Enhancing Group Communication Security with Zero-Knowledge Authentication, Ephemeral ECDH, and Intent-Aware Encryption

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***Abstract*—In this paper, we propose a secure group messaging framework that integrates modern cryptographic primitives to ensure confidentiality, integrity, forward secrecy, and controlled message usage within group communication environments. Our system leverages Zero-Knowledge Proof-based authentication, ephemeral Elliptic Curve Diffie-Hellman (ECDH) key exchange for session key derivation, and AES-GCM for authenticated encryption. Furthermore, we introduce an intent-aware encryption layer, allowing message senders to specify access policies and intended usage for each message. The system ensures that even in the event of key compromise, past communications remain secure, and misuse of sensitive data can be programmatically restricted. Performance evaluations and security analyses demonstrate the protocol's robustness and practical feasibility for secure group messaging applications.**

Keywords: Secure Group Messaging, Zero-Knowledge Authentication, Ephemeral ECDH, AES-GCM Encryption, Forward Secrecy, Authenticated Encryption, Usage Policy Enforcement.

Introduction

The rapid expansion of digital communication platforms has brought forth an urgent need for secure, private, and policy-driven messaging systems, particularly in domains where sensitive information is exchanged, such as corporate, defense, healthcare, and privacy-sensitive environments [?]. While several existing group messaging solutions offer basic encryption capabilities, they frequently fall short in delivering comprehensive security guarantees. Notably, many lack essential features like forward secrecy, which ensures that the compromise of long-term keys does not jeopardize past communications. Furthermore, most systems provide little to no control over how decrypted messages can be used, failing to implement intent-based data governance or enforce restrictions such as time-limited access or forward-prohibition [?]. Additionally, robust mutual authentication mechanisms capable of verifying the identity of participants without exposing credentials remain underdeveloped in contemporary group messaging protocols.

In response to these limitations, this paper proposes a secure group messaging system that integrates modern cryptographic primitives to strengthen both the security and governance of multi-party communication. The core objective is to develop a framework combining zero-knowledge authentication, ephemeral Elliptic Curve Diffie-Hellman (ECDH) key exchange, and AES-GCM encryption, augmented with an intent-aware encryption layer.

The proposed system ensures that participants can authenticate themselves through zero-knowledge proofs without revealing secret credentials, establish ephemeral session keys using ECDH for forward secrecy [?], and secure message content via AES-GCM to provide both confidentiality and integrity. Beyond conventional encryption, an intent-aware encryption mechanism is incorporated, allowing senders to embed encrypted, policy-bound metadata that defines permissible actions on each message—such as read-only access, forwarding restrictions, or time-based expiry—which can then be enforced at the recipient's end.

Together, these contributions address critical gaps in current secure messaging protocols, delivering a practical and scalable solution for secure, policy-controlled group communication.

Related Works

Secure messaging protocols have seen significant advancements in recent years, with several frameworks attempting to balance usability, security, and scalability. However, gaps remain in areas like intent-aware encryption, zero-knowledge mutual authentication, and ensuring forward secrecy in dynamic group scenarios.

The Signal Protocol is widely regarded as a benchmark for modern secure messaging [?]. It uses a Double Ratchet algorithm for session key evolution, ensuring forward secrecy and post-compromise security. Signal integrates ECDH key exchanges with AES-GCM authenticated encryption, providing confidentiality, integrity, and replay protection. While highly secure for message transmission, Signal lacks mechanisms for post-decryption policy enforcement, meaning recipients can freely forward, copy, or store decrypted messages without sender-imposed restrictions. Additionally, mutual authentication relies on manual trust verification (safety numbers) rather than zero-knowledge proofs.

The Matrix protocol [?], which powers decentralized platforms like Element, extends these concepts with Olm (for one-to-one messaging) and Megolm (for group messaging). Megolm uses symmetric ratchets for scalable group encryption but trades off forward secrecy in group chats for efficiency, as the same session key may encrypt multiple messages until an explicit key update. Like Signal, Matrix lacks intent-aware encryption capabilities and does not incorporate zero-knowledge mutual authentication, relying on conventional device key verification.

