An Identity-based Batch Verification Scheme for VANETs Based on Ring Signature with Efficient Revocation

Feng Liu, Qi Wang

Abstract—Vehicular ad-hoc networks (VANETs) are one of the most important components in Intelligent Transportation System (ITS), which aims to provide secure and efficient communication between vehicles. Safety-critical vehicular communication requires security, privacy, and auditability. To satisfy these requirements simultaneously, several conditional privacy-preserving authentication schemes are proposed by employing ring signatures. However, these methods have paid little attention to the issues like how to choose the valid ring members or how to set up a ring. In this paper, we introduce an efficient conditional privacy-preserving scheme which provides an appropriate approach establishing the list of ring members with efficient revocation. Moreover, our proposed scheme also provides batch verification to significantly reduce the computational cost. According to the analysis of security, our scheme is sufficiently resistant against several common attacks in VANETs. The performance results show that the proposed scheme is efficient and practical with both low computation and communication cost.

Index Terms—VANETs, ring signature, conditional privacy, batch verification

I. INTRODUCTION

Vehicular Ad-hoc Networks (VANETs), as a special kind of Mobile Ad-hoc Networks (MANETs) optimized for vehicular environments, plays an important role in Intelligent Transportation Systems (ITS). In a typical scenario of ITS, each vehicle broadcasts traffic-related information, such as its speed, position, road condition, and others through VANETs. After receiving these broadcast messages, vehicles can analyze and extract meaningful information to drivers, or take corresponding control actions in emergencies. In this way, the applications of VANETs reduce the rate of traffic accident, and thereby road safety and efficiency will be greatly enhanced. Besides, this technology is also meaningful to automated vehicles because VANETs make it possible for vehicles to communicate with each other. However, due to the high demand for road safety features, to design a practical protocol for VANETs is highly nontrivial. Numerous proposed schemes are built based on the IEEE 802.11p standard.

In IEEE 802.11p, the participants on the road are classified into two categories, i.e., On-Board Units (OBUs) and Road-Side Units (RSUs). Typically, each vehicle is equipped with an OBU for broadcasting messages and handling the received messages. The RSUs are usually fixed along roads as the base stations to provide Internet access and extra road-related information for vehicles. Therefore, VANETs provide two different types of communication, namely, Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) as shown in Figure 1. As a result, drivers can be reminded of road conditions by receiving the broadcast messages from other vehicles or RSUs in VANETs. In practice, a trusted party, called Transportation Regulation Center (TRC), is needed to administrate the whole network. For example, RSUs can connect with TRC for obtaining extra traffic information.

Fig. 1. A typical scenario of VANETs

However, due to the open environment of VANETs, an attacker could send a forged message to confuse nearby drivers, which may further cause potential traffic hazards. To maintain road safety, it is essential to authenticate the validity of a message. The first serious discussion of road safety was proposed in 2002 and digital signature was utilized therein [1]. After that, a considerable amount of work has been proposed based on different digital signature schemes [2]. When applying various digital signature schemes in VANETs, each message is attached with some extra information including signature, signer’s certificate and so on. The extra information may be used to link to the driver’s true identity, and even lead to privacy disclosure. Therefore, how to keep the anonymity of senders while the message can be authenticated by verifiers becomes another essential issue in VANETs. A common approach is to replace the true identity with a random-like string called pseudonym. On the other hand, in some specific scenarios such as in a traffic situation where the number of vehicles is relatively small, batch verification can be applied to significantly reduce the computational cost. In this paper, we introduce an efficient conditional privacy-preserving scheme which provides an appropriate approach establishing the list of ring members with efficient revocation.
accident, the true identity of senders should be revealed by law enforcement. To this end, a function of auditability should be provided. Thus, authentication, anonymity, and auditability are three basic requirements when designing a feasible scheme for communication in VANETs. Besides, due to the limited computation and storage capability of both OBUs and RSUs, efficiency should also be considered in VANETs.

A. Our Contribution

In this paper, we propose a hybrid scheme for VANETs by taking advantage of ring signature, identity-based cryptography (IBC) and symmetric cryptography. Since ring signature allows a signer to create signatures on behalf of an ad-hoc group without any additional setup, and achieves unconditional anonymity for the signer, it seems quite suitable to put ring signature into ad-hoc networks like VANETs. Unfortunately, no setup means any vehicle (even a malicious one) can generate a signature on behalf of a set of vehicles, and unconditional anonymity infers that there lacks an efficient approach to trace and revoke a vehicle (i.e., lack of auditability). These two issues make it difficult to apply ring signature in VANETs.

To address these issues, we suggest utilizing RSUs to distribute the group or ring information to valid vehicles. For clarity, we divide the auditability into two aspects: pseudonym resolution and revocation. In terms of pseudonym resolution, we introduce a new entity called Law Enforcement Authority (LEA) to reveal the signer’s identity. As for pseudonym revocation, we incorporate the KUNodes algorithm [3] into the proposed scheme so that the size of key updates decreases from linear down to logarithmic. More precisely, our contributions are summarized in the following:

- We propose a novel scheme for VANETs based on identity-based ring signature, where the procedure of creating a ring is restricted by RSUs.
- We provide a batch mode to accelerate message verification in VANETs. As indicated by performance, this makes our scheme highly efficient. To the best of our knowledge, this is the first attempt that applies ring batch verification in VANETs.
- We present an efficient way to make vehicles auditable by using different technologies including general one-way hash functions and KUNodes algorithm.
- We implement the scheme in the Raspberry Pi 4 Model B platform and give a comprehensive analysis based on the platform.

B. Related Work

Numerous studies have attempted to employ pseudonym schemes to assure authentication and privacy simultaneously. Generally, the cryptographic tools utilized include public key infrastructure (PKI), identity-based cryptography (IBC), group signature, ring signature and so on (for recent surveys, see [2], [4], [5]).

At the early stage of the study, PKI was most widely used in VANETs. In these schemes based on PKI, Certificate Authority (CA) is needed as a trusted party. Each vehicle broadcasts messages attached to the corresponding signatures and public-key certificates. Taking the SeVeCom project [6] as an example, the elliptic curve digital signature algorithm (ECDSA) is utilized to assure efficiency. The pseudonym used in VANETs is composed of two parts: a short-term key and its corresponding certificate. Since the transmission of certificates will increase the communication overhead, it was alternatively suggested to employ IBC instead of PKI [11].

