

# Anonymous Multi-Receiver Certificateless Hybrid Signcryption for Broadcast Communication

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**Keywords:** mKEM-DEM, Hybrid Signcryption, Certificateless, Multireceiver, Pseudo-Identity, Confidentiality, Authentication, Anonymity.


**Abstract:** Confidentiality, authentication, and anonymity are fundamental security requirements in broadcast communication achievable by Digital Signature (DS), encryption, and Pseudo-Identity (PID) techniques. Signcryption, particularly hybrid signcryption, offers both DS and encryption more efficiently than “sign-then-encrypt”, with lower computational and communication costs. This paper proposes an Anonymous Multi-receiver Certificateless Hybrid Signcryption (AMCLHS) scheme for secure broadcast communication. AMCLHS combines public-key cryptography and symmetric key to achieve confidentiality, authentication, and anonymity. We provide a simple and efficient construction of a multi-recipient Key Encapsulation Mechanism (mKEM) to create a symmetric session key. This key, with the sender’s private key, is used in Data Encapsulation Mechanism (DEM) to signcrypt the message, ensuring confidentiality and authentication. The scheme generates identical ciphertext for multiple recipients while maintaining their anonymity by assigning a PID to each user. Security notions are demonstrated for indistinguishability against chosen-ciphertext attack using the elliptic curve computational diffie-hellman assumption in the random oracle model and existential unforgeability against chosen message attack under elliptic curve diffie-hellman assumption. The AMCLHS scheme operates in a multireceiver certificateless environment, preventing the key escrow problem. Comparative analysis shows that our scheme is computationally efficient, provides optimal communication cost, and simultaneously ensures confidentiality, authentication, anonymity, non-repudiation, and forward security.


## 1 INTRODUCTION

Confidentiality, authentication, and anonymity are the basic security requirements in broadcast communication (Peng et al., 2020). The current solution to provide for these security requirements are encryption and Digital Signature (DS). However, the traditional “sign-then-encrypt” approach results in high computational costs. Signcryption, on the other hand, allows both the encryption and DS operations to be performed simultaneously, providing both the confidentiality and authentication more efficiently. Signcryption was first proposed by Zhang *et al.* as a novel cryptographic primitive (Zheng, 1997). Malone-Lee proposed the first Identity (ID)-based signcryption

scheme that provides forward security and public verifiability (Malone-Lee, 2002). However, in ID-based schemes, the public key generator generates the user’s private key, leading to the issue of private key escrow. To solve the key escrow problem, Al-Riyami *et al.* proposed a Certificateless Public Key Cryptography (CLPKC) (Al-Riyami and Paterson, 2003). In CLPKC, the Key Generation Center (KGC) only generates a partial private key (ppk) of the user. The user then combines ppk and a secret value to generate the actual private and public key pair. Therefore, the KGC does not have knowledge of the user’s complete private key. Following that, Barbosa and Farshim proposed the first certificateless signcryption scheme (Barbosa and Farshim, 2008). The signcryption methods mentioned above are designed for single receiver, which are not suitable for broadcast communication. When sending the same message to multiple recipients, the user encrypts a message for each individual recipient, increasing computation time and communication lag. To address this, Selvi *et al.* pro-

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posed the first multireceiver certificateless signcryption scheme (Selvi et al., 2008). Generally, the construction of signcryption can be achieved through two methods: (i) Public key signcryption: With public key signcryption, both message encryption and signing take place in a public key setting (Selvi et al., 2008). (ii) Hybrid signcryption: Hybrid signcryption provides the advantages of combining symmetric key encryption with asymmetric key signature while ensuring integrity, authentication, and non-repudiation (Selvi et al., 2009). Hybrid signcryption is generally efficient in resource constrained environments than pure asymmetric signcryption because, in asymmetric signcryption alone, large messages are sent with the large public key values. For more reading, we refer to Dent's work (Dent, 2005b; Dent, 2005a) on Hybrid signcryption schemes.

In this paper, we propose a multi-receiver anonymous certificateless hybrid signcryption based on multi-recipient Key Encapsulation Mechanism-Data Encapsulation Mechanism (mKEM-DEM) for broadcast communication. For confidentiality, we prove Indistinguishability against Chosen-Ciphertext Attack (*ind-cca2-I*) for Type-I adversary, and (*ind-cca2-II*) for Type-II adversary using Elliptic Curve based Computational Diffie-Hellman (ECCDH) assumption. For unforgeability, we prove Existential Unforgeability against Chosen Message Attack (*euf-cma-I*) for Type-I adversary, and (*euf-cma-II*) for Type-II adversary, respectively, based on Elliptic Curve Discrete Logarithm (ECDL) assumption. Additionally, to ensure anonymity, each user is assigned a Pseudo-Identity (PID) and we further demonstrate the security for non-repudiation and forward security. Finally, we compare our scheme with existing multireceiver certificateless hybrid signcryption schemes, demonstrating its efficiency in terms of computation cost, communication cost, and security requirements. In comparison to existing schemes, our scheme demonstrates higher efficiency, with the signcryption cost increasing linearly with the number of designated receivers, while the unsigncryption cost remains constant. Our scheme simultaneously satisfy all the security requirements in terms of confidentiality, unforgeability, anonymity, non - repudiation, and forward security.

## 1.1 Our Contributions

The objective of this paper is to provide an anonymous certificateless hybrid signcryption scheme by utilizing mKEM and DEM. Our main contributions are as follows:

1. We propose an Anonymous Multireceiver Certifi-

cateless Hybrid Signcryption (AMCLHS) scheme based on mKEM-DEM. The AMCLHS scheme uses a combination of PKC and symmetric key to signcrypt a message in broadcast communication.

2. The AMCLHS scheme achieves anonymity for each receiver by assigning a PID to each user (sender and receiver) and enables the sender to signcrypt an identical message for multiple receivers while keeping their real identities anonymous from each other.
3. The scheme operates in a multireceiver certificateless environment, preventing the key escrow problem. We achieve confidentiality by demonstrating security against *ind-cca2-I* and *ind-cca2-II* and unforgeability by demonstrating *euf-cma-I* and *euf-cma-II*, respectively. The security is proven using ECCDH and ECDL assumptions under the Random Oracle Model (ROM).

The remainder of the paper is as follows: The related work is provided in Sec. 2. Sec. 3 describes the mathematical assumptions and definitions. In Sec. 4, we introduce the AMCLHS framework and security model of the scheme in Sec. 5. Sec. 6 introduces the proposed AMCLHS scheme and in Sec. 7, we provide the security analysis under the hard assumption. Sec. 8 provide the performance analysis and comparison of the proposed scheme. Lastly, in Sec. 9, we conclude the work.

## 2 RELATED WORK

### 2.1 Certificateless Signcryption

Signcryption was first introduced by Zheng *et al.* in 1997 combining the signature and encryption to provide authentication and confidentiality more efficiently than sign-then-encrypt (Zheng, 1997). Several ID-based signcryption schemes have been proposed, however, the key issue is the presence of a key escrow problem. To address this, Barbosa and Farshim proposed the first certificateless signcryption scheme that provides both confidentiality and authentication and is secure under the ROM (Barbosa and Farshim, 2008). Chen *et al.* and Cui *et al.* proposed a certificateless signcryption scheme for the Internet of Medical Things without pairings and the Internet of Vehicles (IoVs), respectively. The schemes provides confidentiality and authentication and proves security under ECDL and Computational Diffie-Hellman (CDH) assumptions (Chen et al., 2023; Cui et al., 2022). Similarly, a certificateless signcryption scheme without ROM was proposed by ZHOU *et al.* that achieves

confidentiality and unforgeability however, does not provide anonymity (ZHOU, 2018). Kasyoka *et al.* proposed a certificateless signcryption for wireless sensor networks (Kasyoka et al., 2021). Additionally, Cui *et al.* presented a pairing-free certificateless signcryption scheme for the IoVs (Cui et al., 2022). Li *et al.* proposed a signcryption scheme for resource-constrained smart terminals in cyber-physical power systems (Li et al., 2022). However, all the aforementioned schemes are designed for single receivers, which are not suitable for broadcast communication. Yu *et al.* introduced the first multireceiver signcryption scheme based on ID-based PKC, enabling message encryption for  $n$  designated receivers (Yu et al., 2007). The security of the scheme is based on CDH assumption under the ROM. Later on, several multireceiver certificateless signcryption schemes were proposed. In 2022, Niu *et al.* proposed a privacy-preserving mutual heterogeneous signcryption scheme based on 5G network slicing, where the sender is in a public key infrastructure environment, and the receiver is in a certificateless environment (Niu et al., 2022a). The proposed scheme is secure against *ind-cca2* and *euf-cma* under the hardness assumptions of CDH and Discrete Logarithm (DL). In addition, numerous multireceiver certificateless signcryption schemes have been introduced in edge computing, Internet of Things (IoT), and IoT-enabled maritime transportation systems (Peng et al., 2020; Qiu et al., 2019; Yang et al., 2022; Yu et al., 2022). The above schemes based on large and resource-constrained environment are proven secure in public key settings, however, they may become computationally expensive when dealing with large messages, compared to hybrid settings. On the other hand, hybrid signcryption is generally more efficient than public key signcryption alone because it uses the combination of symmetric key and PKC. A message is encrypted using a symmetric key algorithm, which is faster and more efficient (Dent, 2005b; Dent, 2005a).

