Efficient Privacy-Preserving Authentication Protocol for Vehicular Communications with Trustworthy Security

Hu Xiong†‡, Jianbin Hu†, Tao Yang†, Wei Xin‡, Zhong Chen†
†School of Electronics Engineering and Computer Science, Peking University, Beijing, P.R.China
‡School of Computer Science and Engineering, University of Electronic Science and Technology of China, Chengdu, P.R. China
Email: {xionghu.uestc,hujianbin.pku}@gmail.com, {ytao,xinwei}@pku.edu.cn, chen@ss.pku.edu.cn,

Abstract—In this paper, we introduce an efficient and trustworthy conditional privacy-preserving communication protocol for VANETs based on proxy re-signature. The proposed protocol is characterized by the Trusted Authority (TA) designating the Roadside Units (RSUs) to translate signatures computed by the On-Board Units (OBUs) into one that are valid with respect to TA’s public key. In addition, the proposed protocol offers both a priori and a posteriori countermeasures: it not only provide fast anonymous authentication and privacy tracking, but guarantees message trustworthiness for vehicle-to-vehicle (V2V) communications. Furthermore, it reduces the communication overhead and offers fast message authentication and, low storage requirements. We use extensive analysis to demonstrate the merits of the proposed protocol and to contrast it with previously proposed solutions.

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) are very likely to become the most pervasive and applicable of mobile ad hoc networks (MANETs) in this decade. Different from the traditional MANETs, VANET contains not only mobile vehicles, but also stationary roadside infrastructures. Equipped with communication devices, vehicles can communicate with each other or with the roadside units (RSUs) located at critical points of the road, such as intersections or construction sites. Different from vehicles, RSUs usually have no buffer constraint and can store a lot of information. According to the Dedicated Short Range Communications (DSRC) [1], each vehicle equipped with OBU will broadcast routine traffic messages, such as the position, current time, direction, speed, acceleration/deceleration, and traffic events, etc. In this way, drivers can get better awareness of the driving environment and take early actions to the abnormal situation to improve the safety of both vehicle drivers and passengers [2]. However, before the above attractive applications come into reality, the security and privacy issues should be addressed. Otherwise, the safety of both vehicle drivers and passengers [2]. However, before the above attractive applications come into reality, the security and privacy issues should be addressed. Otherwise, the VANET could be subject to many security threats, which will lead to increasing malicious attacks and service abuses. More precisely, an adversary can either forge bogus messages to mislead other drivers or track the locations of the intended vehicles. Therefore, how to secure vehicle-to-vehicle communication in VANETs has been well-studied in recent years [3]–[21].

Dealing with fraudulent messages in VANETs is a thorny issue due to its inherent self-organization. The situation is further deteriorated by the privacy requirements, i.e., the malicious vehicles are anonymous and cannot be identified in case of dispute. Countermeasures against fraudulent messages fall into two classes: a posteriori and a priori.

With a posteriori countermeasure, a trusted authority can disclose the real identity of targeted OBU in case of a traffic event dispute, even though the OBU itself is not traceable by the public. In this way, punishment will be taken against vehicles who have been proven to have originated fraudulent messages (e.g., the violators will be excluded from the network). The existing posteriori solutions for VANETs can mainly be categorized into following classes. The first one is based on a large number of anonymous keys (denoted as LAB in the rest of this paper) [3], [4], the second one is based on a pure group-oriented signature, such as group signature and ring signature (denoted as GSB in the following) [5], [6], [8], while the last one employs the roadside units (RSUs) to assist the vehicle in authenticating messages (denoted as RSUB in the following) [10]–[12]. Though all of these solutions can meet the conditional privacy requirement, they are in vain against irrational attackers such as terrorists. Even for rational attackers, damage has already occurred when punitive action is taken.