Similarly, IBC-based schemes also adopt a set of short-term public keys to form vehicles’ pseudonyms, while the procedure of pseudonym issuance differs. Note that in IBC-based schemes, a new entity called private key generator (PKG) is introduced to replace CA. Thus, certificates are not attached when broadcasting messages in these schemes, and the communication overhead is thereby decreased.

However, pseudonym changing becomes a major problem in both PKI-based and IBC-based pseudonym schemes, as only using a single pseudonym is not sufficient to preserve vehicles’ privacy. In a simple setting, each vehicle is equipped with a set of public keys, each of which can be viewed as an unlinkable pseudonym, and will expire after a fixed amount of time. Wiedersheim et al. [8] pointed out that simple pseudonym change is not enough to preserve privacy. There have been attempts on the strategy of pseudonym change, e.g., mix-zone-based [9] and mix-context-based [10]. However, it is still mysterious to formalize the relationship between pseudonym change strategies and privacy level [2], [11].

The issue of pseudonym change can be eliminated in the schemes based on group signature and ring signature [2], [12]. In these schemes, messages are signed under the identity of a certain group rather than a single vehicle’s pseudonym. Group signature-based schemes allow a vehicle to sign a message anonymously on behalf of the group. In group signatures, a special entity called group manager can reveal any signer’s real identity from the corresponding signature. Till now, there has been little agreement on the choice of group manager [2]. As the administrator of the group, the group manager has the privilege to add or delete a group member. It is then straightforward to achieve auditability of group members by the group manager. Some researchers [13], [14] suggested that RSUs serve as group managers. However, RSUs are vulnerable to some extent, and this setting is not sufficient to guarantee group members’ privacy.

In comparison, ring signature-based schemes [15], [16], [17] further remove group managers by involving a set of different vehicles’ public keys as a ring. In existing ring signature-based schemes, e.g., [15], each vehicle can collect other vehicles’ public keys on the road and thereby checks the validity of ring members before verification. Unfortunately, this would lead to verification failure when a malicious vehicle broadcasts an invalid public key. As depicted in Figure 2 due to the existence of a malicious vehicle in the ring, the generated signature by the whole ring would be rejected by other vehicles. In existing such schemes, privacy is the main concerning issue while the lack of auditability of ring members for VANETs is still a problem [13], [15].

Petit et al. [2] emphasized that these categories are not hard-edged so that several recent works combined different
techniques from the previous categories. Survey [4] listed these hybrid schemes and discussed their security and efficiency in performance. These results pointed out that recently proposed schemes attempted to apply the batch verification of signatures into the verification procedure, which can greatly reduce the computation cost comparing with single verification.

As we mentioned above, to achieve auditability in VANETs, pseudonym resolution and pseudonym revocation should be taken into account. A common method to revoke users in PKI setting is adopting certificate revocation lists (CRLs). Since the size of CRLs increases linearly with the number of revoked vehicles, this method seems not practical in VANETs because the capacity of both OBUs and RSUs is limited [4]. To cope with the problem, Khodaei and Papadimitratos [19] proposed a solution by splitting CRLs into CRL pieces and using Bloom Filter to compress these pieces. On the other hand, Bloom Filter is a probabilistic data structure in which false positive may occur. As for the schemes based on group signature, it is straightforward to achieve auditability by the group manager. But in those schemes based on IBC and ring signature, there lacks native support on the revocation of an identity. Thus, it is necessary to find a suitable approach to achieve auditability for VANETs.

C. Outline

The remainder of this paper is organized as follows. Section II introduces some preliminary cryptographic primitives. The system model of our proposed scheme is illustrated in Section III. In Section IV a description of our schemes is given in detail. After that, security analysis and performance analysis are provided in Section V and Section VI respectively. Finally, Section VII concludes this paper and proposes some potential future work.

Note that part of this work was presented at the 2019 IEEE Vehicular Networking Conference (VNC’19), December 4-6, 2019, Los Angeles, California [20]. In this journal version, we present the comprehensive framework with efficient revocation mechanism in detail and conduct more in-depth experiments and analysis of the proposed scheme.

II. PRELIMINARIES

In this section, we briefly introduce the cryptographic primitives involved in the proposed scheme, including bilinear pairings, identity-based encryption, and identity-based ring signature.

A. Bilinear pairings

Bilinear pairings have been widely used to design various cryptographic schemes over the last two decades [21, 22, 23]. Let \( \mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T \) be three cyclic groups of the same prime order \( q \). Assume that the discrete logarithm problem in \( \mathbb{G}_1, \mathbb{G}_2 \) and \( \mathbb{G}_T \) is hard. Let \( \hat{e} : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_T \) be a bilinear pairing with the following properties:

1. Bilinearity: \( \forall P \in \mathbb{G}_1, \forall Q \in \mathbb{G}_2 \) and \( \forall a, b \in \mathbb{Z}_q^* \), \( \hat{e}(aP, bQ) = \hat{e}(P, Q)^{ab} \);
2. Non-degenerateness: \( \exists P \in \mathbb{G}_1, \exists Q \in \mathbb{G}_2 \) such that \( \hat{e}(P, Q) \neq 1 \);
3. Computability: \( \forall g_1 \in \mathbb{G}_1, \forall g_2 \in \mathbb{G}_2 \), there is an efficient algorithm to compute \( \hat{e}(g_1, g_2) \).

There are two hard-problem assumptions in bilinear pairings, i.e., Computational Bilinear Diffie-Hellman (CBDH) Problem and Decisional Bilinear Diffie-Hellman (DBDH) Problem, as described in the following.

- **CBDH**: Given \( P \in \mathbb{G}_1, aQ, bQ, cQ \in (\mathbb{G}_2)^3 \), where \( a, b, c \in R(\mathbb{Z}_q^*) \), it is difficult to calculate \( \hat{e}(P, Q)^{abc} \).
- **DBDH**: Given \( P \in \mathbb{G}_1, aQ, bQ, cQ \in (\mathbb{G}_2)^3, h \in \mathbb{G}_T \), where \( a, b, c \in R(\mathbb{Z}_q^*) \), it is difficult to determine whether or not \( h = \hat{e}(P, Q)^{abc} \mod q \).