## 2.2 Certificateless Hybrid Signcryption

Dent *et al.* proposed the first hybrid signcryption scheme with insider and outsider security (Dent, 2005a; Dent, 2005b). Following that, Li *et al.* proposed the first certificateless hybrid signcryption scheme (Li et al., 2009). Wu *et al.* proposed a certificateless hybrid signcryption scheme for IoT (Wu et al., 2022). The scheme utilizes PKC to generate a symmetric key and is used to signcrypt the message. While the scheme provides confidentiality, authentication, forward security, and public verification under CDH and Decisional Bilinear Diffie-

Hellman (DBDH) assumptions, it incurs high computational cost due to Bilinear Pairing (BP) operation. Yin *et al.* proposed a certificateless hybrid signcryption scheme for wireless sensor network (WSN) (Yin and Liang, 2015). Similarly, Gong *et al.* presented a lightweight and secure certificateless hybrid signcryption scheme for the IoT (Gong et al., 2022). It ensures data confidentiality, integrity, and authenticity. The scheme utilizes BP for initialization and key construction and proves security under CDH and DBDH assumptions. Hongzhen *et al.* presented certificateless signcryption scheme for Vehicular Ad hoc Networks (VANETs) without BP (Hongzhen et al., 2021). Moreover, Zhang *et al.* introduced a certificateless hybrid signcryption scheme suitable for the IoT (Zhang et al., 2022). The scheme is constructed to achieve both confidentiality and unforgeability under DL, CDH, DBDH, and BDH assumptions. In 2017, Niu *et al.* proposed a heterogeneous hybrid signcryption for multi-message and multi-receiver (Niu et al., 2017). The scheme proves security against *ind-cca* and *euf-cma* attacks under the ROM based on the hardness assumptions of DBDH and variants of DBDH and Computational BDH. In 2022, Niu *et al.* presented a broadcast signcryption scheme based on certificateless cryptography for WSN (Niu et al., 2022b). The scheme aims to ensure the confidentiality and integrity of the data transmitted, while protecting by the privacy of the receiver's ID under ECDH and ECDL assumptions. The scheme uses a trusted third party to outsource the encryption operation and assumes that the trusted third party is always available. However, it may not be realistic in some scenarios, for instance, if the trusted third party is offline, the scheme may not work properly. Moreover, the scheme incurs higher computational costs compared to the AMCLHS scheme.

## 3 PRELIMINARIES AND ASSUMPTIONS

1. **Elliptic Curve Based Computational Diffie-Hellman (ECCDH) Assumption.** The security assumption of ECCDH is according to (Cohen et al., 2005).

**Definition 3.1.** *The ECCDH assumption holds given  $(P, xP, yP) \in \mathbb{G}$ , where  $x, y \in \mathbb{Z}_q^*$ , it is computationally infeasible for any Probabilistic Polynomial-Time (PPT) algorithm to compute  $xyP$ .*

2. **Elliptic Curve Discrete Logarithm (ECDL) Assumption.** The security assumption of ECDL

is adopted from (Cohen et al., 2005).

**Definition 3.2.** Given  $P$  and  $Q \in \mathbb{G}$ , it is hard to find an  $x \in \mathbb{Z}_q^*$  for any PPT algorithm with non-negligible probability such that  $Q = xP$ .

3. **The Multi-Recipient Key Encapsulation Mechanism (mKEM) and Data Encapsulation Mechanism (DEM).** The notion of mKEM was first proposed by N.P Smart (Smart, 2004) and has a KEM like construction which takes multiple receiver’s public keys  $pk_{r_i}$  where  $1 \leq i \leq t$  and  $t < n$  as input and generates a single symmetric session key  $K$  and an encapsulation  $C$  of  $K$ .

**Definition 3.3.** The mKEM construction below is according to the (Smart, 2004):

- (a) mKEM. It consists of four algorithms defined as follows (Setup, KeyGen, mKEM.Encaps, mKEM.Decaps):
- Setup. On input the security parameter  $1^\lambda$ , the algorithm outputs  $PP$ .
  - KeyGen. Taking  $PP$  as input, the algorithm outputs  $(pk, sk)$  for each user.
  - mKEM.Encaps. On input  $PP$  and a set of receiver public keys  $pk_{r_i}$  where  $1 \leq i \leq t$ , this algorithm outputs a symmetric session key  $K$  and an encapsulation  $C_1$  of  $K$  where  $K$  is used in DEM.
  - mKEM.Decaps. Taking  $PP$ , receiver’s private key  $sk_{r_i}$ , and an encapsulation  $C_1$  as input, this algorithm outputs  $K$ . The correctness holds if  $K = \text{mKEM.Decaps}(PP, sk_{r_i}, C_1)$ .
- (b) DEM: It consists of two algorithms ( $\text{Enc}_K, \text{Dec}_K$ ) (Niu et al., 2017) defined as follows:
- $\text{Enc}_K$ . On input  $(K, m)$ , this algorithm outputs a ciphertext  $C_2$ .
  - $\text{Dec}_K$ . Taking  $(K, C_2)$  as input, this algorithm outputs  $m'$ . The correctness of DEM holds if  $m' = m$ .

4. **KEM-DEM Hybrid Signcryption Scheme.**

**Definition 3.4.** The construction of KEM-DEM hybrid signcryption scheme is given by (Dent, 2005a). It consists of four algorithms (Setup, KeyGen, Gen – Enc, Dec – Ver) defined as follows:

- (a) Setup. It takes as input a security parameter  $1^\lambda$  and outputs  $PP$ .
- (b) KeyGen. Taking  $PP$  as input, this algorithm outputs a public and private key pair for sender  $(pk_s, sk_s)$  and receiver  $(pk_r, sk_r)$ .
- (c) Gen – Enc. In Gen – Enc, the sender runs following algorithms:

- Encaps. On input  $(PP, sk_s, pk_r, m)$ , it outputs a symmetric session key  $K$  and an encapsulation  $C_1$ .
  - $\text{Enc}_K$ . It takes  $K$  as input and outputs  $C_2$ . The receiver outputs ciphertext  $CT = (C_1, C_2)$ .
- (d) Dec – Ver. In this phase, the receiver runs following algorithms:
- Decaps. On input  $(sk_r, C_1)$ , it outputs  $K$ . If  $K = \perp$ , the sender stops. Otherwise, the receiver runs next algorithmic step.
  - $\text{Dec}_K$ . On input  $(C_2, K)$ , outputs  $m$ . If  $m = \perp$ , the receiver stops. Else, it runs next step.
  - Ver. Taking  $(pk_s, m, C_1)$  as input, it outputs either valid or not. If valid, outputs  $m$ , else  $\perp$ .

## 4 AMCLHS FRAMEWORK

### 4.1 Framework

The framework of the AMCLHS scheme consists of four entities: KGC, a Registration Authority (RA), and  $n$  users such as  $n = (PID_s, \{PID_1, \dots, PID_{r_i}, \dots, PID_{r_t}\})$ . Assume, a sender with  $PID_s$  sends an arbitrary length message  $m$  to  $t$  designated receivers with  $PID_{r_i}$  where  $1 \leq i \leq t$ . The role of each entity is defined below:

- **KGC.** The KGC is a trusted authority that is responsible for generating public parameters ( $PP$ ), master secret key ( $mSK$ ) of KGC, master public key ( $mpk$ ) of KGC, and partial private key ( $ppk$ ) for each user taking part in communication.
- **RA.** The RA is a semi-trusted authority that generates its private key  $sk_{RA}$  and public key  $pk_{RA}$ . RA is also responsible for user registration, ID verification, and PID assigning.
- **Sender.** The sender with  $PID_s$  encrypts a  $m$  using the set of designated receiver’s public key  $pk_{r_i}$ , signs with its private key  $sk_s$  and sends the sign-crypted ciphertext  $CT$  to  $t$  designated receivers.
- **Receiver.** The designated receiver with  $PID_{r_i}$  and  $sk_{r_i}$ , decrypt the  $CT$ , and verify the signature using sender’s public key  $pk_s$ .