A priori countermeasure attempts to prevent the generation of fraudulent messages. In this approach, a message is not considered valid unless it has been endorsed by a number of vehicles above a certain threshold. This approach is based on the assumption that most users are honest, and therefore, they will not endorse any message containing false data. To achieve this, messages received must be distinguishable. The use of an honest majority to prevent generation of fraudulent messages has previously been proposed in [15]–[17]. However, although the underlying assumption that there is a majority of honest vehicles in VANETs generally holds, it cannot be excluded that a number of malicious vehicles greater than or equal to the threshold are present in specific locations. Furthermore, for convenience in implementation, most of schemes assume that the threshold, i.e., the number of honest vehicles in all cases, should be treated as a one-size-fits-all concept. However, we
argue that threshold is a \textit{scenario-specific} concept in the sense that different scenario may have varying threshold requirements. Indeed, the threshold should be adaptive according to the traffic density and the message scope: A low density of vehicles calls for a lower threshold, whereas a high density and a message relevant to all of the traffic in a city require a sufficiently high threshold.

To address these issues, this paper proposes an efficient and trustworthy conditional privacy preserving authentication protocol for vehicle-to-vehicle communication based on proxy re-signature [22]. Compared to previous message-authentication schemes [3]–[21], our scheme (which we dub PRSB) has the following unparalleled features that, we believe, make it an excellent candidate for the future VANETs:

- **Achieving both priori and posteriori countermeasures:** Using the proxy re-signature to secure the vehicle-to-vehicle communication, the RSUs can be allowed to transform an OBU’s signature into a TA’s signature on the same message. This conceals the unique identity of the OBU to prevent information leakage to the malicious adversary, while still allowing for internal auditing by the RSUs. Furthermore, the RSUs can distinguish by itself whether the message was signed by the same cheating vehicle multiple times or by multiple honest vehicles. By this way, our scheme enables the RSUs only transform the messages endorsed by a number of vehicles greater than or equal to a threshold, and the vehicles endorsing cheating messages can later be traced. We also note that a recent proposal in [17] also achieves both priori and posteriori countermeasures by drawing on the linkable group signature.

- **Efficiency:** Different from GSB protocols [5], [6], [17], the proposed protocol can efficiently deal with a growing revocation list and does not rely on updating the group public key and private key at all unrevoked vehicles. Furthermore, our protocol does not rely on a large storage space at each vehicle. Clearly, since the OBU only need to generate the \textit{general} signature instead of the \textit{anonymous} signature, the OBU communication and computation overhead will be reduced at a fairly large scale.

- **Threshold-adaptivity:** The threshold in our proposal can be adaptive according to the traffic context, unlike most previous schemes in which the threshold has to be preset during the stage of system initialization. This feature enables our proposal to be deployed in complicated traffic scenarios.

The remainder of this paper is organized as follows. Section II presents background information related to vehicular network design and operation and surveys additional related work. Section III presents the problem formulation, system architecture, and design objectives as well as the key cryptographic techniques our solution is based on: bilinear maps and proxy re-signatures. Section IV details the proposed security protocol, followed by the security analysis and the performance analysis in Section V and Section VI, respectively. Section VII concludes this paper.

II. BACKGROUND AND RELATED WORK

A. System Model

Similar to previous work [10]–[13], the considered system includes three types of entities: the top Trusted authority (TA), the immobile RSUs at the roadside, and the moving vehicles equipped with on-board units (OBUs).

- **OBU:** A vehicle needs to be registered to the TA with its public system parameters and corresponding private key before it joins the VANET. The secret information such as private keys to be used generates the need for a tamper-proof device in each vehicle. Similar to previous work we assume that access to this tamper-proof device is restricted to authorized parties. OBUs are mobile and moving most of the time. When the OBUs are on the road, they regularly broadcast routine safety messages, such as position, current time, direction, speed, traffic conditions, traffic events. The information system on each vehicle aggregates and processes these messages to enable drivers form a better awareness of their environment (Fig. 1). The population of OBUs in the system could be up to billions (as, today, there are about a quarter of billion light vehicles in the US only).

- **RSU:** The RSUs are subordinated by the TA, which hold storage units for storing information coming from the TA and the OBUs. The main tasks of RSUs are (1) translating a OBU’s signature under the TA’s public key on the same message, and (2) assisting the TA to efficiently track the real OBU identity of any safety message. Without the authorization of the TA, the RSUs will not disclose any inner information. We remark that each RSU is physically secure and cannot be compromised. Meanwhile, RSUs cannot generate signatures on behalf of either the OBU or the TA. Different from the vehicles, we assume that RSUs have neither computation and energy constraints nor buffer size constraints. Due to the fact that there is no
computation and storage constraints at RSUs, RSUs can be able to serve as the proxy to translate the signatures from OBUs.