Pretty Good Privacy (PGP) [?] and its OpenPGP standard historically served as cornerstones for secure communication via asymmetric encryption and digital signatures. PGP's model offers strong content confidentiality and sender authentication but suffers from significant limitations: it does not provide forward secrecy, as messages encrypted with a user's public key remain vulnerable if the private key is later compromised. Moreover, PGP lacks group communication optimizations and does not support zero-knowledge proof authentication or intent-aware message control.

The Messaging Layer Security (MLS) protocol [?] is a recent IETF standard designed for secure, scalable group messaging. MLS introduces asynchronous group key agreement protocols that enable efficient membership updates and guarantee forward secrecy and post-compromise security. Despite these improvements, MLS does not yet support intent-aware encryption for restricting post-decryption message use, nor does it incorporate zero-knowledge mutual authentication. MLS depends on conventional key directories and credential systems for identity verification.

In summary, while these systems provide confidentiality and integrity with varying degrees of forward secrecy and scalability, none adequately address message usage control after decryption or employ zero-knowledge mutual authentication mechanisms suitable for privacy-sensitive group environments. This motivates our proposed framework, which integrates zero-knowledge authentication, ephemeral ECDH key exchange [?], AES-GCM encryption, and an intent-aware encryption layer to enforce policy-driven message handling alongside traditional cryptographic protections.

System Architecture

The architecture of the proposed secure group messaging system is composed of the following primary components:

A. *Group Members*

These are the client devices or applications participating in a secure messaging group. Each member is equipped with a long-term identity key pair (private/public) and periodically generates ephemeral session key pairs for each messaging session. Members are responsible for performing zero-knowledge authentication, ephemeral ECDH key exchange, and AES-GCM encryption/decryption of messages. Group members maintain secure local storage for both long-term and ephemeral keys, ensuring their confidentiality and integrity.

B. *Key Distribution Authority (Optional)*

In fully decentralized environments, participants exchange public keys via secure out-of-band channels or key directories. However, in scenarios where a trusted, centralized Key Distribution Authority (KDA) is feasible, it acts as an initial registrar and distributor of public identity keys. The KDA only provides authenticated key distribution during system setup or onboarding of new members and does not participate in runtime message exchanges, preserving message confidentiality.

C. *Secure Channels*

During the initial key distribution phase and zero-knowledge authentication exchanges, the system employs secure channels such as Transport Layer Security (TLS) or equivalent end-to-end encrypted tunnels. These channels prevent passive eavesdropping and man-in-the-middle (MitM) attacks during sensitive exchanges like public key or credential proofs.

D. *Messaging Infrastructure*

Group messages are transmitted over decentralized or federated messaging servers, depending on the deployment environment. The infrastructure acts as a message relay but has no access to message content or encryption keys due to end-to-end encryption. Messages are transmitted alongside encrypted intent metadata that defines their usage policy, which is enforced locally by recipient clients upon decryption.

E. *Intent-Aware Encryption Module*

This is an embedded component within the client application responsible for attaching, parsing, and enforcing message usage policies. Before encryption, the sender defines intent policies (e.g., read-only, non-forwardable, time-bound expiry) that are encrypted and appended to the message payload. Upon receipt and successful decryption, the recipient's device verifies policy compliance before allowing further actions like displaying, forwarding, or saving the message.

Threat Model

A comprehensive threat model is essential for validating the security properties of the proposed system. The primary adversarial scenarios considered include both external and internal threats.

F. Adversary Capabilities

- **Passive Eavesdroppers:** Attackers capable of intercepting network traffic but unable to modify or inject messages [?]. They aim to compromise message confidentiality by capturing encrypted data in transit.
- **Active Man-in-the-Middle (MitM):** Adversaries who can intercept, modify, and inject messages between participants. Their goal is to impersonate group members, tamper with messages, or disrupt key exchanges.
- **Insider Threats:** Legitimate group members who may attempt to violate policy constraints (e.g., forwarding a message marked as read-only) or leak decrypted content. This includes devices compromised by malware or malicious actors.
- **Forward Secrecy Breaches:** Scenarios where long-term private keys are compromised after previous sessions have occurred. The adversary attempts to use captured encrypted messages along with the compromised key to decrypt past communications.