### 4.2 Definition of AMCLHS

The AMCLHS scheme represents a hybrid approach, leveraging both mKEM and DEM components. Before signcryption the message, RA verifies user’s real identity  $ID_R$ , registers, and assigns a PID to each corresponding user. For signcryption, this framework firstly utilizes mKEM that takes a set of receiver’s



public keys as input, and generates a symmetric session key  $K$  and an encapsulation  $C_1$  of that key. The mKEM also takes a sender's private key to generate the signature  $S$  which is encapsulated in  $C_1$  and verifies in the unsigncryption phase as given in Def. 4.1. Following this, the DEM and session key  $K$  are jointly used to symmetrically encrypt  $m$ , producing a ciphertext  $C_2$ . This ciphertext is then represented as a signcrypted ciphertext pair  $CT = (C_1, C_2)$ . For decryption, the process starts with the decapsulation of  $C_1$  using mKEM and the receiver's private key to retrieve  $K$ . After this, the message  $m$  is decrypted from  $C_2$  using  $K$ . Once the  $m$  is decrypted, the receiver verifies the signature  $S$  using Ver algorithm by taking sender's public key and  $C_1$  as input. Hence, the AMCLHS scheme introduces an effective and secure mechanism for data signcryption and unsigncryption, employing both symmetric and asymmetric key strategies in a unique hybrid methodology.

**Definition 4.1.** *In the AMCLHS scheme, the sender with  $PID_s$  sends an arbitrary length  $m$  to  $t$  designated receivers denoted with  $PID_{r_i}$  where  $1 \leq i \leq t$ . The AMCLHS scheme follows the Defs. 3.3 and 3.4. The proposed scheme consists of eight polynomial time algorithms as follows:*

1. **Setup.** On input the security parameter  $1^\lambda$ , the KGC generates  $(PP, msk, mpk)$ . Next, RA generates  $sk_{RA}$  and  $pk_{RA}$ .
2. **Pseudo-Identity.** Takes Real Identity  $(ID_R)$  and  $pk_{RA}$  as input and outputs a PID.
3. **Partial Private Key.** For each PID, the KGC takes  $(mpk, msk)$  as input, it outputs the partial private key  $(ppk)$ .
4. **Secret Value.** On input the PID, each user generates a secret value  $(sv)$ .
5. **Private Key.** Taking  $(ppk, sv)$  as input, each user generates the  $sk$ .
6. **Public Key.** On input the  $sv$ , each user outputs the  $pk$ .
7. **Signcryption.** To signcrypt the  $m$  and generate the CT, the sender runs this algorithm in two phases. In Phase 1, the sender runs mKEM.Encaps and in Phase 2, the sender runs  $Enc_K$  according to the Def. 3.3. The phases are defined as follows:
  - Phase 1 (mKEM.Encaps) Taking  $PP$ ,  $sk_s$ , a plaintext  $m$  and a set  $pk_{r_i}$  for  $1 \leq i \leq t$ , this algorithm outputs  $C_1$  and  $K$
  - Phase 2 ( $Enc_K$ ) On input  $(K, m)$ , this algorithm outputs  $C_2$  and sets signcrypted ciphertext  $CT = (C_1, C_2)$ .

8. **Unsigncryption.** To unsigncrypt the CT and retrieve  $m$ , the receiver runs this algorithm in three phases. Phase 1 consists of mKEM.Decaps, Phase 2 consists of  $Dec_K$ , and Phase 3 consists of Ver algorithm according to the Def. 3.3.

- Phase 1 (mKEM.Decaps). Taking  $(sk_{r_i}, C_1)$  as input, this algorithm outputs  $K$ .
- Phase 2 ( $Dec_K$ ). On input  $(K, C_2)$ , this algorithm outputs  $m'$ . If  $m' \neq m$ , the receiver rejects the  $m$ . If  $m' = m$ , the receiver verifies the signature in Phase 3.
- Phase 3 (Ver). Taking  $(m', C_1, pk_s)$  as input, this algorithm verifies the signature  $S$ . If it is valid, accept the  $m$ , or else return  $\perp$ .

## 5 SECURITY MODEL

We define the security Game-I for *ind-cca2-I* and *ind-cca2-II* in Sec. 5.1, to evaluate the security against Type-I adversary ( $\mathcal{A}_I$ ) and Type-II adversary ( $\mathcal{A}_{II}$ ), respectively. Moreover, in Sec. 5.2, we introduce the security Game-II for *euf-cma-I* and *euf-cma-II* to evaluate the security against  $\mathcal{A}_I$  and  $\mathcal{A}_{II}$  and are defined as follows:

1.  $\mathcal{A}_I$ .  $\mathcal{A}_I$  is an honest-but-curious user who cannot access  $msk$  but can replace the  $pk$  of any ID with the value of his/her own choice.  $\mathcal{A}_I$  is not allowed to ask a  $ppk$  query  $q_{ppk}$  for any of the target ID.
2.  $\mathcal{A}_{II}$ .  $\mathcal{A}_{II}$ , also known as malicious KGC, cannot make public key replace query  $q_{pr}$  for the target ID.  $\mathcal{A}_{II}$  is not allowed to make  $sv$  extract queries  $q_{sv}$ . If the  $q_{pr}$  has been done for the target ID, then the  $q_{sv}$  is not allowed for the same ID.

### 5.1 Game-I

The Game-I is interaction between the Challenger  $C$  and  $\mathcal{A}$  in three phases. In each phase, the  $\mathcal{A}$  asks a polynomially bounded number of hash and public and private key queries. Finally,  $\mathcal{A}$  provides a target plaintext pair  $(m_0, m_1)$  to  $C$ .  $C$  picks  $\beta \in \{0, 1\}^*$  randomly and responds with a challenge  $CT^*$ .  $\mathcal{A}$  returns  $\beta' \in \{0, 1\}^*$  and wins the Game-I if  $\beta = \beta'$ .

**Definition 5.1.** *The ind-cca2 requires that there exists no PPT Adversary  $\mathcal{A}$  which could distinguish ciphertexts. The advantage of  $\mathcal{A}$  is defined as the probability that  $\mathcal{A}$  wins the game.*

1. **Phase-1.** The  $\mathcal{A}$  asks polynomially bounded number of hash queries  $q_{H_l}$  where  $l = \{1, 2, 3\}$ . The  $C$  keeps a list  $L_l$  of  $q_{H_l}$  to record the responses.

- **Setup.**  $C$  generates  $(PP, msk, mpk, sk_{RA}, pk_{RA})$  and passes to  $\mathcal{A}$ . Then  $\mathcal{A}$  selects  $t$  target  $PID_{r_i}$  where  $1 \leq i \leq t$ .
- 2. **Phase-2.** The  $\mathcal{A}$  proceeds to make a series of queries, subject to the restrictions defined in Sec. 5. The queries include public key retrieve query  $q_{pk}$ , partial private key query  $q_{ppk}$ , secret value extract query  $q_{sv}$ , public key replace query  $q_{pr}$ , signcryption query  $q_{sc}$ , and unsigncryption query  $q_{usc}$ . An initially empty list  $L_{pk}$  is maintained by the  $C$  to store public and secret information. The  $C$  responds to each query as follows:
  - $q_{pk}$ . Upon receiving such query for  $PID$ , the  $C$  searches  $L_{pk}$  for  $pk$ . If it does not exist,  $C$  runs the secret value algorithm to generate a  $sv$  for  $PID$ , and performs the public key algorithm to return the  $pk$  to  $\mathcal{A}$ .
  - $q_{ppk}$ . Given  $PID$ , the  $C$  checks if  $PID = PID^*$ . If it does, the  $C$  aborts. Otherwise, it fetches the  $ppk$  from  $L_{pk}$ . If it does not exist,  $C$  runs a partial private key algorithm to return  $ppk$  and updates  $L_{pk}$ .
  - $q_{sv}$ . Upon  $q_{sv}$ , the  $C$  checks  $L_{pk}$  for  $sv$ . If it does not exist,  $C$  runs a secret value algorithm and returns  $sv$  to  $\mathcal{A}$ .
  - $q_{pr}$ . Given  $PID$  as input, the  $C$  replaces  $pk$  with  $pk'$  and updates  $L_{pk}$ .
  - $q_{sc}$ . On input  $(m, PID_s, PID_{r_i})$ , the  $C$  checks if  $PID_{r_i} = PID^*$ . If it is not,  $C$  performs normal signcryption operation by taking values from  $L_{pk}$ . Otherwise, it performs the signcryption algorithm to generate  $CT$ .
  - $q_{usc}$ . Upon receiving  $(CT, PID_s, PID_{r_i})$  as input, the  $C$  checks if  $PID_{r_i} = PID^*$ . If it is not,  $C$  performs normal unsigncryption operation. Otherwise,  $C$  performs the unsigncryption algorithm to answer  $m$ .
- 3. **Challenge.** The  $\mathcal{A}$  outputs a target plaintext  $(m_0, m_1)$ . The  $C$  picks  $\beta \in \{0, 1\}^*$  at random, sets challenge  $CT^*$ , and sends  $CT^*$  to  $\mathcal{A}$ .
- 4. **Phase-3.** The  $\mathcal{A}$  can make further queries except that the  $CT^*$  is not allowed to appear in the  $q_{usc}$ .
- 5. **Guess.** Finally,  $\mathcal{A}$  responds with its guess  $\beta' \in \{0, 1\}^*$ . If  $\beta = \beta'$ ,  $\mathcal{A}$  wins the Game-I. The advantage of  $\mathcal{A}_I$  is defined as:

