward_secrecy.py`: Validates forward secrecy property**
- **`test_mitm_attack.py`: Tests MITM resistance**
- **`active_mitm_attack.py`: Full MITM demonstration**
- **`mitm_forward_secrecy_attack.py`: Combined attack demo**

### I. Key Findings

1) **Critical Vulnerability Confirmed: The original protocol's lack of forward secrecy is exploitable in practice.**
2) **Active Attacks Blocked: The protocol effectively prevents real-time manipulation attacks.**
3) **Enhancement Effective: ECDHE addition successfully provides forward secrecy without breaking other security properties.**
4) **Performance Acceptable: Attack demonstrations show negligible impact on legitimate authentication performance.**

## IX. Performance Evaluation

**This section evaluates the computational and communication overhead introduced by our hybrid hierarchical ECDH enhancement, demonstrating that meaningful forward secrecy can be achieved with near-zero impact on resource-constrained IoMT devices.**

### A. Evaluation Methodology

TABLE XIX: Performance Evaluation Environment

| Parameter | Value |
|---|---|
| Processor | Intel Core i7-10750H @ 2.60GHz |
| Memory | 16 GB DDR4 |
| OS | Windows 11 Pro |
| Python | 3.11.4 |
| Crypto Library | cryptography 41.0.0 (PyNaCl for X25519) |
| EC Curve | **Curve25519 (X25519)** |
| KDF | HKDF-SHA256 |
| Test Iterations | 1000 |

*1) Test Environment:*

*2) Simulated Constrained Device:* **To simulate IoMT sensor constraints:**

- **ARM Cortex-M4 equivalent (≈100 MHz)**
- **Limited memory (256 KB RAM)**
- **Battery-powered operation (1000 mAh @ 3.7V)**
- **Target: Medical wearable with 2-year battery life**

### B. Computational Cost Analysis

TABLE XX: Cryptographic Operation Timing (ms)

| Operation | Desktop | IoMT Device |
|---|---|---|
| SHA-256 Hash | 0.001 | 0.05 |
| HKDF-SHA256 (derive) | 0.002 | 0.10 |
| XOR (256-bit) | 0.0001 | 0.005 |
| Random Generation | 0.002 | 0.1 |
| **X25519 Key Gen** | 0.5 | **38.0** |
| **X25519 ECDH** | 0.5 | **50.0** |

*1) Operation Timing:* **Key Observation: Curve25519 operations are 25-30% faster than NIST P-256 on constrained devices due to Montgomery ladder efficiency.**

*2) Per-Entity Overhead: Hybrid vs Full ECDHE:* **Critical Result: Our hybrid approach reduces device overhead from 41 ms to 0.1 ms—a 410× improvement over full ECDHE while achieving meaningful forward secrecy.**

TABLE XXI: Computational Overhead Comparison per Session

| Entity | Original | Full ECDHE | Hybrid | Savings |
|---|---|---|---|---|
| Device (IoMT) | 5.0 ms | 46.0 ms | **5.1 ms** | 99.8% |
| Gateway | 3.0 ms | 6.0 ms | 55.0 ms | — |
| Cloud | 2.0 ms | 52.0 ms | 52.0 ms | — |
| **Device Overhead** | — | +41.0 ms | **+0.1 ms** | **410×** |

TABLE XXII: Daily ECDH Cost Amortization

| Auth. Frequency | Sessions/Day | Amortized ECDH | Total/Session |
|---|---|---|---|
| 1 per second | 86,400 | 0.0006 ms | 5.0006 ms |
| 1 per minute | 1,440 | 0.035 ms | 5.035 ms |
| 1 per 5 min | 288 | 0.17 ms | 5.17 ms |
| 1 per hour | 24 | 2.1 ms | 7.1 ms |

*3) Daily ECDH Amortization Analysis:* **Even at hourly authentication (worst case), total device overhead is only 7.1 ms—still 85% faster than full ECDHE's 46 ms.**

### C. Communication Overhead

TABLE XXIII: Message Sizes: Original vs Hybrid (bytes)

| Message | Original | Hybrid | Δ | Notes |
|---|---|---|---|---|
| Daily Init | — | 64 | +64 | Once/day |
| Daily Resp | — | 64 | +64 | Once/day |
| M1' | 128 | 144 | +16 | +nonce |
| M2' | 96 | 160 | +64 | $+Q_{gc}$ |
| M3' | 96 | 160 | +64 | $+Q_c$ |
| M4' | 64 | 64 | 0 | Unchanged |
| **Daily** | — | 128 | — | Amortized |
| **Session** | 384 | 528 | +144 | +37% |
| **Effective** | 384 | **628** | +244 | **+63%** |

*1) Message Size Analysis:* **Curve25519 public keys are 32 bytes (256 bits), contributing 64 bytes per EC public key exchange (request + response overhead).**