- **TA:** The TA is in charge of the registration of all RSUs and OBUs each vehicle is equipped with. The TA can reveal the real identity of a safety message sender by incorporating with its subordinate RSUs. To the end, the TA requires ample computation and storage capability, and the TA cannot be compromised and is fully trusted by all parties in the system.

The network dynamics are characterized by quasi-permanent mobility, high speed, and (in most cases) short connection times between neighboring vehicles or between a vehicle and a roadside infrastructure network access point. The assumed communication protocol between neighboring OBUs or between an OBU and a RSU is 5.9 GHz Dedicated Short Range Communication (DSRC) [1] IEEE 802.11p.

### B. Related Work

To achieve both message authentication and conditional anonymity, Raya et al. [3], [4] introduced the LAB protocol. Their key idea is to install on each OBU a large number of private keys and their corresponding anonymous certificates. To sign each launched message, a vehicle randomly selects one of its anonymous certificates and uses its corresponding private key. The other vehicles use the public key of the sender enclosed with the anonymous certificate to authenticate the source of the message. These anonymous certificates are generated by employing the pseudo-identities of the vehicles, instead of taking any real identity information of the drivers. Each certificate has a short life time to meet the drivers’ privacy requirement. Although LAB protocol can effectively meet the conditional privacy requirement, it is inefficient and may meet a scalability bottleneck. The reason is that a sufficient numbers of certificates must be issued to each vehicle to maintain anonymity over a significant period of time. As a result, the certificate database to be searched by the TA in order to match a compromised certificate to its owner’s identity is huge. In addition, the protocols of [4] are extended for providing confidentiality in specific scenarios of VANET implementations in [19]. Subsequently, Lin et al. [9] developed the ‘time-efficient and secure vehicular communication’ scheme (TSVC) based on the TESLA (Timed Efficient Stream Loss-tolerant Authentication) standard (RFC 4082) [23]. With TSVC, a vehicle first broadcasts a commitment of hash chain to its neighbors and then uses the elements of the hash chain to generate a message authentication code (MAC) with which other neighbors can authenticate this vehicles’ following messages. Because of the fast speed of MAC verification, the computation overhead of TSVC is reduced significantly. However, TSVC also requires a huge set of anonymous public/private key pairs as well as their corresponding public key certificates to be preloaded in each vehicle. Furthermore, TSVC may not be robust when the traffic becomes extremely dynamic as a vehicle should broadcast its key chain commitment much more frequently.

Lin et al. [6], [7] proposed the GSB protocol, based on the group signature [24]. With GSB, each vehicle stores only a private key and a group public key. Messages are signed using the group signature scheme without revealing any identity information to the public. Thus privacy is preserved while the trusted authority is able to track the identity of the sender. However, the time for safety message verification grows linearly with the number of revoked vehicles in the revocation list in the entire network. Hence, each vehicle has to spend additional time on safety message verification. Furthermore, when the number of revoked vehicles in the revocation list is larger than some threshold, the protocol requires every remaining vehicle to calculate a new private key and group public key based on the exhaustive list of revoked vehicles whenever a vehicle is revoked. Lin et al. [6], [7] do not explore solutions to effectively updated the system parameters for the participating to vehicles in a timely, reliable and scalable fashion. This issue is not explored and represents an important obstacle to the success of this scheme. To address the scalability concern, Xiong et al. [8] proposed a spontaneous protocol based on the revocable ring signature [25], which allows the vehicle to generate the message without requiring online assistance from the RSUs or the other vehicles. In this solution, the remaining vehicles are not required to update their system parameters regardless of the number of revoked vehicles. However, this protocol suffers larger communication overhead than that of other protocols because the length of ring signature depends on the size of the ring.

Recently, Zhang et al. [10], [11] proposed a novel RSU-aided message authentication scheme (RSUB), which makes the RSUs responsible for verifying the authenticity of messages sent from vehicles and for notifying the results back to vehicles. Compared to the solutions previously mentioned, this scheme enables lower computation and communication overheads for each vehicle. Independently, Lu et al. [12] introduced an efficient conditional privacy preservation protocol for VANETs based on generating on-the-fly short-lived anonymous keys for the communication between vehicles and RSUs. These keys enable fast anonymous authentication and conditional privacy. Furthermore, Wasef et al. [18] proposed a RSUs-aided Distributed Certificate Service (DCS) scheme along with a hierarchical authority architecture. In this way, vehicles can update their pseudonymous certificate sets from the RSUs. However, all of the above solutions fall into the post-attack countermeasures, which can only exclude the rational attackers by punishing the malicious users after the attack.