$$Adv_{\mathcal{A}_I}^{IND-CCA2} = |\Pr[\beta = \beta'] - 1/2| \quad (1)$$

The advantage of  $\mathcal{A}_{II}$  is defined as:

$$Adv_{\mathcal{A}_{II}}^{IND-CCA2} = |\Pr[\beta = \beta'] - 1/2| \quad (2)$$

## 5.2 Game-II

Game-II consists of two phases. In each phase, the  $\mathcal{A}$  asks a polynomially bounded number of hash,  $pk$  and  $sk$  queries. In the end,  $\mathcal{A}$  outputs the forged ciphertext.  $\mathcal{A}$  wins if unsigncryption does not return  $\perp$ .

**Definition 5.2.** An AMCLHS scheme is *euF-cma-secure* if every PPT  $\mathcal{A}$  has a negligible advantage in winning the Game-II.

1. **Phase-1.** Phase-1 remains same as in Def. 5.1 except that  $\mathcal{A}$  selects a target identity as  $PID_s^*$
2. **Phase-2.** The  $\mathcal{A}$  asks a number of queries with the restrictions defined in Sec. 5. The queries include  $q_{pk}$ ,  $q_{ppk}$ ,  $q_{pr}$ ,  $q_{sv}$ ,  $q_{sc}$ , and  $q_{usc}$  and are defined in Phase-2 in Def. 5.1.  $C$  maintains an initially empty list  $L_{pk}$  to store the  $pk$  and  $sk$  information.
3. **Forgery.**  $\mathcal{A}$  outputs the forged CT under a targeted  $PID_s^*$ .  $\mathcal{A}$  wins if unsigncryption does not return  $\perp$ .

## 6 THE PROPOSED AMCLHS SCHEME

In this section, we focus on the construction of the proposed AMCLHS scheme, built upon the mKEM-DEM framework, according to the Def. 4.1. The structure of the scheme is shown in Fig. 1.

1. **Setup.** The KGC initializes the system by taking the security parameter  $1^\lambda$  as input. It chooses a group  $\mathbb{G}$  of large prime order  $q$ , derived from an elliptic curve  $E$  over a finite field  $\mathbb{F}_q$ . The KGC selects a generator point  $P \in \mathbb{G}$  and generates four hash functions. The first hash function is  $H_0 : \{0, 1\}^\ell \rightarrow \mathbb{G}$ , where  $\ell$  is a positive integer. The second is  $H_1 : \{0, 1\}^* \times \mathbb{G} \rightarrow \mathbb{G}$ . The third hash function is  $H_2 : \mathbb{G} \rightarrow \{0, 1\}^k$ , where  $k$  denotes the plaintext box length. The fourth is  $H_3 : \{0, 1\}^* \times \mathbb{G} \times \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{Z}_q^*$ . The KGC generates  $PP = \{\mathbb{G}, E, P, q, H_0, H_1, H_2, H_3\}$ , randomly selects  $x_0 \in \mathbb{Z}_q^*$  as the master secret key  $msk$ , and calculates the master public key  $mpk = x_0P$ . It then publishes  $PP$  and  $mpk$ , while keeping  $msk$  secret. Subsequently, the RA selects  $v \in \mathbb{Z}_q^*$  at random as its secret key  $sk_{RA}$  and calculates its public key  $pk_{RA} = vP$ . The RA publicizes  $pk_{RA}$  and keeps  $sk_{RA}$  as a secret.
2. **Pseudo-Identity.** This algorithm is run by each user and RA as follows:
  - User. Each user chooses a random  $ID_R \in \{0, 1\}^\ell$  and computes  $R = \alpha P$  where  $\alpha \in \mathbb{Z}_q^*$ . Tak-

- ing  $(ID_R, \alpha)$  as input, it computes  $PID = ID_R \oplus H_0(\alpha pk_{RA})$  and sends  $(PID, R)$  to RA.
- RA. On input  $(PID, R)$ , RA verifies  $ID_R = PID \oplus H_0(Rv)$ . If it holds, RA accepts the registration request, confirms and assigns  $PID = ID_R \oplus H_0(\alpha pk_{RA})$  to each corresponding user ID. Else, RA discards the PID and cancels the registration request.
3. **Partial Private Key.** Taking  $(PID, mpk, msk)$  as input, the KGC computes  $Q_{PID} = H_1(PID || mpk)$  as a public component. Taking  $Q_{PID}$ , the KGC computes  $ppk$  as  $d = x_0 Q_{PID}$ .
  4. **Secret Value.** Each user with PID chooses a random  $x \in \mathbb{Z}_q^*$  randomly as a sv.
  5. **Private Key.** On input  $(d, x)$ , each user with PID sets  $sk = (d, x)$ .
  6. **Public Key.** Taking  $x$  as input, each user with PID computes  $pk = xP$ .
  7. **Signcryption.** The sender with  $PID_s$  and  $sk_s$  runs following phases to signcrypt a  $m$  and sends CT to receivers with  $PID_{r_i}$  and  $pk_{r_i}$   $1 \leq i \leq t$ :
    - Phase 1 (mKEM-Encaps).
      - (a) Randomly chooses  $r \in \mathbb{Z}_q^*$  and computes  $U = rP$ .
      - (b) Taking  $pk_{r_i}$  and  $Q_{PID_{r_i}}$  as input, computes  $Z_{1i} = d_s Q_{PID_{r_i}}$  and  $Z_{2i} = x_s pk_{r_i}$ .
      - (c) Computes  $\psi_i = (Z_{1i}, Z_{2i})$  and  $K = H_2(\psi_i)$ .
      - (d) Computes a hash  $f_i = H_3(m, \psi_i, pk_s, pk_{r_i})$  and Signature  $S_i = r^{-1}(f_i || wd_s x_s)$  where  $w = x_U \bmod q$  which is the x-coordinate of  $U$ .
      - (e) Sets  $C_{1i} = (f_i, S_i)$  and outputs  $(C_{1i}, K)$ .
    - Phase 2 ( $Enc_K$ ).
      - (a) Computes  $C_{2i} = Enc_K(m)$ . Sets  $CT_i = (C_{1i}, C_{2i})$  and sends to  $t$  designated receivers.
  8. **Unsigncryption.** Each designated receiver with  $PID_{r_i}$  takes  $(sk_{r_i}, pk_s)$  as input for  $i^{th}$  receiver and runs the following phases to unsigncrypt the  $CT_i$  and generate  $m$ :
    - Phase 1 (mKEM-Decaps).
      - (a) Taking  $(x_{r_i}, d_{r_i})$  as input, computes  $Z'_{1i} = d_{r_i} Q_{PID_s}$  and  $Z'_{2i} = pk_s x_{r_i}$ .
      - (b) Computes  $\psi'_i = (Z'_{1i}, Z'_{2i})$  and  $K = H_2(\psi'_i)$ . If  $K = \perp$ , the receiver aborts else, decrypts  $m$  as follows:
        - Phase 2 ( $Dec_K$ ).
          - (a) Calculates  $m' = Dec_K(C_{2i})$ . If  $m' = m$ , verifies the  $S_i$  else rejects.
        - Phase 3 (Ver).
          - (a) Inputs  $(C_{1i}, pk_s)$ , outputs  $f'_i = H_3(m', \psi'_i, pk_s, pk_{r_i})$ .
    - (b) If  $f'_i = f_i$ , verifies  $S_i$  by checking if  $U = rP$  and  $w' = x_U \bmod q$ . If  $w' = w$ , the receiver will accept the signcrypted  $m$  else returns  $\perp$  and aborts.