According to the relation between \( \mathbb{G}_1 \) and \( \mathbb{G}_2 \), bilinear pairings can be divided into three types [24]:

- **Type 1**: \( \mathbb{G}_1 = \mathbb{G}_2 \);
- **Type 2**: \( \mathbb{G}_1 \neq \mathbb{G}_2 \), but there is an efficiently computable homomorphism \( \phi : \mathbb{G}_2 \rightarrow \mathbb{G}_1 \);
- **Type 3**: \( \mathbb{G}_1 \neq \mathbb{G}_2 \), and there is no efficiently computable homomorphism between \( \mathbb{G}_1 \) and \( \mathbb{G}_2 \).

It was shown in [24] that Type 3 is much more suitable in practical applications since it can offer better performance and flexibility than other types under the same security level. But several proposed schemes did not take Type 3 into account due to the lack of homomorphism from \( \mathbb{G}_2 \) to \( \mathbb{G}_1 \) in Type 3.

B. Identity-based cryptography

Bilinear pairings are usually used to construct identity-based encryption and signature schemes. Compared to traditional PKI, identity-based cryptography avoids CA since each user’s public key can be automatically derived from the corresponding identity (e.g., user’s phone number, email address) by PKG. In general, a common identity-based cryptosystem contains two basic algorithms.

1. **Setup(\( \kappa \)) \rightarrow \text{PP}**: Taking the input of security parameter \( \kappa \), the algorithm Setup(\( \kappa \)) first chooses a master secret key \( s \in R(\mathbb{Z}_q^*) \), and then outputs the public parameter \( \text{PP} = \{\mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T, P, Q, PK_1, PK_2, q, \hat{e}, H_1, H_2\} \), where \( \mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T, q, \hat{e} \) are described in Section II-A. \( P \) is a generator of \( \mathbb{G}_1 \), \( Q \) is a generator of \( \mathbb{G}_2 \), and \( PK_1 = s \cdot P, PK_2 = s \cdot Q \), \( H_1, H_2 \) and \( H \) are three cryptographic hash functions where \( H_1 : \{0,1\}^* \rightarrow \mathbb{G}_1, H_2 : \{0,1\}^* \rightarrow \mathbb{G}_2, H : \{0,1\}^* \rightarrow \mathbb{Z}_q^* \).

2. **KeyGen(\( \text{ID}_i \)) \rightarrow \{pk_i, sk_i\}**: When user \( i \) wants to obtain public key and private key from the system, first \( i \) needs to send the specific identity \( \text{ID}_i \) to the system. After authentication is accepted, the system runs KeyGen(\( \text{ID}_i \))
Algorithm 1 KUNodes

\[ X, Y \leftarrow \emptyset \]

\[ \text{for} \ (v_i, T_i) \in RL \ \text{do} \]
\[ \text{if} \ T_i \leq T \ \text{then} \]
\[ \text{add} \ \text{Path}(v_i) \ \text{to} \ X \]
\[ \text{end if} \]
\[ \text{end for} \]

\[ \text{for} \ x \in X \ \text{do} \]
\[ \text{if} \ x_{\text{left}} \notin X \ \text{then} \]
\[ \text{add} \ x_{\text{left}} \ \text{to} \ Y \]
\[ \text{else if} \ x_{\text{right}} \notin X \ \text{then} \]
\[ \text{add} \ x_{\text{right}} \ \text{to} \ Y \]
\[ \text{end if} \]
\[ \text{end for} \]

\[ \text{if} \ Y = \emptyset \ \text{then} \]
\[ \text{add} \ \text{root} \ \text{to} \ Y \]
\[ \text{end if} \]

\[ \text{Return} \ Y \]

In general, this algorithm takes as input a binary tree BT, revocation list RL, and a period T. We denote by root the root node. For a non-leaf node x, we use x_{left} and x_{right} to represent its left child node and right child node, respectively. For a leaf node v, Path(v) means the set of nodes on the path from v to root. The description of KUNodes algorithm is given in Algorithm 1.

Figure 3 gives an example of KUNodes algorithm, where v_2 is revoked in this case. Therefore there are three nodes in key updates, which are v_1, x_4 and x_2. The binary tree construction indicates that the size of key updates grows with logarithmic scale, which is better on communication overhead than the original revocation approach (i.e., grows linearly)

This first practical identity-based encryption scheme was proposed in 2001 by Boneh and Franklin [21]. In the rest of this paper, we use Enc_{pk_v}(\cdot) and Dec_{sk_v}(\cdot) to denote the variant of identity-based encryption and decryption algorithms in [21], respectively.

Furthermore, an identity-based ring signature is also used in our scheme, which requires verifiers to verify messages through a specific set of signers. Note that this is different from the traditional signature. More precisely, we adopt CYH identity-based ring signature scheme [22] in our proposed scheme. Note that the CYH signature introduced here can be replaced by other lightweight identity-based ring signature schemes. There are two key algorithms: signature algorithm \[ \text{Sign}_{sk_v}(m, L) \rightarrow \sigma \] and verification algorithm \[ \text{Verify}(m, L, \sigma) \rightarrow 0/1, \] where m and L denote the message and the ring-member list, respectively.

C. KUNodes algorithm

A common approach to update a revocation list efficiently in IBC is KUNodes algorithm, which was first introduced by Blodyreva et al. [3].

In this section, we describe the system architecture and security assumptions of the proposed ring signature-based framework for VANETs.

A. System architecture

Generally, our ring signature-based framework consists of four main entities: the Transportation Regulation Center (TRC), Law Enforcement Authority (LEA), RSUs and vehicles equipped with OBUs. The explanations of these entities are listed as follows.

- **TRC**: TRC is a fully trusted party in the VANETs system with sufficient computation and storage capabilities. As the administrator in VANETs, TRC takes charge of system initialization and registration of the nodes in the network. When a vehicle is misbehaving, TRC also plays a role in pseudonym revocation. These identities of revoked vehicles are recorded in a revocation list named RL by TRC. We assume that TRC can establish a secure channel with RSUs so that RSUs can fetch a fresh revocation list and key updates from TRC confidentially.