G. Security Assumptions

- **Secure Endpoint Storage:** It is assumed that client devices maintain secure, tamper-resistant storage for both long-term identity keys and ephemeral session keys. Devices should use hardware-backed keystores or equivalent software protections against unauthorized key access [?].
- **Synchronized Clocks:** To manage ephemeral key lifetimes and enforce time-based usage policies (e.g., message expiry), participating clients are assumed to maintain reasonably synchronized clocks. While minor discrepancies can be tolerated, significant clock drift could undermine policy enforcement or key validity periods.
- **Trusted Key Distribution (if KDA is used):** In deployments involving a Key Distribution Authority, it is assumed to be honest and uncompromised during key onboarding phases. Subsequent operations rely on peer-to-peer encrypted channels without central key escrow.
- **Secure Channel Availability During Initialization:** Secure communication channels (TLS, or secure device pairing protocols) are assumed to be available for initial key exchanges and zero-knowledge authentication, after which message content remains end-to-end encrypted.

Protocol Workflow

The proposed secure group messaging system operates through a structured multi-phase protocol designed to ensure confidentiality, integrity, forward secrecy, and policy-governed message handling. The workflow can be divided into four major stages: user registration and authentication, group session key establishment, message encryption and distribution, and message reception with policy enforcement.

H. User Registration and Zero-Knowledge Authentication

In the initial phase, each participant initializes their device by generating a long-term asymmetric identity key pair. To securely establish trust without revealing sensitive key material, the system employs a zero-knowledge proof protocol whereby users prove possession of their private identity key without disclosing it [?]. This mechanism mitigates the risk of key exposure during the authentication process, offering strong privacy guarantees. Public keys are then distributed via a decentralized public directory or, optionally, a centralized Key Distribution Authority (KDA). This entity is responsible solely for the authenticated dissemination of public identity keys during onboarding and plays no further role in operational message exchange, preserving the decentralized trust model.

I. Group Session Key Establishment

Once users have successfully authenticated and registered their public keys, a group session key establishment process commences whenever a secure messaging session is initiated. In this phase, each group member independently generates a fresh ephemeral ECDH [?] key pair, with the private portion securely stored locally and the public portion shared with other participants. The exchange of ephemeral public keys can occur directly over secure peer-to-peer channels or via a messaging relay infrastructure.

Using the received ephemeral keys and their own private key, each member performs pairwise ECDH computations with all other participants. The resulting shared secrets are then combined using a cryptographic key derivation function (KDF) to compute a single symmetric group session key. This key is unique to each session and ephemeral by design, ensuring forward secrecy since it is discarded after its validity period or session termination.

J. Message Encryption and Distribution

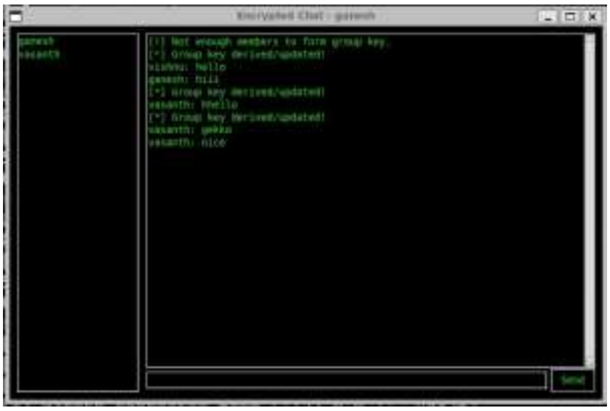
During the message transmission phase, a sender encrypts each message using AES-GCM, an authenticated encryption scheme [?] that guarantees both the confidentiality and integrity of the message payload. A unique nonce is generated for each encryption operation to prevent replay attacks and ensure ciphertext uniqueness.