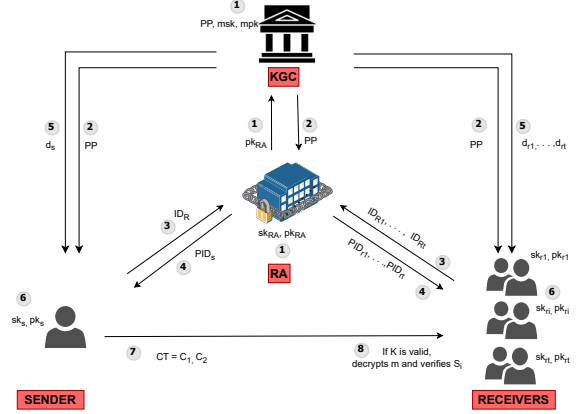


Figure 1: Our Proposed AMCLHS Scheme.

## 7 SECURITY ANALYSIS

The security analysis of the proposed AMCLHS scheme is based on the security model defined in Sec. 5. The message confidentiality is based on Theorems 7.1 and 7.2 which demonstrates that the scheme is secure against  $ind\text{-}cca2$   $\mathcal{A}_I$  and  $\mathcal{A}_{II}$  in Def. 5.1. Similarly, unforgeability is based on Theorems 7.3 and 7.4 and follows that the scheme is secure against  $euf\text{-}cma$   $\mathcal{A}_I$  and  $\mathcal{A}_{II}$  in Def. 5.2.

### Confidentiality

**Theorem 7.1.** Suppose that the  $ind\text{-}cca2\text{-I}$  has a non-negligible advantage  $\epsilon$  in winning the game then, there is  $C$  that can solve the ECCDH with the non-negligible advantage  $\epsilon'$ .

*Proof.* Given a random instance  $(P, xP, yP) \in \mathbb{G}$  of the ECCDH assumption, the  $C$  has to compute  $xyP$  as Def. 3.1 by interacting with the  $\mathcal{A}_I$  as follows:  $\square$

1. **Phase-1.** A polynomially bounded number of queries  $q$  are made by an  $\mathcal{A}_I$ . The  $C$  keeps a list  $L_1$  of  $qH_1$  to record the responses.
  - **Setup.** The  $C$  runs this algorithm to generate  $PP = \{\mathbb{G}, E, P, q, H_0, H_1, H_2, H_3\}$ . The  $C$  sets new value for the  $mpk = \theta P$  and sends  $PP$  and  $mpk$  to the  $\mathcal{A}_I$ . The  $\mathcal{A}_I$  selects  $t$  target identities denoted by  $PID_i^*$  where  $1 \leq i \leq t$ .
  - **$H_1$ -Query.** Upon  $H_1$  query,  $C$  determines if the tuple  $(Q_{PID_i}, mpk, PID_i)$  exists in  $L_1$  or not. If it already exists,  $C$  returns  $Q_{PID_i}$  to  $\mathcal{A}_I$ . Else, if  $PID_i \neq PID_i^*$ ,  $C$  sets  $Q_{PID_i} = H_1(PID_i || mpk)$ .

- If  $PID_i = PID_i^*$ ,  $C$  chooses  $\gamma \in \mathbb{Z}_q^*$ , computes  $Q_{PID_i} = \gamma P$ , adds in  $L_1$  and sends  $Q_{PID_i}$  to  $\mathcal{A}_I$ .
- **$H_2, H_3$ -Query.** Upon  $H_2$  and  $H_3$  queries, the  $C$  determines if the tuple  $(K, \psi_i, Z_{1_i}, Z_{2_i}), (m, \psi_i, f_i)$  exists in  $L_2$  and  $L_3$ . If it does,  $C$  returns  $K$  and  $f_i$  to  $\mathcal{A}_I$ . Else, the  $C$  chooses  $K \in \{0, 1\}^k$  and  $f_i \in \mathbb{Z}_q^*$  randomly, updates both tuples. The  $C$  sends  $\psi_i$  and  $f_i$  to  $\mathcal{A}_I$ .
2. **Phase-2.** The  $\mathcal{A}_I$  asks queries including  $q_{pk}, q_{ppk}, q_{pr}, q_{sv}$ , and  $q_{usc}$ . The  $C$  maintains an initially empty list  $L_{pk}$  to store the public and secret information. The  $C$  responds to the queries as follows:
- $q_{pk}$ . Upon  $pk_i$  query for  $PID_i$ ,  $C$  checks if  $pk_i$  exists in  $L_{pk}$ . If it exists,  $C$  returns  $pk_i$  to  $\mathcal{A}_I$ . Otherwise,  $C$  chooses  $x_i \in \mathbb{Z}_q^*$  and computes  $pk_i = x_i P$ , adds the tuple  $(PID_i, -, pk_i, x_i)$  in  $L_{pk}$  and returns  $pk_i$  to  $\mathcal{A}_I$ .
  - $q_{ppk}$ . Upon  $q_{ppk}$ , if  $PID_i = PID_i^*$ , the  $C$  aborts. Otherwise, if it exists in  $L_{pk}$ ,  $C$  sends  $d_i$  to  $\mathcal{A}_I$ , if it does not,  $C$  randomly chooses  $Q_{PID_i} = \gamma P$  from  $L_1$  and return  $d_i = mpk_{Q_{PID_i}}$  to  $\mathcal{A}_I$ . The  $C$  then updates the tuple  $(PID_i, d_i, pk_i, x_i)$  in  $L_{pk}$ .
  - $q_{sv}$ . Upon receiving  $q_{sv}$ ,  $C$  checks if it exists in  $L_{pk}$ , if it does,  $C$  sends  $x_i$  to  $\mathcal{A}_I$ . If not,  $C$  performs the  $q_{pk}$  and return  $x_i$  to  $\mathcal{A}_I$ .
  - $q_{pr}$ . Upon  $q_{pr}$ ,  $C$  replaces the  $pk_i$  with  $pk'_i$  for  $PID_i$  and updates the tuple  $(PID_i, d_i, pk'_i, -)$ .
  - $q_{sc}$ . Upon receiving the query with  $PID_s, PID_{r_i}$  and  $m$ , the  $C$  checks if  $PID_{r_i} = PID_i^*$ . If not, the  $C$  performs the normal signcryption operation by taking values from  $L_{pk}$ . Otherwise, the  $C$  performs the signcryption as follows:
    - If  $pk_i$  is replaced,  $\mathcal{A}_I$  provides another value.
    - Chooses  $r \in \mathbb{Z}_q^*$  and computes  $U = rP$ .
    - Gets  $Q_{PID_{r_i}}$  from  $L_1$  and computes  $Z_{1_i} = d_s Q_{PID_{r_i}}, Z_{2_i} = x_s pk_{r_i}, \psi_i = (Z_{1_i} Z_{2_i}), K = H_2(\psi_i)$ , and updates  $L_2$ .
    - Computes  $f_i = H_3(m, \psi_i, pk_s, pk_{r_i})$  and updates  $L_3$ .
    - Computes  $S_i, C_{1_i} = (f_i, S_i), C_{2_i} = Enc_K(m)$  and returns  $CT_i = (C_{1_i}, C_{2_i})$  to  $\mathcal{A}_I$ .
  - $q_{usc}$ . Upon  $q_{usc}$  with  $PID_s, PID_{r_i}$  and a CT, the  $C$  checks whether  $PID_{r_i} = PID_i^*$ . If not, the  $C$  performs the normal unsigncryption operation. Otherwise, the  $C$  unsigncrypts  $m$  as follows:
    - If  $pk_i$  is replaced,  $\mathcal{A}_I$  provides another value.
    - Searches the lists  $L_2$  and  $L_3$  for  $(K, \psi'_i, Z'_{1_i}, Z'_{2_i})$  and  $H_3(m, \psi'_i, f'_i)$ .
    - If the record does not exist,  $C$  returns "failure". If it exists, the  $C$  computes  $K \neq \perp$  and  $m' = Dec_K(C_{2_i})$ .
- Checks if  $f'_i = f_i$ , if it holds then checks if  $U = rP$  and  $w' = x_U \bmod q$  holds or not. If yes, the  $C$  answers  $m$  else, returns  $\perp$ .
3. **Challenge.** The  $\mathcal{A}_I$  chooses equal length plaintext message pair  $(m_0, m_1)$  and sends the target plaintext to the  $C$ . The  $\mathcal{A}_I$  takes a sender  $PID_s$  and a target  $PID_{r_i}$ . Moreover, the  $\mathcal{A}_I$  can not ask for the sk of the target  $PID_{r_i}$ . If  $PID_{r_i} \neq PID_i^*$ , the  $C$  returns  $\perp$ . Otherwise, it chooses  $\beta \in \{0, 1\}^*$  and performs the following steps to generate a  $CT_i^*$ :
- Chooses  $r^* \in \mathbb{Z}_q^*$  and computes  $U^* = r^* P$
  - Computes  $Z_{1_i}^* = d_s Q_{PID_{r_i}}, Z_{2_i}^* = x_s pk_{r_i}$ , and  $\psi_i^* = (Z_{1_i}^* Z_{2_i}^*)$ . Computes  $K^* = H_2(\psi_i^*)$ .
  - $f_i^* = H_3(m, \psi_i^*, pk_s, pk_{r_i})$ . Computes  $S_i^* = r^{*-1}(f_i^* || w_{d_s} x_s)$  and  $C_{1_i}^* = (f_i^*, S_i^*)$ .
  - $C_{2_i}^* = Enc_{K^*}(m)$  and computes  $CT_i^* = (C_{1_i}^*, C_{2_i}^*)$ .
4. **Phase-3.**  $\mathcal{A}_I$  may issue further polynomially bounded queries as in *Phase-1*, however,  $\mathcal{A}_I$  cannot send the  $q_{ppk}$  of the target  $PID_{r_i}$ , or the unsigncryption query for  $CT_i^*$ .
5. **Guess.** The  $\mathcal{A}_I$  will respond with the guess bit  $\beta' \in \{0, 1\}^*$ .  $\mathcal{A}_I$  wins the game if  $\beta' = \beta$ . The  $C$  will win the game by evaluating  $\frac{\theta Z_{1_i} - d_i r}{(d_s - U)} = \theta \gamma P$  using  $mpk = \theta P, Q_{PID_i} = \gamma P$  which is the solution to the ECCDH assumption.
- Next, we evaluate the advantage of  $C$  winning the Game-I (*ind-cca2-I*) by calculating the probability of aborting the game during the following events:
1. In  $q_{ppk}$ , the game aborts for  $PID_i = PID_i^*$ . The probability is  $\Pr(E_{q_{ppk}}) = 1/q_{ppk}$ .
  2. In  $q_{usc}$ , the game aborts due to invalid  $m$ . The probability is  $\Pr(E_{q_{usc}}) = q_{usc}/2^k$ .
  3. In the challenge phase,  $C$  aborts if the adversary queries against the identity  $PID_{r_i} \neq PID_i^*$ . The probability is  $\Pr(E_{q_{H_1}}) = (1 - 1/q_{H_1})$ .
- Moreover, the  $C$  fetches  $L_1$  to retrieve  $Q_{PID_i}$  and  $L_2$  to retrieve  $Z_{1_i}$  and evaluates  $\frac{\theta Z_{1_i} - d_i r}{(d_s - U)} = \theta \gamma P$  with probability  $(1/q_{H_1} + 1/q_{H_2})$ . Therefore, the probability of the  $C$  winning the game with advantage  $\epsilon'$  is:
- $$\epsilon' \geq \epsilon \left( \frac{1}{q_{H_1}} + \frac{1}{q_{H_2}} \right) \left( \frac{1}{q_{H_1}} \right) \left( 1 - \frac{1}{q_{ppk}} \right) \left( 1 - \frac{q_{usc}}{2^k} \right) \quad (3)$$
- Theorem 7.2.** Suppose that the *ind-cca2-II* has a non-negligible advantage  $\epsilon$  in winning the game then, there is a  $C$  that can solve the ECCDH assumption with the non-negligible advantage  $\epsilon'$ .