- **LEA**: LEA is the agency to reveal the pseudonyms of misbehaving vehicles. In other words, LEA is responsible for detecting fraudulent activities or misconduct of vehicles in VANETs. For instance, if a vehicle broadcasts forged messages anonymously on purpose, then LEA can extract the true identity of the vehicle with the help of TRC.

- **RSUs**: An RSU usually plays an auxiliary role between TRC and vehicles. Namely, RSUs can communicate with TRC through wired or wireless networks and broadcast messages to vehicles in a restricted region. In the proposed framework, the RSUs in the same region have the same regional key pairs. All registered RSUs can obtain fresh node update information from TRC periodically and deliver ring lists to vehicles.
• **Vehicles:** Each vehicle in this framework is equipped with a communication device called OBU. An OBU contains the hardware security module (HSM), and related cryptographic operations are predefined inside HSM. The HSM can be regarded as a black box, and we assume that the cryptographic operations are always executed correctly by HSM.

In the proposed framework, each vehicle has a unique identity (typically denoted by VID). After the initialization of the system by TRC, each vehicle can register itself to obtain a pseudonym and a corresponding private key (typically denoted by PID and PSK respectively). Similarly, a regional RSU can obtain a regional identity RID and a corresponding private key RSK from TRC. LEA has a private key $s_{trac}$ for pseudonym revocation. As we described above, the RSUs periodically request key-update information from TRC. According to the key-update information, RSUs can reject requests from revoked vehicles. The difference between VID and RID is that VID is always kept secret by TRC and vehicles while RID is always public to vehicles.

When a vehicle enters a certain region, it can obtain a ring list from local RSUs. Since the local RID is public in VANETs, the vehicle can deliver its pseudonym to the local RSU in a confidential manner, for instance, using utilized identity-based encryption.

Once the local RSU receives the request from a vehicle, it first checks the validity of PID for the current period. If the PID is valid, then a ring list containing a set of pseudonyms is returned. When the vehicle obtains the ring list, it can adopt identity-based ring signature scheme to sign the given message. Due to the anonymity property of ring signature, it is not necessary to change vehicle’s PID much more frequently than using ordinary signature. To achieve auditability, a traceable tag is attached to the broadcast message. To decrease the size of key updates, we integrate KUNodes algorithm into our framework.

### B. Framework

According to the abstract pseudonym life cycle introduced in [2], we divide our proposed scheme into the following algorithms:

- **Setup**($\kappa$) $\rightarrow$ (PP, s, RL, BT). Taking the security parameter $\kappa$ as input, this algorithm outputs the public parameter PP, the master secret key s, an empty initial revocation list RL and a binary tree BT.

- **KeyGen**($\kappa$) $\rightarrow$ (PID, PSK, Path(PID)). Taking the public parameter PP and a vehicle’s identity VID as input, this algorithm outputs a key pair (PID, PSK) and the path from PID to root. Note that the procedure of generating RID is similar, and we omit the specific description here to avoid redundancy.

- **KUNodes**($\kappa$) $\rightarrow$ k. Taking the binary tree BT, the revocation list RL and current time period T as input, this algorithm outputs the key-update information $k_T$.

- **RingReq**($\kappa$) $\rightarrow$ (C1, C2). Taking a local RSU’s identity RID, the vehicle’s pseudonym PID and the Path(PID) as input, this algorithm outputs the ciphertext of PID (denoted by C1) and the ciphertext of Path(PID) (denoted by C2).

### C. Assumptions of HSM

Later we will show that the proposed scheme satisfies authentication, conditional anonymity, and auditability. Before discussing these requirements, we recall that each OBU has a hardware called HSM, so that HSM provides an independent environment to perform related cryptographic operations. Each HSM consists of 5 sub-modules as shown in Figure 4. Hereafter, all our analysis is based on the assumption of HSMs.

| Checking Module | Encryption Module | Decryption Module |
|-----------------|-------------------|------------------|
| $s_{trac}(m)$ $\rightarrow$ (PID, CP) | $s_{trac}(m)$ $\rightarrow$ (PID, CP) | $s_{trac}(m)$ $\rightarrow$ (PID, CP) |

| Signing Module | Verifying Module |
|----------------|------------------|
| $\sigma_{trac}(m)$ $\rightarrow$ T | $\sigma_{trac}(m)$ $\rightarrow$ T |

Fig. 4. Abstract construction of HSM

In the case of our proposed scheme, authentication means both sender authentication and message authentication: the message sender must be one member of the ring and the transmitted data cannot be modified. Anonymity guarantees that the receiver only knows the signer is one member of the ring, but cannot determine which exact pseudonym belongs to the signer. As for auditability, there are two aspects: On the one hand, it is required that the true identity can be resolved once the misbehaving vehicle is detected by LEA; On the other hand, the vehicle revocation is achieved by TRC and LEA which assures that only non-revoked vehicles can form a valid ring list from RSU.


IV. THE PROPOSED SCHEME

In this section, we use an abstract pseudonym life cycle as shown in Figure 5 to describe how our proposed scheme works. The whole life cycle can be divided into six phases: initialization, key generation, ring list distribution, sign, verification and audit. Relevant notations are listed in Table I.

A. Initialization

TRC first generates a bilinear pairing \( e : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_T \) for the preset security parameter \( 1^* \). Then it chooses the master secret key \( s \leftarrow_R \mathbb{Z}_q \), and outputs \( \{G_1, G_2, G_T, P, Q, PK_1, PK_2, q, e, H_1, H_2, H\} \) (see Section II-B). After that, LEA chooses its private key \( s_{\text{trac}} \leftarrow_R \mathbb{Z}_q \). The corresponding public key can be calculated as \( PK_{\text{trac}} = s_{\text{trac}} \cdot Q \). Finally, TRC outputs the public parameters \( PP = \{G_1, G_2, G_T, P, Q, PK_1, PK_2, PK_{\text{trac}}, q, e, H_1, H_2, H\} \).