To reduce the damage to a bare minimum, the priori countermeasures have been proposed to prevent the generation of fake messages. In this approach, a message is not considered valid unless it has been endorsed by a number of vehicles above a certain threshold. Most recently, Kounag et al. [16] proposed a solution that permits vehicles to verify the reliability of information received from anonymous origins. In this solution, each vehicle can generate the public/private key pairs by itself. However, the assumption in this solution
is very restricted in that additional hardware is needed on the OBU. After that, a proposal is also presented following the priori protection paradigm based on threshold signature by Daza et al. [15]. Nevertheless, to obtain the anonymity, this protocol assumes that the OBU installed on the vehicle can be removable and multi OBUs could alternatively be used with the same vehicle (like several cards can be used within a cell phone in the same time). Thus, this assumption may enable malicious adversary to mount the so-called Sybil attack: vehicles using different anonymous key pairs from corresponding OBUs can sign multiple messages to pretend that these messages were sent by different vehicles. Since multi OBUs can be installed on the same vehicle, no one can find out whether all of these signatures come from the same vehicle or not. After that, Wu et al. [17] proposed a novel protocol based on linkable group signature, which is equipped with both priori and posteriori countermeasures. However, they face the same adverse conditions in GSB protocol in which the verification time grows linearly with the number of revoked vehicles and every remaining vehicle need to update its private key and group public key when the number of revoked vehicles is larger than some threshold.

III. PRELIMINARIES

A. Objectives

To avoid reinventing the wheel, we refer the readers to other works [3], [6], [17] for a full discussion of the attacker model. In the context of this work, we focus on the following security objectives.

1) Efficient anonymous authentication of safety messages: The proposed scheme should provide an efficient and anonymous message authentication mechanism. First, all accepted messages should be delivered unaltered, and the origin of the messages should be authenticated to guard against impersonation attacks. Meanwhile, from the perspective of vehicle owners, it may not be acceptable to leak personal information, including identity and location, while authenticating messages. Therefore, providing a secure yet anonymous message authentication is critical to the applicability of VANETs. Furthermore, the proposed scheme should have low overheads for safety message verification and storage at OBUs.

2) Efficient tracking of the source of a disputed safety message: An important and challenging issue in these conditions is enabling the TA to retrieve a vehicle’s real identity from its pseudo identity. If this feature is not provided, anonymous authentication can only prevent an outside attack, but cannot deal with an inside one. Furthermore, the system should not only provide safety message traceability to prevent inside attacks, but also have reasonable overheads for the revealing the identity of a message sender.

3) Threshold authentication: A message is viewed as trustworthy only after it has been endorsed by at least \( n \) vehicles, where \( n \) is a threshold. The threshold mechanism is a priori countermeasure that improves the confidence of other vehicles in a message. In addition, the threshold in the proposed scheme should be adaptive, that is to say, the sender can dynamically change the threshold according to the traffic context and scenarios.

B. Bilinear Maps

Since bilinear maps [26] are the basis of our proposed scheme, we briefly introduce them here.

Multiplicative cyclic groups \((\mathbb{G}, \mathbb{G}_T)\) of prime order \( q \) are called bilinear map groups if there is an efficiently computable mapping \( \hat{e} : \mathbb{G} \times \mathbb{G} \to \mathbb{G}_T \) with the following properties:

1) Bilinearity: For all \( g, h \in \mathbb{G} \), and \( a, b \in \mathbb{Z} \), \( \hat{e}(g^a, h^b) = \hat{e}(g, h)^{ab} \).

2) Non-degeneracy: \( \hat{e}(g, h) \neq 1_{\mathbb{G}_T} \) whenever \( g, h \neq 1_{\mathbb{G}} \).

Such an admissible bilinear map \( \hat{e} \) can be constructed by the modified Weil or Tate pairing on elliptic curves. For example, the Tate pairing on MNT curves [27] gives the efficient implementation, and the representations of \( \mathbb{G} \) can be expressed in 161 bits when the order \( q \) is a 160-bit prime. By this construction, the discrete logarithm problem in \( \mathbb{G} \) can reach 80-bit security level.