*Proof.* Given a random instance  $(P, xP, yP) \in \mathbb{G}$  of the ECCDH assumption, the  $C$  has to compute  $xyP$  as Def. 3.1 by interacting with  $\mathcal{A}_{\Pi}$  as follows:  $\square$

1. **Phase-1.** A polynomially bounded number of queries  $q$  are made by an  $\mathcal{A}_{\Pi}$ .
  - **Setup.** The  $C$  generates PP and mpk as in Theorem 7.1 and sends PP and mpk to the  $\mathcal{A}_{\Pi}$ .
  - **$H_1$ -Query.** The response of  $H_1$  query to  $\mathcal{A}_{\Pi}$  is same as in Theorem 7.1.
  - **$H_2, H_3$ -Query.** This query remains the same as in Theorem 7.1 and the  $C$  sends  $\psi_i$  and  $f_i$  to  $\mathcal{A}_{\Pi}$ .
2. **Phase-2.**  $\mathcal{A}_{\Pi}$  asks a number of queries including  $q_{pk}, q_{sv}$ . The  $C$  responds as follows:
  - $q_{pk}$ . Upon  $pk_i$  for  $PID_i$ , the  $C$  checks if  $pk_i$  exists in the  $L_{pk}$  as  $(PID_i, d_i, pk_i, x_i)$ . If it exists,  $C$  returns  $pk_i$  to  $C$ . Otherwise,  $C$  chooses  $x_i \in \mathbb{Z}_q^*$ ,  $pk_i = x_iP$ , adds the tuple  $(PID_i, -, pk_i, x_i)$  in  $L_{pk}$  and returns  $pk_i$  to  $\mathcal{A}_{\Pi}$ .
  - $q_{sv}$ . Upon  $q_{sv}$ ,  $C$  checks if  $PID_i = PID_i^*$ . If it holds, the  $C$  aborts because, in this case, the  $PID_i$  is a target ID. Otherwise, it checks if  $x_i$  already exists in the  $L_{pk}$ . If it exists, the  $C$  returns  $x_i$  to  $\mathcal{A}_{\Pi}$ . Otherwise,  $C$  runs  $q_{pk}$ , computes  $pk_i = x_iP$ , adds the tuple  $(PID_i, d_i, pk_i, x_i)$  in  $L_{pk}$  and returns  $x_i$  to  $\mathcal{A}_{\Pi}$ .
  - $q_{sc}$ . The  $q_{sc}$  query from  $\mathcal{A}_{\Pi}$  and the response from  $C$  will be similar to the Theorem 7.1.
  - $q_{usc}$ . The  $q_{usc}$  query from  $\mathcal{A}_{\Pi}$  and the response from  $C$  will be same as in Theorem 7.1.
3. **Challenge.** The  $\mathcal{A}_{\Pi}$  chooses target plaintext  $m_0, m_1$  and sends to the  $C$ .  $\mathcal{A}_{\Pi}$  takes a  $PID_s$  and a target  $PID_{r_i}$ . Moreover, the  $\mathcal{A}_{\Pi}$  can not ask for the sk of the receiver  $PID_{r_i}$ . If  $PID_{r_i} \neq PID_{r_i}^*$ , the  $C$  returns  $\perp$ . Otherwise, it chooses  $\beta \in \{0, 1\}^*$  and performs the following steps to generate a challenge  $CT^*$ :
  - Chooses  $r^* \in \mathbb{Z}_q^*$  and computes  $U^* = r^*P$ .
  - Computes  $Z_{1_i} = d_s Q_{PID_{r_i}}$ ,  $Z_{2_i} = x_s pk_{r_i}$ , and  $\psi_i^* = (Z_{1_i}^*, Z_{2_i}^*)$ . Computes  $K^* = H_2(\psi_i^*)$ .
  - Computes  $f_i^* = H_3(m, \psi_i^*, pk_s, pk_{r_i})$ . Computes  $S_i^* = r^{*-1}(f_i^* || wd_s x_s)$  and  $C_{1_i}^* = (f_i^*, S_i^*)$ .
  - $C_{2_i}^* = Enc_K^*(m)$  and  $CT_i^* = (C_{1_i}^*, C_{2_i}^*)$ .
4. **Phase-3.** The  $\mathcal{A}_{\Pi}$  may issue further queries as in *Phase-1* however,  $\mathcal{A}_{\Pi}$  cannot send the  $q_{sv}$  for the target  $PID_{r_i}^*$  and the  $q_{uns}$  for  $CT_i^*$ .
5. **Guess.** The  $\mathcal{A}_{\Pi}$  will respond with the guess bit  $\beta' \in \{0, 1\}^*$ . The adversary wins the game if  $\beta' = \beta$ . The  $C$  will win the game by obtaining

$\theta\gamma P$ , which is the solution to the ECCDH assumption. The  $C$  obtains it by evaluating  $\frac{\theta Z_{1_i} - d_i r}{(d_s - U)} = \theta\gamma P$  since  $mpk = \theta P$ ,  $Q_{PID_i} = \gamma P$ .

Next, we will analyse the advantage of the  $C$  in winning the game. The  $C$  advantage is based on the occurrence of the events in which the game aborts. The  $C$  aborts under the following events:

- The  $q_{sv}$  where the game aborts for  $PID_i = PID_i^*$ . The probability is  $\Pr(E_{q_{sv}}) = 1/q_{sv}$ .
- The  $q_{usc}$  where the game aborts due to invalid  $m$ . The probability is  $\Pr(E_{q_{usc}}) = q_{usc}/2^k$ .
- In the challenge phase,  $\mathcal{A}_{\Pi}$  queries for  $PID_{r_i}^* \neq PID_{r_i}^*$ . The probability is  $\Pr(E_{q_{H_1}}) = (1 - 1/q_{H_1})$ .