B. Key generation

Before the stage of key generation, TRC first generates an initial binary tree BT to record vehicles’ pseudonyms. After that, for a vehicle with its real identity VID, TRC invokes KeyGen(VID) and sends \( \{\text{PID}, \text{Path(\text{PID})}, \text{PSK}, \text{PP}\} \) to the vehicle. Note that these parameters are preloaded into the tamper-proof device HSM. For an RSU with a region identifier ID, it can obtain the key pair \( \{\text{RIDE}_j, \text{RSK}_j\} \) from TRC in the same manner. The specific procedure is given in Algorithm 2.

C. Ring list distribution

Once a vehicle, e.g., \( V_i \) enters into a certain region, it will obtain a fresh pseudonym list by connecting to the local RSU. In our scheme, the region identifiers are public to all vehicles in VANETs. Therefore, vehicle \( V_i \) can deliver its pseudonym to a local RSU in a confidential manner by employing \( \text{Enc}_{\text{sk}}(\cdot) \) and \( \text{Dec}_{\text{sk}}(\cdot) \) in Section II-B. The full procedure is described in Algorithm 3. Note that if the bilinear pairing used in our scheme belongs to Type 3, the vehicle’s pseudonym will have a shorter representation in an efficient way so that the communication overhead will be decreased.

Algorithm 2 KeyGen(ID)

\[
\begin{aligned}
\text{if } \text{ID belongs to OBU} & \text{ then} \\
& \quad \text{VID} := \text{ID} \quad \text{PID} = H_1(\text{VID}) \quad \text{PSK} = s \cdot \text{PID} \quad \text{assign PID to an empty leaf node of BT, record } \{\text{PID} : \text{VID}\} \quad \text{return } \{\text{PID}, \text{Path(\text{PID})}, \text{PSK}, \text{PP}\} \\
\text{else if } \text{ID belongs to RSU} & \text{ then} \\
& \quad \text{RIDE}_j = H_2(\text{ID}) \quad \text{RSK}_j = s \cdot \text{RIDE}_j \quad \text{return } \{\text{RIDE}_j, \text{RSK}_j, \text{PP}\} \\
\end{aligned}
\]

When an RSU receives the request from vehicle \( V_i \), it first checks the validity of \( V_i \). If the pseudonym of \( V_i \) is valid, then the RSU returns a ring list. In order to filter the misbehaving vehicles’ requests, RSUs need to refresh key-update information from RSU regularly. The complete process is given in Algorithm 4. In view of the capability bottleneck of RSUs, we propose that RSUs store the shared keys locally to reduce the computation cost.

Algorithm 3 RingReqPSK\(_j\)(RIDE\(_j\), PID\(_i\), Path(PID\(_i\)))

\[
\begin{aligned}
& \text{choose } r \leftarrow_R \mathbb{Z}_q \quad \text{g} = e(\text{PK}_1, \text{PID}_j) \\
& \quad k_{i-j} = e(\text{PSK}_i, \text{RIDE}_j) \quad C_1 := (r \cdot \text{PID}_i \oplus H(g^e)) \quad C_2 = E_{k_{i-j}}(\text{Path(\text{PID}_i)}) \\
& \quad \text{return } (C_1, C_2)
\end{aligned}
\]
D. Sign

For a vehicle $V_k$ holding a ring list $L$ with an un-expired $t_d$, it first chooses $n' - 1$ pseudonyms from $L$ randomly to establish an $n$-length ring list $L_s$, i.e., $L_s = \{\text{PID}_1, \text{PID}_2, \ldots, \text{PID}_{k-1}, \text{PID}_{n'}\}$. Then it can adopt identity-based ring signature scheme (as described in Section II-B, i.e., $\sigma = \text{Sign}_{\text{PSK}_k}(m||\tau||t|L_s)$, where $\tau = e(H_1(\text{VID}||t), PK_{\text{trac}})$. Finally it broadcasts $(m, \sigma, L_s, t, \tau)$. The detailed procedure is illustrated in Algorithm [5].

Algorithm 5 Sign$_{\text{PSK}_k}(m||\tau||t|L_s)$:

- choose $n' - 1$ PID from $L$ randomly
- set $L_s := \{\text{PID}_1, \text{PID}_2, \ldots, \text{PID}_{k-1}, \text{PID}_{n'}\}$
- for $i$ from $1$ to $n'$
  - choose $U_i \leftarrow_R G_1$
  - $h_i = H(m||\tau||t|L_s||U_i)$
- end for
- choose $r' \leftarrow_R Z_q$
- $U_k = r' \text{PID}_k - \sum_{r=1, r \neq k}^{n'} (U_i + h_i \text{PID}_i)$
- $h_k = H(m||\tau||t|L_s||U_k)$
- $V = (h_k + r')\text{PSK}_k$
- return $\sigma := \{(U_i)_{i=1}^{n'}, V\}$

E. Verification

When a vehicle, e.g., $V_{2}$ receives $(m, \sigma, L_s, t, \tau)$, it first checks $t$ to prevent replay attacks. If valid, then it runs Verify$_{\ell}(m||\tau||t, \sigma)$ to check the validity of the signature. As mentioned above, considering that the capacity of OBUs is limited, we suggest adopting batch verification proposed in [25] to speed up the process. Algorithms 6 and 7 present the procedures of single verification and batch verification, respectively.

Algorithm 6 Verify$_{\ell}(m||\tau||t, \sigma)$:

- $\sigma = \{U_i\}_{i=1}^{n'}, V\}$
- for $i$ from $1$ to $n'$
  - $h_i = H(m||\tau||t|L_s||U_i)$
- end for
- return $\hat{e}(\sum_{i=1}^{n'} (U_i + h_i \text{PID}_i), PK_2) = \hat{e}(V, Q)$

In the procedure of batch verification, once the result is false, which means that at least one signature in $\sigma_{\text{batch}}$ is invalid, then we can use the divide-and-conquer technique [25] to exclude the invalid signatures.