C. Proxy Re-Signature

Proxy re-signature schemes, introduced by Blaze, Bleumer, and Strauss [28], and formalized later by Ateniese and Hofheinz [29], allow a semi-trusted proxy to transform a delegatee's signature into a delegator's signature on the same message by using some additional information. Proxy re-signature can be used to implement anonymizable signatures in which outgoing messages are first signed by specific users. Before releasing them to the outside world, a proxy translates signatures into ones that verify under a system’s public key so as to conceal the original issuer’s identity and the internal structure of the organization. Recently, Libert et al. [22] have introduced the first multi-hop unidirectional proxy re-signature scheme wherein the proxy can only translate signatures in one direction and messages can be resigned a polynomial number of times. We use this scheme as the basis for our efficient and trustworthy conditional privacy-preservation protocol.

IV. EFFICIENT AND TRUSTWORTHY VEHICULAR COMMUNICATIONS SCHEME

This section describes in detail our efficient and trustworthy privacy-preserving protocol for VANET. TA, the delegator, will designate the RSUs translating signatures computed from OBUs, the delegatee, into one that is valid w.r.t. TA's public key by storing the re-signature key at the RSUs. Upon receiving OBU’s signatures, the RSUs can validate them and re-sign the message using the re-signature key. This message can be anonymously authenticated by any vehicle participating in the system by verifying this signature (the only information needed for verification is the TA's public keys). By this way, proxy re-signatures can be used to conceal identities of the OBU. Furthermore, RSUs could log which OBU signed the
message for solving the dispute, but keep that information confidential to the public.

The notation used throughout this paper is listed in Table I. The proposed security protocol is an extension of proxy re-signature scheme [22] in order to support conditional anonymity authentication with trustworthy. Specifically, the proposed security protocol contains four phases, which are described in the following paragraphs.

A. System Initialization

Firstly, as described in section II-A, we assume each vehicle is equipped with a tamper-proof device, which is secure against any compromise attempts in any circumstance. With the tamper-proof device on vehicles, an adversary cannot extract any data stored in the device including key material, data, and codes [3]. We assume that there is a Trusted Authority (TA) which is in charge of registering the RSUs and the OBUs installed on the vehicles. Prior to the network deployment, the TA sets up the system parameters for each OBU and RSU as follows:

- Let $G, G_T$ be two cyclic groups of same order $q$. Let $e: G \times G \rightarrow G_T$ be a bilinear map.
- The TA first randomly chooses $x_{TA} \in R \mathbb{Z}^*_q$ as its private key, and computes $X_{TA} = g^{x_{TA}}$ as its public key. The TA also chooses two secure cryptographic hash functions $H_1: \{0,1\}^* \rightarrow \mathbb{Z}^*_q$ and $H_2: \{0,1\}^* \rightarrow G$, and a secure symmetric encryption algorithm $Enc_{\kappa}()$ with secret key $\kappa$.

- The TA generates public/private key pair for each subordinate RSU works at location $L_j$ as follows:
  - The TA randomly selects an integer $x_{RSU_j} \in R \mathbb{Z}^*_q$ and computes $X_{RSU_j} = g^{x_{RSU_j}}$.
  - The TA sends the public/private key pair to $RSU_j$ through a secure channel.
- Each vehicle $V_i$ with real identity $RID_i$ generates its public/private key pair as follows:
  - Select $x_i \in R \mathbb{Z}^*_q$ as its private key, and computes $X_i = g^{x_i}$ as its public key.
  - $V_i$ randomly selects an integer $t_i \in R \mathbb{Z}^*_q$ to determine the verification information of $X_i: a_i = H_1(g^{t_i} \parallel RID_i)$ and $b_i = (t_i + x_i \cdot a_i)$. Then $V_i$ sends $\{X_i, RID_i, a_i, b_i\}$ to TA.

- After receiving $\{X_i, RID_i\}$, TA checks whether the following equation holds:

$$a_i = H_1((g^{b_i}X_i^{-a_i}) \parallel RID_i)$$

If it holds, then $\{X_i, RID_i\}$ is identified as the valid public key and identity. Otherwise, it will be rejected. After that, the TA stores the $(X_i, RID_i)$ in its records.