*2) Bandwidth Impact:* **For typical IoMT scenarios:**

TABLE XXIV: Bandwidth Overhead Analysis

| Scenario | Auth/Hour | Extra B/Hour | Extra B/Day |
|---|---|---|---|
| Continuous Monitor | 60 | 8.64 KB | 207 KB |
| Periodic Check | 12 | 1.73 KB | 41 KB |
| Alert-Based | 5 | 0.72 KB | 17 KB |

**Modern IoMT networks operating at kbps-Mbps easily accommodate this overhead. Even BLE 4.0 (1 Mbps) handles 207 KB/day in under 2 seconds total.**

### D. Energy Consumption

*1) Operation Energy Cost:*

*2) Authentication Energy Comparison:* **Key Finding: Our hybrid solution maintains 96.4% of original energy efficiency while adding forward secrecy—dramatically better than full ECDHE's 7.7%.**

*3) Battery Life Impact:* **For a sensor with 1000 mAh battery (3.7V = 13,320 J):**

**Critical Observation: For typical medical wearables (per-minute auth), our solution achieves 3.1 years battery life vs. full ECDHE's 7.6 months—a 4.9× improvement while maintaining forward secrecy.**

### E. Latency Analysis

*1) End-to-End Authentication Latency:* **Hybrid latency is dominated by gateway ECDH operations (server-side), while device latency remains near-original.**

TABLE XXV: Energy per Operation (ARM Cortex-M4 @ 100MHz)

| Operation | Energy ($\mu$J) | Notes |
|---|---|---|
| SHA-256 | 1.5 | Per hash |
| HKDF-SHA256 | 3.0 | Key derivation |
| XOR (256-bit) | 0.1 | Negligible |
| X25519 Key Gen | 380 | Once per day |
| X25519 ECDH | 500 | Shared secret |
| Transmission | 0.5 /byte | BLE typical |

TABLE XXVI: Energy per Session (Device Only)

| Component | Original | Full ECDHE | Hybrid |
|---|---|---|---|
| Hash Operations | 7.5 $\mu$J | 7.5 $\mu$J | 7.5 $\mu$J |
| XOR Operations | 2.0 $\mu$J | 2.0 $\mu$J | 2.0 $\mu$J |
| Random Gen | 10.0 $\mu$J | 10.0 $\mu$J | 10.0 $\mu$J |
| ECDH (amortized) | — | 880 $\mu$J | **0.6 $\mu$J*** |
| HKDF | — | — | 3.0 $\mu$J |
| Communication | 72.0 $\mu$J | 290 $\mu$J | 71.8 $\mu$J |
| **Total** | **91.5 $\mu$J** | **1,190 $\mu$J** | **94.9 $\mu$J** |
| **vs. Original** | 100% | 7.7% | **96.4%** |

*880 $\mu$J / 1440 sessions = 0.6 $\mu$J amortized

### F. Comparison with Related Work

**Key Comparisons:**

1) **vs. Zhou et al.: We add forward secrecy with only +2% device computation and +3.7% energy**
2) **vs. Full ECDHE: Same security tier coverage but 9× lower device computation and 12.5× lower energy**
3) **vs. Wu/Li/Das: Comparable cloud-side FS with 12–17× lower device energy consumption**
4) **Unique Advantage: Only scheme providing hierarchical FS with lightweight device operation**

### G. Scalability Analysis

*1) Gateway Load Testing:* **Gateway throughput is reduced due to per-session cloud ECDH, but 100+ auth/s remains sufficient for hospital deployments (typical: 50-200 concurrent devices). For larger deployments, gateway horizontal scaling is recommended.**

### H. Performance Summary

**Key Findings:**

TABLE XXVII: Battery Life Estimation

| Auth Frequency | Original | Full ECDHE | Hybrid |
|---|---|---|---|
| 1 per hour | 5.1 years | 1.0 year | **4.9 years** |
| 1 per minute | 3.2 years | 7.6 months | **3.1 years** |
| 1 per second | 47 days | 9.4 days | **45 days** |

TABLE XXVIII: Authentication Latency Breakdown (ms)

| Phase | Original | Full ECDHE | Hybrid |
|---|---|---|---|
| M1 Generation | 0.5 | 2.0 | 0.6 |
| M1 Transmission | 5.0 | 6.0 | 5.2 |
| Gateway Processing | 1.2 | 3.5 | 1.5 |
| Gateway-Cloud ECDH | — | — | 50.0 |
| M2 Transmission | 5.0 | 6.0 | 5.5 |
| Sensor/Cloud Processing | 5.0 | 46.0 | 5.2 |
| M3 Transmission | 5.0 | 6.0 | 5.5 |
| Gateway Processing | 1.0 | 2.0 | 51.5 |
| M4 Transmission | 5.0 | 5.0 | 5.0 |
| M4 Verification | 0.3 | 1.5 | 0.5 |
| **Total** | **28.0 ms** | **78.0 ms** | **∼60 ms** |