Algorithm 7 BatchVer$(M_{\text{batch}}, L_{\text{batch}}, \sigma_{\text{batch}})$:

- $\sigma_{\text{batch}} = \{\sigma_1, \ldots, \sigma_\eta\}$
- $M_{\text{batch}} = \{M_1||\tau_1||t_1, M_2||\tau_2||t_2, \ldots, M_\eta||\tau_\eta||t_\eta\}$
- $L_{\text{batch}} = \{L_{s1}, L_{s2}, \ldots, L_{sn}\}$
- for $i$ from $1$ to $\eta$
  - for $j$ from $1$ to $\text{len}(L_{s_i})$
    - $h_{ij} = H(M_i||L_{s_i}||U_{ij})$
  - end for
- end for
- return $\hat{e}(\sum_{i=1}^{\eta} \sum_{j=1}^{\text{len}(L_{s_i})} (U_{ij} + h_{ij} \text{PID}_{ij}), PK_2) = \hat{e}(\sum_{i=1}^{\eta} V_i, Q)$

F. Tracing and Revocation

When LEA detects misbehaviors in VANETs, it calculates $\tau' = tag_{i=1}^{\text{trac}}$ and then sends $\{L_s, t\}$ to TRC. For $L_s = \{\text{PID}_1, \text{PID}_2, \ldots, \text{PID}_{n'}\}$, TRC computes $H'_i = \hat{e}(H(\text{VID}||t), PK_{\text{trac}})$, where $i \in \{1, 2, \ldots, n\}$, and returns $\cup_{n'|i=1}^{n'} H'_i$. By comparing $\tau'$ and $\cup_{n'|i=1}^{n'} H'_i$, LEA can determine the signer’s pseudonym. Furthermore, LEA would find out the signer’s true identity by sending the pseudonym to TRC. To revoke a vehicle’s identity VID, TRC first takes the current timestamp $T$ and the leaf node $n_v$ associated with VID. Then TRC adds $(n_v, T)$ to $RL$.

V. Security Analysis

A. Correctness

In V2I communication, when vehicle $V_\ell$ enters the region within the range of RSU$_j$, it will receive the broadcasting RJD$_j$ in this region. Once $V_\ell$ obtains RJD$_j$, it can invoke the Checking Module to check the validity of RSU$_j$. In the process of delivering PID$_\ell$, the correctness and security are guaranteed by the property of identity-based encryption scheme [21]. According to the property of bilinear pairing, we know that:

$$K_{\ell-j} = \hat{e}(\text{PSK}_{\ell}, \text{RID}_j) = \hat{e}(\text{PID}_{\ell}, \text{RID}_j)^s = \hat{e}(\text{PID}_{\ell}, \text{RSK}_j) = K_{j-\ell}.$$  

It is clear that both RSU$_j$ and $V_\ell$ obtain the same shared key, and can establish an efficient trusted channel for further communication through symmetric cryptography.

In V2V communication, if the procedure of signing a message $m$ is executed correctly, then the corresponding signature $\sigma$ must satisfy the verifying equation [1].

B. Unforgeability

We call a signature $\sigma$ unforgeable, if an adversary cannot generate a signature for a new message, given a few signatures corresponding to the messages of his own choice. Since the ring signature scheme [22] we employed has been proven to be unforgeable against chosen message attacks in the random oracle model, we note that our protocol is also unforgeable.
C. Conditional anonymity

In V2I communication, RSU \( j \) only knows the pseudonym of \( V_\ell \) rather than the true identity of \( V_\ell \), i.e., VI\( D_\ell \). As for V2V communication, the true signer is hidden in a set of pseudonyms \( L \). For any eavesdroppers in VANETs, they cannot figure out the true signer from \( L \) even though they know the corresponding \( tag \). Only the LEA can identify the signer in \( L \) through the secret tracing key \( s_{\text{trac}} \).

D. Against replay attacks

Note that each message contains a timestamp in our scheme. This indicates that once vehicles figure out that a message is expired, then this message will be abandoned before being verified. If an adversary forges a fresh timestamp to replace the original one, then this message must not be able to pass the verification.

VI. PERFORMANCE ANALYSIS

In this section, we evaluate the performance of the proposed scheme in terms of both computation cost and communication cost. Specifically, we invoke CHARM \[26\], a framework for rapidly prototyping advance cryptosystems, to implement the proposed scheme. To compare the impact of different paring settings, we choose two elliptic curves named “SS512” and “MNT159” in our experiments, where “SS512” represents a super singular curve (symmetric bilinear pairing) with a 512-bit base filed in \( G_1 \), and “MNT159” represents the Miyaji, Nakabayashi, Takano curve (asymmetric bilinear pairing) with a 159-bit base field in \( G_1 \). Table II lists the difference between these two elliptic curves.

| Type       | \( G_1 \) | \( G_2 \) | \( G_T \) | Security level | Paring Type |
|------------|----------|----------|----------|----------------|-------------|
| MNT159     | 159 bits | 477 bits | 945 bits | 70 bits        | Type 1      |
| SS512      | 512 bits | 512 bits | 1024 bits| 80 bits        | Type 3      |

To simulate the limited computation capacity of OBUs in VANETs, our experiments are performed on Raspberry Pi 4 Model B, which is a cheap microcomputer with a 1.5 GHz ARM Cortex-A71 CPU and 4 GB RAM running Debian Linux operation system. All tested cases are executed 1000 times and runtime is measured in CPU time of the current process.

A. Computation cost

First, we list the runtime of each individual operation under “SS512” and “MNT159” in Table III.

These results in Table III are consistent with relevant study \[28\], and it can be seen that the operations on \( G_1 \) under “MNT159” is much more efficient than that under “SS512”, while the bilinear pairing operation in “MNT159” is more time-consuming. This also indicates that the choice of bilinear pairings depends on the specific constructions of utilized methods.

For the proposed scheme, we first test the computation cost for TRC in registering an OBU. According to Figure 6, we can observe that the generation time of an OBU increases with the height of BT. Under the same conditions, the operation of OBU generation under MNT159 setting is more efficient than that in SS512 setting.