- In the end, TA generates the re-signature key $R_i = X_i^{1/x_{TA}} = g^{x_{TA}}/x_{TA}$ which allows turning signatures from vehicle $V_i$ into signatures from TA, and sends the item $(R_i, X_i)$ to all RSUs through a secure channel.

- Each vehicle is preloaded with the public parameters $\{G, G_T, q, X_{TA}, H, Enc_{\kappa}\}$. In addition, the tamper-proof device of each vehicle is preloaded with its private/public key pairs $(x_i, X_i)$ and corresponding anonymous certificates (these certificates are generated by taking the vehicle’s pseudo-identity $ID_i$).

B. OBU Safety Message Generation

The format of the safety messages sent by the OBU is defined in Table II, which consists of five fields: message ID, payload, timestamp, $RSU_j$’s public key, and signature.

| Message ID | Payload | Timestamp | $RSU_j$’s Public Key | Signature |
|------------|---------|-----------|----------------------|-----------|
| 2          | 100 bytes | 4 bytes | 20 bytes | 20 bytes |

- The vehicle $V_i$ first chooses $x_i \in R \mathbb{Z}^*_q$ as its private key, and computes $X_i = g^{x_i}$ as its public key.
- $V_i$ randomly selects an integer $t_i \in R \mathbb{Z}^*_q$ to determine the verification information of $X_i: a_i = H_1(g^{t_i} \parallel RID_i)$ and $b_i = (t_i + x_i \cdot a_i)$. Then $V_i$ sends $\{X_i, RID_i, a_i, b_i\}$ to TA.

- The TA first randomly chooses $x_{TA} \in R \mathbb{Z}^*_q$ as its private key, and computes $X_{TA} = g^{x_{TA}}$ as its public key. The TA also chooses two secure cryptographic hash functions $H_1: \{0,1\}^* \rightarrow \mathbb{Z}^*_q$ and $H_2: \{0,1\}^* \rightarrow G$, and a secure symmetric encryption algorithm $Enc_{\kappa}()$ with secret key $\kappa$.

- The TA generates public/private key pair for each subordinate $RSU_j$ works at location $L_j$ as follows:
  - The TA randomly selects an integer $x_{RSU_j} \in R \mathbb{Z}^*_q$ and computes $X_{RSU_j} = g^{x_{RSU_j}}$.
  - The TA sends the public/private key pair to $RSU_j$ through a secure channel.
- Each vehicle $V_i$ with real identity $RID_i$ generates its public/private key pair as follows:

Table II

MESSAGE FORMAT FOR OBU
4) After receiving $n$ or more valid signatures from the vehicles on the same message $M$, $RSU_j$ search $(R_i, X_i)$ according to $(M, \sigma^{(1)}, X_i)$ from its database. Then $RSU_j$ chooses randomly $s \in R Z^*_q$ and computes

$$\sigma^{(2)} = (\sigma_0, \sigma_1, \sigma_2) = (\sigma^{(1)}, X_i^s, R_i^s) = (H_2(M)^{x_i}, X_i^s, g^{x_i/T_A})$$

where $R_i$ have been preloaded along with $X_i$ in the $RSU_j$ during the initialization phase. Then $RSU_j$ stores the trace evidence table with item $(M, X_i)$ in its local database. In the end, TA broadcast the trustworthy signature $(M, \sigma^{(2)})$ to all vehicles among its coverage range.

Note that the threshold $n$ can adaptively be changed according to the type of message and various scenarios. For instance, if the message is an alert about an emergency braking by the vehicle ahead, the threshold can be set as low as 1. However, if the message is an announcement that will affect many vehicles, the threshold can be set to be appropriately high to improve the trustworthiness by also taking into account the vehicle density among the RSU’s communication range. By this way, the signature $\sigma^{(1)}$ is turned into a trustworthy signature $\sigma^{(2)}$ under TA’s public key.

C. Message Verification

Once a trustworthy message $\sigma^{(2)}$ is received, the receiving vehicle performs signature verification by checking whether the following conditions are true:

$$\hat{e}(\sigma_0, g) = \hat{e}(H_2(M), \sigma_1)$$
$$\hat{e}(\sigma_1, g) = \hat{e}(\sigma_2, X_{TA})$$

This verification provides vehicles with the assurance that such a signature can only have been computed if at least $n$ vehicles have endorsed $M$.