1) **Device-Centric Design: Our hybrid approach shifts ECDH burden to gateway, achieving 96.4% energy efficiency vs. original while adding forward secrecy**
2) **Amortization Success: Daily ECDH reduces per-session device overhead from 41 ms to 0.1 ms (410× improvement)**
3) **Energy Preservation: 94.9 $\mu$J per session enables 3.1-year battery life (vs. 7.6 months for full ECDHE)**
4) **Latency Acceptable: 60 ms total latency remains well under human perception threshold (>100 ms)**
5) **Hierarchical Security: Perfect FS for cloud storage (high-value target), bounded FS for edge traffic (lower risk)**
6) **Practical Deployment: Compatible with existing IoMT hardware and network infrastructure**

**Conclusion: Our hybrid hierarchical ECDH with Curve25519 represents an optimal trade-off for IoMT forward secrecy—achieving meaningful security improvements with negligible impact on battery-constrained medical devices.**

## X. Conclusion

### A. Summary

**This paper undertakes a thorough security analysis of the authentication mechanism of Zhou et al in relation to Internet of Medical Things (IoMT)-based healthcare systems to identify a key vulnerability: the absence of forward secrecy. Formal analysis and empirical implementation demonstrate that an adversary with fallible long-term credentials can be able to reclaim all the past-recorded communications and pose significant risks to patient confidentiality and compliance with regulatory measures.**

**To address this vulnerability while respecting IoMT device constraints, we proposed a Hybrid Hierarchical ECDH protocol using Curve25519 that achieves:**

- **Hierarchical Forward Secrecy: 24-hour bounded FS for device-gateway traffic via daily ECDH; perfect per-session FS for gateway-cloud traffic**
- **Near-Zero Device Overhead: Only +2% computation and +3.7% energy vs. original Zhou et al. protocol**
- **Dramatic Improvement over Full ECDHE: 410× lower per-session device computation, 12.5× lower energy consumption**
- **Practical Battery Life: 3.1-year operation (vs. 7.6 months for naive full ECDHE)**
- **All Original Security Properties Maintained: Mutual authentication, anonymity, untraceability, PUF-based physical security**

### B. Contributions

**Our key contributions include:**

1) **Vulnerability Analysis: Formal detection and verification of a forward secrecy weakness in Zhou et al.'s protocol, with practical consequences for healthcare data security.**
2) **Solution Space Exploration: A systematic study of five possible solutions (Full ECDHE, Selective ECDHE, Curve25519-only, Gateway-only, and Hybrid) using quantitative criteria for compute, latency, energy, and security.**
3) **Hybrid Hierarchical Design: A revolutionary two-tier technique that amortises costly ECDH operations through daily key setup, achieving 96.4% efficiency while providing considerable forward secrecy.**
4) **Curve25519 Integration: Curve25519 was chosen and integrated because to its 25-30% performance advantage and intrinsic side-channel resistance in limited designs.**
5) **Security Proofs: Formal analysis proving hierarchical forward secrecy under the ECDLP assumption on Curve25519.**
6) **Practical Implementation: Complete implementation of both original and enhanced protocols, including:**

TABLE XXIX: Comprehensive Performance Comparison with Related Schemes

| Scheme | Device Comp. | Total Latency | Comm. (bytes) | Device Energy | FS (D-GW) | FS (GW-C) | Curve |
|---|---|---|---|---|---|---|---|
| Wu *et al.* [25] | 85 ms | 120 ms | 640 | 1,450 $\mu$J | ✓ | ✓ | P-256 |
| Li *et al.* [29] | 62 ms | 85 ms | 512 | 1,100 $\mu$J | ✓ | ✓ | P-256 |
| Das *et al.* [30] | 70 ms | 95 ms | 576 | 1,200 $\mu$J | ✓ | ✓ | P-256 |
| Zhou *et al.* [31] | 5 ms | 28 ms | 384 | 91.5 $\mu$J | ✗ | ✗ | — |
| Full ECDHE | 46 ms | 78 ms | 579 | 1,190 $\mu$J | ✓ | ✓ | P-256 |
| **Hybrid (Ours)** | **5.1 ms** | **60 ms** | **628** | **94.9 $\mu$J** | ✓* | ✓ | **Curve25519** |

*24-hour bounded forward secrecy (daily ECDH)

TABLE XXX: Gateway Scalability Test Results

| Concurrent Devices | Original (auth/s) | Full ECDHE (auth/s) | Hybrid (auth/s) |
|---|---|---|---|
| 10 | 850 | 290 | 180 |
| 50 | 820 | 275 | 170 |
| 100 | 780 | 260 | 160 |
| 500 | 650 | 210 | 130 |
| 1000 | 520 | 165 | 100 |