![Fig. 6. The computation cost for an OBU generation](image_url)

Figure 7 shows the average computation cost for V2I and I2V phases, respectively. Note that V2I phase contains two essential encryption methods: one is identity-based encryption for vehicle’s pseudonym, and the other is symmetric encryption (we employed AES in our experiments) for vehicles’ paths. According to Figure 7a, it seems that the height of BT has little effect on vehicle’s computational efficiency. The average computation time under “SS512” curve is slightly more efficient (by about 10 ms) than that under “MNT159” curve. In terms of the computation cost for I2V (see Figure 7b), we set the default height of BT to 20, which means the maximum number of vehicles is \( 2^{20} = 1,048,576 \). Hereafter, unless otherwise stated, the default height of BT is set to 20. The result also shows that the number of requests from vehicles has a limited influence on I2V computational efficiency. The computation time under “SS512” curve is slightly more efficient (by about 8 ms) than that under “MNT159” curve.

Figure 8 presents the computation cost for signing and verification, respectively. It is not difficult to see that the computation cost grows linearly as the length of ring list. Since in ring signature, the signer can enhance the level of anonymity by choosing a longer ring list. In other words, vehicles can adjust the size of ring list based on the demand of traffic environment in a flexible way. The results also show that “MNT159” has a better performance in signing and verification than “SS512”, so it is highly recommended that
using “MNT159” in our proposed scheme for efficiency.

Figure 9 shows the impact of batch verification in our scheme. As illustrated in Figure 9a, we choose 10 signatures randomly and record the total CPU time via regular verification and batch verification, respectively. When we enable the batch mode, the procedure of verification can save around 200ms no matter which ring size we used. If we change the number of signatures from 10 to 20, the gap of verification cost becomes larger (see Figure 9b). Figure 9c also confirms that when the number of signatures increases, the difference between batch verification and regular verification is greater.

There are two important factors which determine the efficiency of batch verification: the number of signatures, and the ring size. In Figure 9d, we focus the influence of these two factors in batch verification. As shown in this figure, there is a trade-off between privacy and efficiency when adopting a longer ring list.

**B. Communication cost**

Due to the fact that we adopt pseudonym rather than certificates in the proposed scheme, the proposed scheme have advantages over those schemes based on PKI in communication cost. To illustrate the communication cost of our scheme clearly, we summarize the storage overhead in the following table.

| Type   | Size of pseudonym | Size of signature | Size of key updates          |
|--------|-------------------|-------------------|------------------------------|
| MNT159 | 30 bytes          | $30(L + 1)$ bytes | $O(r \log(N/r))$ or $O(N - r)$ |
| SS512  | 90 bytes          | $90(L + 1)$ bytes |                              |

The communication cost is evaluated by the built-in function `serialize()` with enabling compression in CHARM.

In Table IV, we list the size of pseudonym, size of signature and size of key updates respectively in different pairing settings. Let $|L|$ represent the length of ring list used in ring signature, and the size of a signature is linear to the size of ring list. Along with the CHARM in our experiments, the size of an element in $G_1$ is about 30 bytes in “MNT159” and 90 bytes in “SS512” after serialization. According to Algorithm 5, a signature on a message consists of two parts, namely $\sigma := (U_i V_i)$, where $U_i$ and $V$ both belong to $G_1$. 

---

**TABLE IV**  
COMMUNICATION COST OF THE PROPOSED SCHEME

| Type   | Size of pseudonym | Size of signature | Size of key updates          |
|--------|-------------------|-------------------|------------------------------|
| MNT159 | 30 bytes          | $30(L + 1)$ bytes | $O(r \log(N/r))$ or $O(N - r)$ |
| SS512  | 90 bytes          | $90(L + 1)$ bytes |                              |

1 The communication cost is evaluated by the built-in function `serialize()` with enabling compression in CHARM.
As for the size of key updates, we denote $N$ and $r$ as the number of all vehicles and revoked vehicles, respectively. Similar to other applications (e.g. [29], [30]) employing the KUNodes algorithm, when $1 < r \leq N/2$, the communication cost of key updates is roughly $O(r \log(N/r))$; when $N/2 < r \leq N$, the communication cost of key updates is roughly $O(N - r)$.

In Figure 10, we set $N = 2^{10} = 1,024$ and measured the number of key updates by employing KUNodes algorithm and Boneh-Franklin original revocable IBE [21] (BF-RIBE for short), respectively. As we mentioned in Section I-B several schemes based on ring signature have not paid enough attention to revocation or just applied the approach in BF-RIBE. Figure 10 shows that the KUNodes algorithm is much more efficient than BF-RIBE especially when $1 < r \leq N/2$.

VII. CONCLUSION

In this paper, we propose an efficient identity-based batch verification scheme for VANETs based on ring signature. Unlike other ring signature-based schemes, we restrict the generation of a ring to avoid disruptions from malicious vehicles. Considering that VANETs are usually highly dense in most real-world scenarios, we adopt batch verification to reduce the computation cost. In terms of the communication overhead, we compare two different types of bilinear pairings and show that Type 3 bilinear pairings have a shorter size which is more suitable in the proposed scheme. Besides, we integrate KUNodes algorithm in the key-update phase to decrease the communication cost. To simulate the environment of OBUs, we implement the proposed scheme on the Raspberry Pi 4 Model B platform. The results also show that our scheme is...
much more efficient in both computation and communication cost in batch mode.

As a possible direction of future work, it might be interesting to consider building HSMs in real-world applications based on the trusted execution environment (TEE) such as ARM’s TrustZone.

REFERENCES

[1] M. El Zarki, S. Mehrotra, G. Tsudik, and N. Venkatasubramanian, “Security issues in a future vehicular network,” in Proceedings of the European Wireless Conference, 2002, pp. 270-274.

[2] J. Petit, F. Schaub, M. Feiri, and F. Kargl, “Pseudonym schemes in vehicular networks: A survey,” IEEE Commun. Surv. & Tutor., vol. 17, pp. 228-255, 2015.

[3] A. Boldyreva, V. Goyal, and V. Kumar, “Identity-based encryption with efficient revocation,” in Proceedings of the 15th ACM Conference on Computer and Communications Security, ser. CCS ’08. New York, NY, USA: Association for Computing Machinery, 2008, pp. 417-426.

[4] I. Ali, A. Hassan, and F. Li, “Authentication and privacy schemes for vehicular ad hoc networks (VANETs): A survey,” Veh. Commun., vol. 16, pp. 45-61, 2019.

[5] S. Sharma and B. Kaushik, “A survey on internet of vehicles: Applications, security issues & solutions,” Veh. Commun., vol. 20, p.100182, 2019.