D. OBU fast tracing

If a vehicle produced a signature on the message $M$ and this message was found to be fraudulent, a membership tracing operation is started to determine the real identity of the signature originator. In detail, the TA first position the $RSU_j$ by extracting the RSU’s public key $X_{RSU_j}$ from the message $[ID_{Type} \| Payload \| Timestamp \| X_{RSU_j}]$. According to the TA’s demand, the $RSU_j$ then retrieves the public key of the source of the disputed safety message $M$ by searching his trace evidence table with item $(M, X_i)$ and returns $X_i$ to the TA, and then the TA recovers the real identity from the returned public key.

V. SECURITY ANALYSIS

We analyze the security of the proposed scheme in terms of the following four aspects: message authentication, user identity privacy preservation, traceability by the TA, and threshold authentication.

- **Message authentication.** Message authentication is the basic security requirement in vehicular communications. In the proposed scheme, the signature $\sigma^{(1)}$ w.r.t public key $X_i$ can only be generated by the vehicle $V_i$, who holds the corresponding private key $x_i$. Without knowing the discrete logarithms $x_i$ of the public keys $X_i$, it is infeasible to forge a valid signature $\sigma^{(1)}$. If a signature $\sigma^{(1)}$ w.r.t public key $X_i$ passes the verification procedure, it must be an intact fresh message generated by $V_i$. This implies that the attacker cannot cheat RSU by forging a new valid message, modifying an existing valid message, or replaying a once valid but now expired message. Meanwhile, the signature $\sigma^{(2)}$ can only be translated by the RSU from $\sigma^{(1)}$ by using the corresponding re-signature key $R_i$. Furthermore, the RSU cannot generate the valid signature $\sigma^{(2)}$ on behalf of $V_i$ using $R_i$. Thus, the adversary cannot forge the valid signature $\sigma^{(2)}$ even when it only knows the corresponding re-signature key $R_i$.

- **Threshold authentication.** If a vehicle $V_i$ tends to cheat RSU by endorsing the same message more than once, then the RSU can easily link the multi signatures by comparing the public key $X_i$ along with the message. This kind of message can be either simply discarded or
sent to the TA to trace the cheating vehicle. Hence, the Sybil attack can be avoided in our privacy-preserving scheme.

- **Identity privacy preservation.** The message \( M \) and the signature \( \sigma^{(1)} \) with respect to public key \( X_i \) is only explored to \( RSU_j \) and \( V_i \) since the communication between \( V_i \) and \( RSU_j \) is confidential. Finding the shared secret key \( \phi \) from \( \psi \) and \( X_{RSU_j} \) is an instance of the CDH problem: given \( g, \psi = g^r, X_{RSU_j} = g^{x_{RSU_j}} \), find \( \phi = g^{x_{RSU_j}} \). Thus, only the \( RSU_j \) can link the \((X_i, \sigma^{(1)})\) to the corresponding message \( M \). Given a valid signature \( \sigma^{(2)} \) of some message, it is computationally difficult to identify the actual sending vehicle by any vehicles in the system since the only information needed to verify the correctness of signature \( \sigma^{(2)} \) is TA’s public key \( X_{TA} \).

- **Traceability.** Given the disputed signature, only the corporation between TA and the \( RSU_j \), can trace the real identity of a message sender using the OBU tracking procedure described in section IV-D. Besides, the tracing process carried by the TA does not require any interaction with the message generator. Instead, the signature itself provides the authorship information to TA. Therefore, once a signature is in dispute, the TA has the ability to trace the disputed message, in which the traceability can be well satisfied.

VI. PERFORMANCE EVALUATION

This section evaluates the performance of the proposed scheme in terms of storage requirements, and computational and communication overheads.