Moreover, the  $C$  fetches  $L_1$  to retrieve  $Q_{PID_i}$  and  $L_2$  to retrieve  $Z_{1_i}$  and evaluates  $\theta\gamma P$  with probability  $(1/q_{H_1} + 1/q_{H_2})$ . Therefore, the probability of the  $C$  winning the game with advantage  $\epsilon'$  is:

$$\epsilon' \geq \epsilon \left( \frac{1}{q_{H_1}} + \frac{1}{q_{H_2}} \right) \left( \frac{1}{q_{H_1}} \right) \left( 1 - \frac{1}{q_{sv}} \right) \left( 1 - \frac{q_{usc}}{2^k} \right) \quad (4)$$

### Unforgeability

**Theorem 7.3.** *Suppose that the euf-cma-I adversary  $\mathcal{A}_I$  has a non-negligible advantage  $\epsilon$  in winning the game then, there is  $C$  that can solve the ECDL with the non-negligible advantage  $\epsilon'$ .*

*Proof.* Given a generator point  $P \in \mathbb{G}$  and a new generator  $Q = \phi P$  in the same group, the  $C$  has to find  $\phi$  by interacting with  $\mathcal{A}_I$ .  $\square$

1. **Phase-1.**  $\mathcal{A}_I$  makes same queries as in the *Phase-1* of Theorem 7.1.
  - **Setup.** The  $C$  runs setup algorithm to generate  $PP = \{\mathbb{G}, E, P, q, H_0, H_1, H_2, H_3\}$ . The  $C$  sets  $mpk = \theta P$  and sends PP and mpk to the  $\mathcal{A}_I$ . The  $\mathcal{A}_I$  selects a target identity as  $PID_s^*$ .
2. **Phase-2.** The queries and responses are the same as in *Phase-2* of Theorem 7.1 except the response to  $q_{ppk}$  is as follows:
  - $q_{ppk}$ . Upon  $q_{ppk}$ , if  $PID = PID_s^*$ , the  $C$  aborts. Otherwise, if it exists in  $L_{pk}$ , the  $C$  sends  $d_i$  to  $\mathcal{A}_I$ , if it does not, the  $C$  randomly chooses  $\phi \in \mathbb{Z}_q^*$  and computes  $d_i = \phi Q_{PID_i}$ . The  $C$  returns  $d_i = \phi Q_{PID_i}$  to  $\mathcal{A}_I$  and updates  $L_{pk}$ .
3. **Forgery.** Taking the targets  $PID_s^*$  and  $PID_{r_i}$ ,  $\mathcal{A}_I$  outputs a forged  $CT_i^* = (C_{1_i}^*, C_{2_i}^*)$  on  $m^*$  where  $C_{1_i}^* = (f_i^*, S_i^*)$  and  $C_{2_i}^* = Enc_K^*(m)$  which is the valid signcrypted ciphertext and is not the result of signcryption oracle.

- Case-1 ( $\text{PID} \neq \text{PID}_s^*$ ): The  $C$  returns  $\perp$ .
- Case-2 ( $\text{PID} = \text{PID}_s^*$ ): The  $C$  extracts the  $L_{\text{pk}}$  for the record  $(\text{PID}_i^*, d_i^*, \text{pk}_i^*, x_i^*)$  and  $L_3$  for the record  $(m^*, \psi_i^*, f_i^*)$ .

According to Forking Lemma,  $C$  replays the  $\mathcal{A}_I$  with the same random tape but distinct attributes from  $H_1$  and  $H_3$ . It implies that,  $h_1^* = H_1(\text{mpk}, \text{PID}_i^*)$  and  $h_1'^* = H_1(\text{mpk}, \text{PID}_i^*)$ , and  $h_1^* \neq h_1'^*$  i.e.  $Q_{\text{PID}_s^*}^* \neq Q_{\text{PID}_s^*}'^*$ . Similarly,  $h_3^* = H_3(m^*, \psi_i^*, \text{pk}_s^*, \text{pk}_{r_i}^*)$ ,  $h_3'^* = H_3(m^*, \psi_i^*, \text{pk}_s^*, \text{pk}_{r_i}^*)$  and  $h_3^* \neq h_3'^*$  i.e.  $f_i^* \neq f_i'^*$ . Finally, the  $\mathcal{A}_I$  outputs another forged  $\text{CT}_i^* = (C_{1_i}^*, C_{2_i}^*)$  on the same  $m^*$  where  $C_{1_i}^* = (f_i^*, S_i^*)$  and  $C_{2_i}^* = \text{Enc}_K^*(m)$ . Finally,  $C$  will have two valid signatures:

$$S_i^* = r^{*-1}(f_i^* \| \text{wd}_s^* x_s) \quad (5)$$

$$S_i'^* = r'^{-1}(f_i'^* \| \text{wd}_s'^* x_s) \quad (6)$$

where  $r^* = r'^*$  and  $d_s^* = d_s'^*$ . From the Equations 8 and 9 above,  $C$  can extract  $\phi$  as follows:

$$\phi = r^{*-1}(f_i'^* - f_i^*) + (S_i^* - S_i'^*)(r^{*-1}(\text{wd}_s^* x_s - \text{wd}_s'^* x_s))^{-1}$$

Given that, the  $C$  solves the ECDL assumption  $Q = \phi P$  with the advantage  $\epsilon'$ :

$$\epsilon' \geq \epsilon \left( \frac{1}{qH_1} + \frac{1}{qH_2} \right) \left( \frac{1}{qH_1} \right) \left( 1 - \frac{1}{q_{\text{ppk}}} \right) \left( 1 - \frac{q_{\text{usc}}}{2^k} \right) \quad (7)$$

**Theorem 7.4.** Suppose that the euf-cma-II adversary  $\mathcal{A}_{\text{II}}$  has a non-negligible advantage  $\epsilon$  in winning the game then, there is  $C$  that can solve the ECDL assumption with the non-negligible advantage  $\epsilon'$ .

*Proof.* Given a  $P \in \mathbb{G}$  and a new generator  $Q = \pi P$  in the same group where  $\pi \in \mathbb{Z}_q^*$ . The  $C$  has to find  $\pi$  by interacting with the  $\mathcal{A}_{\text{II}}$  such that  $Q = \pi P$ .  $\square$

1. **Phase-1.** The queries are similar to Theorem 7.2.

- **Setup.** The  $C$  generates  $(\text{PP}, \text{mpk})$  as in Theorem 7.3 and sends to the  $\mathcal{A}_{\text{II}}$ .

2. **Phase-2.** The queries and responses are same as in Phase-2 of Theorem 7.2, except the response to  $q_{sv}$  is as follows:

- $q_{sv}$ . Upon  $q_{sv}$ , the  $C$  checks if  $\text{PID} = \text{PID}_s^*$ . If it holds,  $C$  aborts because, in this case, the PID is a target ID. Otherwise, it checks if  $x_i$  exists in  $L_{\text{pk}}$ . If it exists, the  $C$  returns  $x_i$  to  $\mathcal{A}_{\text{II}}$ . Otherwise, computes  $\text{pk}_i = \pi P$  where  $x_i = \pi \in \mathbb{Z}_q^*$  and adds in  $L_{\text{pk}}$  and returns  $x_i$  to  $\mathcal{A}_{\text{II}}$ .

3. **Forgery.** Taking the target  $\text{PID}_s^*$  and  $\text{PID}_{r_i}$ ,  $\mathcal{A}_{\text{II}}$  outputs a forged  $\text{CT}_i^* = (C_{1_i}^*, C_{2_i}^*)$  on  $m^*$  where  $C_{1_i}^* = (f_i^*, S_i^*)$  and  $C_{2_i}^* = \text{Enc}_K^*(m)$  which is the valid signcrypted ciphertext and is not the result of signcryption oracle.

- Case-1 ( $\text{PID} \neq \text{PID}_s^*$ ). The  $C$  returns  $\perp$ .
- Case-2 ( $\text{PID} = \text{PID}_s^*$ ). The  $C$  extracts the  $L_{\text{pk}}$  for the record  $(\text{PID}_i^*, d_i^*, \text{pk}_i^*, x_i^*)$  and  $L_3$  for the record  $(m^*, \psi_i^*, f_i^*)$ .