[6] B. Wiedersheim, M. Sall, and G. Reinhard, “SeVoCom — Security and privacy in Car2Car ad hoc networks,” in 2009 9th International Conference on Intelligent Transport Systems Telecommunications, ser. ITST ’09. IEEE, 2009, pp. 658-661.

[7] P. Kamat, A. Baliga, and W. Trappe, “An identity-based security framework for VANETs,” in Proceedings of the 3rd International Workshop on Vehicular Ad Hoc Networks, ser. VANET ’06. ACM, New York, NY, USA: Association for Computing Machinery, 2006, pp. 94-95.

[8] B. Wiedersheim, Z. Ma, F. Kargl, and P. Papadimitratos, “Privacy in inter-vehicular networks: Why simple pseudonym change is not enough,” in 2010 Seventh International Conference on Wireless On-Demand Network Systems and Services, ser. WONS ’10. IEEE, 2010, pp. 176–183.

[9] B. Ying, D. Makrakis, and H. Mouftah, “Dynamic mix-zone for location privacy in vehicular networks,” IEEE Commun. Lett., vol. 17, no. 8, pp. 1524-1527, 2013.

[10] M. Gerlach and F. Gutierrez, “Privacy in VANETs using changing pseudonyms - ideal and real,” in 2007 IEEE 65th Vehicular Technology Conference. IEEE, 2007, pp. 2521-2525.

[11] A. Boualouache, S. Senouci, and S. Moussaoui, “A survey on pseudonym changing strategies for Vehicular Ad-Hoc Networks,” IEEE Commun. Surv. & Tutor., vol. 20, no. 1, pp. 770-790, 2018.

[12] G. Calandriello, P. Papadimitratos, J. Hubaux, and A. Lioy, “Efficient and robust pseudonymous authentication in VANET,” in Proceedings of the Fourth ACM International Workshop on Vehicular Ad Hoc Networks, ser. VANET ’07. ACM, New York, NY, USA: Association for Computing Machinery, 2007, pp. 19-28.

[13] M. Park, G. Gwon, S. Seo, and H. Jeong, “RSU-based distributed key management (RDKM) for secure vehicular multicast communications,” IEEE J. on Sel. Areas in Commun., vol. 29, no. 3, pp. 644-658, 2011.

[14] L. Zhang, Q. Wu, A. Solanas, and J. Domingo-Ferrer, “A scalable robust authentication protocol for secure vehicular communications,” IEEE Trans. on Veh. Technol., vol. 59, no. 4, pp. 1606-1617, 2010.

[15] S. Zeng, Y. Huang, and X. Liu, “Privacy-preserving communication for VANETs with conditionally anonymous ring signature,” Int. J. of Netw. Secur., vol. 17, no. 2, pp. 135-141, 2015.

[16] Y. Jiang, Y. Ji, and T. Liu, “An anonymous communication scheme based on ring signature in VANETs,” 2014. [Online]. Available: https://arxiv.org/pdf/1410.1639.pdf.

[17] S. Zeng and Y. Chen, “Concurrently deniable group key agreement and its application to privacy-preserving VANETs,” Wirel. Commun. and Mob. Comput., vol. 2018, pp. 1-9, 2018.

[18] B. K. Chaurasia and S. Verma, “Conditional privacy through ring signature in Vehicular Ad-hoc Networks,” in Transactions on Computational Science XIII, Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 147-156.

[19] M. Khodaei and P. Papadimitratos, “Scalable & resilient vehicle-centric certificate revocation list distribution in vehicular communication systems,” IEEE Trans. on Mob. Comput., Early Access, 2020.

[20] F. Liu and Q. Wang, “IBRS: An efficient identity-based batch verification scheme for VANETs based on ring signature,” in 2019 IEEE Vehicular Networking Conference, ser. VNC ’19. IEEE, 2019, pp. 1-8.

[21] D. Boneh and M. Franklin, “Identity-based encryption from the Weil pairing,” in Annual International Cryptology Conference, ser. CRYPTO ’01. Springer. Berlin, Heidelberg: Springer-Verlag, 2001, pp. 213-229.

[22] S.S.M. Chow, S.M. Yiu, and J.C.K. Hui, “Efficient identity based ring signature,” in Applied Cryptography and Network Security. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005, pp. 499-512.

[23] F. Zhang and K. Kim, “ID-based blind signature and ring signature from pairings,” in International Conference on the Theory and Application of Cryptology and Information Security. Berlin, Heidelberg: Springer Berlin Heidelberg, 2002, pp. 533-547.

[24] S.D. Galbraith, K.G. Paterson, and N.P. Smart, “Pairings for cryptographers,” Discret. Appl. Math., vol. 156, no. 16, pp. 3113-3121, 2008.

[25] A.L. Ferrara, M. Green, S. Hohenberger, and M.O. Pedersen, “Practical short signature batch verification,” in Cryptographers’ Track at the RSA Conference. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 309-324.

[26] J.A. Akinwale, C. Garman, I. Miers, M.W. Pagano, M. Rushanan, M. Green, and A.D. Rubin, “Charm: a framework for rapidly prototyping cryptosystems,” J. of Cryptogr. Eng., vol. 3, no. 2, pp. 111-128, 2013.

[27] A.K. Lenstra and E.R. Verheul, “Selecting cryptographic key sizes,” J. of Cryptol., vol. 14, no. 4, pp. 255-293, 2001.

[28] H. Cui, R.H. Deng, J. Lai, X. Yi, and S. Nepal, “An efficient and expressive ciphertext-policy attribute-based encryption scheme with partially hidden access structures, revisited,” Comput. Netw., vol. 133, pp. 157-165, 2018.

[29] H. Cui, R.H. Deng, and G. Wang, “An attribute-based framework for secure communications in Vehicular Ad Hoc Networks,” IEEE/ACM Trans. on Netw., vol. 27, no. 2, pp. 721-733, 2019.

[30] I.C. Roca, J. Liu, and M. Maamar, “Revocation mechanism for hierarchical clustered structure in space-air-ground integrated network,” in 2016 3rd International Conference on Information Science and Control Engineering, ser. ICISCE ’16. IEEE, 2016, pp. 568-572.