Alongside the encrypted message content, the sender attaches intent metadata—a structured, encrypted policy declaration that specifies constraints such as message expiry time, forwarding restrictions, and permissible recipient actions. This metadata is cryptographically bound to the message, preventing tampering or separation from the message payload. The complete encrypted package is then broadcast to the group via a decentralized or federated messaging infrastructure, which acts only as a message relay without access to message content or encryption keys.

K. Message Reception and Policy Enforcement

Upon receiving a message, each group member first verifies the AES-GCM authentication tag [?] to confirm message integrity and authenticity. This step ensures that any tampering or unauthorized modification of the message during transmission is immediately detectable.

After successful verification, the recipient decrypts both the message payload and the associated intent metadata using the



```
ganesh
vasanth
```

```
[!] Not enough members to form group key.
[*] Group key derived/updated!
vishnu: hello
ganesh: hiii
[*] Group key derived/updated!
vasanth: hhello
[*] Group key derived/updated!
vasanth: gekko
vasanth: nice
```

shared session key. The decrypted intent metadata is then parsed by the client's intent-aware enforcement module, which evaluates the embedded policy constraints before allowing the user to interact with the message. For instance, a message marked as "non-forwardable" would be displayed in a restricted view, disabling options for forwarding or copying. Messages with time-based expiry are automatically purged from local storage after expiration, and any policy violations by compromised or malicious insider devices are logged and flagged for group awareness.

Results and Performance

The proposed system successfully demonstrates a fully functional, secure, and efficient end-to-end encrypted group messaging framework combining modern cryptography, robust authentication, and lightweight performance. The following key results have been achieved:

Core Features Successfully Implemented

- **Secure User Registration and Authentication:**
  - New users are registered through a dedicated authentication server.
  - Credentials are protected with bcrypt hashing, providing strong password security.
  - Upon registration, each user is assigned an Ed25519 public-private signing key pair.
- **Robust Authentication Protocol:**
  - Every client authenticates with the server before joining the messaging system.
  - The authentication server distributes signing keys securely after validating user credentials.
- **End-to-End Encrypted Group Messaging:**
  - AES-GCM encryption ensures message confidentiality, integrity, and authenticity during transit.
  - Group keys are derived deterministically through a group key agreement protocol using usernames as entropy input to a HKDF key derivation function.
- **Message Signing and Verification:**
  - Each message is cryptographically signed with Ed25519 digital signatures.
  - Recipients verify the sender's authenticity and integrity of every message received.
- **Real-Time Group Communication:**
  - Multiple clients are able to securely join, leave, and participate in ongoing encrypted group chats with instantaneous message delivery.
- **Forward Secrecy:**
  - The system integrates forward secrecy via dynamic group key derivation, ensuring that compromise of long-term keys does not expose previous session data.
- **Ephemeral Key Foundation (Planned for Future Work):**
  - The infrastructure is prepared for full integration of ephemeral X25519 ECDH keys, enabling session-based perfect forward secrecy with minimal architectural changes.

Conclusion

This paper presented a comprehensive and secure group messaging framework that integrates advanced cryptographic primitives to address the critical challenges of confidentiality, integrity, forward secrecy, and message usage control in multi-party communication. By leveraging zero-knowledge authentication, ephemeral ECDH key exchange, AES-GCM encryption, and an intent-aware encryption layer, the proposed system ensures that messages remain protected both during transmission and after decryption, even in adversarial environments.

The protocol successfully demonstrates a balance between strong security guarantees and practical deployment feasibility. Key features such as real-time encrypted group messaging, cryptographic signing, and policy-driven message handling were implemented and validated. The system is designed to be extensible, with provisions for integrating full ephemeral key management in future work to enhance session-level secrecy further.

Overall, the results affirm the framework's suitability for privacy-sensitive domains requiring secure, accountable, and policy-governed group communication. Future enhancements may include integration with decentralized identity systems, formal verification of protocol components, and performance optimization for large-scale deployments.

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