According to the Forking Lemma, the  $C$  replays the  $\mathcal{A}_{\text{II}}$  with the same random tape but distinct attributes from  $H_1$  and  $H_3$ . It implies that,  $h_1^* = H_1(\text{mpk}, \text{PID}_i^*)$  i.e.  $h_1^* = H_1(\text{mpk}, \text{PID}_i^*)$  and  $h_1^* \neq h_1'^*$  i.e.  $Q_{\text{PID}_s^*}^* \neq Q_{\text{PID}_s^*}'^*$ . Similarly,  $h_3^* = H_3(m^*, \psi_i^*, \text{pk}_s^*, \text{pk}_{r_i}^*)$ ,  $h_3'^* = H_3(m^*, \psi_i^*, \text{pk}_s^*, \text{pk}_{r_i}^*)$ , and  $h_3^* \neq h_3'^*$  i.e.  $f_i^* \neq f_i'^*$ . In the end, the  $\mathcal{A}_{\text{II}}$  outputs another forged  $\text{CT}_i^* = (C_{1_i}^*, C_{2_i}^*)$  on the same  $m^*$  where  $C_{1_i}^* = (f_i^*, S_i^*)$  and  $C_{2_i}^* = \text{Enc}_K^*(m)$ . Finally,  $C$  will have two valid signatures:

$$S_i^* = r^{*-1}(f_i^* \| \text{wd}_s^* x_s) \quad (8)$$

$$S_i'^* = r'^{-1}(f_i'^* \| \text{wd}_s'^* x_s) \quad (9)$$

where  $r^* = r'^*$  and  $x_s^* = x_s'^*$ . From the Eq. 8 and 9 above, the  $C$  can extract  $\pi$  as follows:

$$\pi = r^{*-1}(f_i'^* - f_i^*) + (S_i^* - S_i'^*)(r^{*-1}(\text{wmpk}(Q_{\text{PID}_s^*}^* - Q_{\text{PID}_s^*}'^*)))^{-1}$$

Given that, the  $C$  solves the ECDL assumption  $Q = \pi P$  with the advantage  $\epsilon'$ :

$$\epsilon' \geq \epsilon \left( \frac{1}{qH_1} + \frac{1}{qH_2} \right) \left( \frac{1}{qH_1} \right) \left( 1 - \frac{1}{q_{sv}} \right) \left( 1 - \frac{q_{\text{usc}}}{2^k} \right) \quad (10)$$

**Anonymity.** Each user utilizes the PID to communicate instead of the  $\text{ID}_R$  where the sender sends same  $m$  to multiple receivers while  $\text{ID}_R$  of the receiver remains private from each other. The PID is assigned by RA after verifying each user's  $\text{ID}_R$  using its private key  $v$ . If  $\text{ID}_R$  is not verified, then the corresponding PID will be discarded. Additionally, since only RA knows its private key, no else could falsely verify the  $\text{ID}_R$ . In case of a dispute, RA can expose the  $\text{ID}_R$ .

**Non-Repudiation.** In our scheme, message  $m$  is signed by the sender with its  $\text{sk}_s$  as  $S_i = r^{-1}(f_i \| \text{wd}_s x_s)$ . The receiver verifies  $m$  using  $\text{pk}_s$  as  $R_i = S_i^{-1}(f_i P \| \text{wmpk}_s Z_{1_i} Q_{\text{PID}_i}^{-1})$ . Since the sender signs  $m$  with its  $\text{sk}_s$  that only the sender knows, it cannot deny sending  $m$ , thus proving non-repudiation.

**Forward Security.** In the proposed AMCLHS scheme, the symmetric session key  $K$  and its encapsulation  $C_{1_i}$  is generated using the  $(\text{sk}, \text{pk})$  using a randomly generated secret value  $x \in \mathbb{Z}_q^*$  and a  $\text{ppk}$ . In this case, even if the  $\text{sk}$  is exploited, the  $\mathcal{A}$  cannot extract the past sessions since the  $x$  is randomly generated and updated for each session.

## 8 PERFORMANCE ANALYSIS

We compare the computational cost, communication cost, and security requirements of the AMCLHS scheme with existing multireceiver signcryption schemes.  $M$  shows point multiplication operation,  $E$  shows exponentiation in  $\mathbb{Z}_q^*$ , and  $n$  represents the number of users. The computational overhead is compared with (Niu et al., 2017; Niu et al., 2022b; Peng et al., 2020) as shown in Table 1. The overhead for signcryption is calculated for multiple recipients as outlined in our scheme, whereas the overhead for unsigncryption is determined on a per-receiver basis. Among the multireceiver signcryption schemes, Niu *et al.* have the highest computational overhead, utilizing a total of  $(2n+4)BP+1M+(2n+2)E$  operations (Niu et al., 2017). Peng et al. require total  $(2n+5)M$  operations (Peng et al., 2020) and Niu *et al.* require a total of  $(4n+6)M$  operations (Niu et al., 2022b). Contrasting with existing solutions, our proposed scheme delivers high efficiency with only  $(2n+5)M$  total operations. It uniquely pairs a linear signcryption cost with a constant unsigncryption cost per receiver, regardless of scale. This optimal combination results in a predictable, scalable system and setting a new performance standard. Given its scalability and robustness, our scheme emerges as a compelling choice for larger, more complex broadcast communication scenarios, providing a significant upgrade over existing schemes.

Table 1: Comparison of Computational Overhead.

Schemes	Signcryption	Unsigncryption	Total
Niu <i>et al.</i> (Niu et al., 2017)	$(2n)BP+1M+(2n)E$	$4BP+2E$	$(2n+4)BP+1M+(2n+2)E$
Peng <i>et al.</i> (Peng et al., 2020)	$(2n+1)M$	$4M$	$(2n+5)M$
Niu <i>et al.</i> (Niu et al., 2022b)	$(2n+4)M$	$(2n+2)M$	$(4n+6)M$
Our scheme	$(2n+2)M$	$3M$	$(2n+5)M$

Table 2: Comparison of Communication Cost.

Schemes	Ciphertext Length	Complexity of Communication	
		Signcryption	Unsigncryption
Niu <i>et al.</i> (Niu et al., 2017)	$n m + \mathbb{G} +2n \mathbb{G} $	$O(n^2)$	$O(n)$
Peng <i>et al.</i> (Peng et al., 2020)	$n m +(n+2) \mathbb{Z}_q^*$	$O(n^2)$	$O(n)$
Niu <i>et al.</i> (Niu et al., 2022b)	$n (m+2) +2 \mathbb{G} +2 \mathbb{Z}_q^*$	$O(n)$	$O(n)$
Our scheme	$n m + \mathbb{Z}_q^* + \mathbb{G} + K $	$O(n)$	$O(1)$

The Table 2 shows the communication cost in terms of the size of the ciphertext generated by each scheme (Niu et al., 2017; Niu et al., 2022b; Peng et al., 2020). The proposed AMCLHS scheme has the optimal communication cost among the four schemes, as it only requires  $n|m|+|\mathbb{Z}_q^*|+|\mathbb{G}|+|K|$  bits to signcrypt a message. Moreover, our scheme has linear communication cost in signcryption while the un-

Table 3: Comparison based on Security Requirements.

Schemes	Confidentiality	Unforgeability	Anonymity	Non-repudiation	Forward Security
Niu <i>et al.</i> (Niu et al., 2017)	✓	✓	✓	✓	✓
Niu <i>et al.</i> (Niu et al., 2022b)	✓	✓	✓	✗	✗
Peng <i>et al.</i> (Peng et al., 2020)	✓	✓	✓	✗	✗
Our scheme	✓	✓	✓	✓	✓

signcryption cost remains constant. In Table 3, we present a comparative analysis of the security requirements between our scheme and existing multireceiver hybrid signcryption schemes (Niu et al., 2017; Niu et al., 2022b; Peng et al., 2020). The comparison parameters are confidentiality, unforgeability, anonymity, non-repudiation, and forward security. Our proposed scheme successfully achieves all security requirements as shown in Table 3, offering superior efficiency with lower computational costs, setting it apart from the others.

## 9 CONCLUSION

Our paper introduces a novel mKEM-DEM based AMCLHS scheme for broadcast communication. The proposed scheme generates a symmetric key using the public and private key pair of the users. The message is then signcrypted with the previously generated symmetric key and the private key of the sender. We provide a detailed security analysis using EC-CDH and ECDL assumptions and demonstrate that the scheme is secure against *ind-cca2* and *euf-cma* attacks for Type-I and Type-II adversaries. Moreover, in this scheme, each user is assigned a PID to ensure user anonymity. Lastly, we compare our scheme with existing single receiver and multireceiver certificateless hybrid signcryption schemes in terms of computation cost, communication cost, and security requirements. We show that the proposed scheme has less communication cost and is computationally more efficient, with the signcryption cost linear with the number of designated receivers while the unsigncryption cost remains constant and simultaneously achieves confidentiality, unforgeability, anonymity, non-repudiation, and forward security.

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