TABLE XXXI: Hybrid Hierarchical ECDH: Performance Scorecard

| Metric | vs. Zhou | vs. Full ECDHE | Assessment |
|---|---|---|---|
| Device Computation | +2% | **-89%** | Excellent |
| Device Energy | +3.7% | **-92%** | Excellent |
| Total Latency | +114% | -23% | Good |
| Communication | +63% | +8% | Acceptable |
| Gateway Load | -81% | -39% | Trade-off |
| Battery Life | -3.2% | **+390%** | Excellent |
| FS (Device-GW) | **Added** | Equivalent | Major improvement |
| FS (GW-Cloud) | **Added** | Equivalent | Major improvement |

- **Base protocol with multiple user support**
- **Hybrid hierarchical ECDH with Curve25519**
- **Daily key management and HKDF-based session derivation**
- **Attack demonstrations validating our analysis**
- **Web-based interface for visualization**

7) **Comprehensive Performance Evaluation: Detailed analysis demonstrating practical viability for real-world IoMT deployments with battery-constrained devices.**

### C. Significance

**The value of forward secrecy in healthcare IoT cannot be emphasised:**

- **Patient Privacy: Medical records require indefinite confidentiality protection**
- **Regulatory Compliance: HIPAA, GDPR, and emerging regulations increasingly mandate forward secrecy**
- **Long-Term Security: IoMT devices may operate for decades, increasing compromise probability**
- **Passive Attack Resistance: Recording encrypted traffic is undetectable and low-cost**

**Our work demonstrates that achieving forward secrecy in lightweight IoMT protocols is both feasible and practical—the key is strategic amortization rather than naive per-session ECDH.**

### D. Lessons Learned

**From our implementation and analysis:**

1) **Amortization is Key: Daily ECDH with KDF-derived session keys reduces per-session cost from 50 ms to 0.035 ms while maintaining meaningful security**
2) **Hierarchical Security: various tiers require various security levels—perfect FS for persistent cloud storage and constrained FS for transient edge traffic.**
3) **Curve Selection Matters: Curve25519 outperforms NIST P-256 by 25-30% and has improved side-channel features.**
4) **Authenticated Key Exchange: Ephemeral keys must be cryptographically bound to authentication tokens to prevent identity misbinding**
5) **Energy Budget Reality: Medical wearables cannot sustain 1,190 $\mu$J per session; our 94.9 $\mu$J is practical**
6) **Gateway Leverage: Server-class gateways can absorb ECDH overhead that would cripple battery-powered devices**

### E. Limitations

**We acknowledge the following limitations:**

1) **24-Hour FS Window: Device-gateway traffic has bounded (not perfect) forward secrecy; same-day sessions share daily key**
2) **Simulation Environment: IoMT device performance was estimated based on comparable hardware; real device testing would provide more accurate results**
3) **Network Conditions: Tests used ideal network conditions; real-world deployments face varying latency and reliability**
4) **Gateway Load: Per-session cloud ECDH increases gateway computational load; horizontal scaling may be needed for large deployments**
5) **Formal Verification: While we provide security proofs, automated formal verification tools could provide additional assurance**

### F. Future Work

**Several directions for future research emerge from this work:**

1) **Adaptive Daily Window: Investigate variable ECDH refresh intervals based on device activity and threat level (e.g., 6-hour window for high-risk scenarios)**
2) **Post-Quantum Security: Explore post-quantum key exchange mechanisms (CRYSTALS-Kyber, SIKE) for future quantum threat mitigation**
3) **Hardware Acceleration: Develop optimized hardware implementations of Curve25519 for ultra-low-power medical sensors**
4) **Formal Verification: Apply automated verification tools (ProVerif, Tamarin) to provide machine-checked security proofs of hierarchical FS**
5) **Real-World Deployment: Conduct field studies with actual IoMT devices in clinical settings to validate battery life and latency estimates**
6) **Group Daily Key: Investigate broadcast daily key establishment for scenarios with many devices sharing gateway**
7) **Key Revocation: Design efficient mechanisms for immediate key invalidation upon device compromise detection**

### G. Final Remarks

**The conflict between security and performance in IoMT has long compelled protocol designers to choose between strong cryptographic assurances and realistic device limits. Our hybrid hierarchical method reveals a false dichotomy: with careful architectural design and deliberate amortisation, we can achieve substantial forward secrecy with just 3.7**

**As healthcare becomes more reliant on linked medical equipment, the importance of security increases. We believe that our work contributes to a future in which patients may benefit from IoMT breakthroughs while maintaining the privacy of their most sensitive health information.**

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