A. OBU Storage Overheads

This subsection compares the OBU storage overhead of our protocol, which we dub PRSB, with three previously proposed protocols: LAB [3], [4], [9], RSUB [12] and GSB [6], [8], [17]. In the LAB protocol, each OBU stores not only its own \( N_{okey} \) anonymous key pairs, but also all the anonymous public keys and their certificates in the revocation list (the notations adopted in the description are listed in Table III). Let each key (with its certificate) occupy one storage unit. If there are \( m \) OBUs revoked, then the scale of revoked anonymous public keys is \( m \cdot N_{okey} \). Thus, the total storage overhead in LAB protocol (denoted as \( S_{LAB} \)) is \( S_{LAB} = (m + 1)N_{okey} \). Assuming that \( N_{okey} = 10^4 \), we have \( S_{LAB} = (m + 1)10^5 \). In the GSB protocol, each OBU stores one private key issued by the trusted party, and \( m \) revoked public keys in the revocation list. Let \( S_{GSB} \) denotes the total storage unit of GSB protocol. Thus, \( S_{GSB} = m + 1 \). Both in the RSUB protocol [12] and our protocol, each OBU stores one public/private key pair issued by the trusted party, and its anonymous certificate issued by the RSU. Since the OBU does not need to store the revocation list, the storage overhead in RSUB protocol is only two units, denoted as \( S_{RSUB} = S_{PRSB} = 2 \).

Fig. 3 shows the storage units of LAB protocol, GSB protocol, RSUB protocol and our protocol as \( m \) increases. Observe that the OBU storage overhead in LAB protocol linearly increases with \( m \), and is much larger than that in the other three protocols. The storage overhead of GSB protocol is still small in spite of its linear increase with \( m \), while the storage overhead in the RSUB and our protocol is the most efficient, which does not increase with \( m \).

B. OBU Communication Overhead

This section compares the communication overheads of the protocols studied. We assume that all protocols generate a timestamp to prevent replay attacks so we exclude the length of the timestamp in this analysis.

For the LAB protocol, each message generates yields 181 bytes as the additional overhead due to cryptographic operations, which includes a certificate and an Elliptic Curve Digital Signature Algorithm (ECDSA) signature\(^1\). For the GSB\(_1\) [6], GSB\(_2\) [8] and GSB\(_3\) [17] protocol , each message generates 197, 60n + 60 and 133 bytes as the additional overhead respectively, where \( n \) represents the number of the public key pairs used to generate the ring signature in [8]. For the RSUB protocols, the additional communication overhead is \( 70/k + 40 + 147 \) bytes, where the first term represents the communication overhead caused by generating the short-term anonymous key, the second term represents the length of the

\(^1\)ECDSA signature scheme of IEEE1609.2 [30] is the current standard for VANETs, where the length of a signature is 42 B.
signatures sent by the vehicle and the last term is the length of the short time anonymous key and its corresponding certificate which are reused across $k$ messages (as the RSUB protocol regenerates the anonymous key only every $k$ messages). For the proposed protocols, the additional communication overhead is $2 + 20 + 20 + 20 + 20$ bytes, where the first term represents the communication overhead caused by the message ID, the second term represents the length of the RSU’s public key, the third term represents the length of the signature sent by the vehicle, the fourth term represents the vehicle’s public key and the last term is the length of the hint (as shown in Table II).

Fig. 4 shows the relationship between the overall communication overhead in 1 min and the traffic load within a vehicle. Obviously, as the number of messages increases, the transmission overhead increases linearly. Clearly, we can observe that the proposed protocol has much lower communication overhead than the other protocols.

**TABLE IV**

| Protocol     | Send a single message | Send $k$ messages |
|--------------|-----------------------|-------------------|
| LAB          | 181 bytes             | 181$k$ bytes      |
| GSB          | 297 bytes             | 297$k$ bytes      |
| GSB$_1$      | 600 + 60 bytes        | (600 + 60)$k$ bytes |
| GSB$_2$      | 133 bytes             | 133$k$ bytes      |
| RSUB         | 70 + 187 bytes        | 70 + 187$k$ bytes |
| PRSB         | 82 bytes              | 82$k$ bytes       |

**C. OBU Computation Overhead**

This subsection compares the OBU computation overhead for the proposed, RSUB and GSB protocols. Since the point multiplication in $\mathcal{G}$ and pairing computations dominates each party’s computation overhead, we consider only these operations in the following estimation. Table V gives the measured processing time (in milliseconds) for an MNT curve of embedding degree $k = 6$ and 160-bit $q$. The implementation was executed on an Intel pentium IV 3.0 GHz machine.

**TABLE V**

| Descriptions | Execution Time |
|--------------|----------------|
| $T_{pmul}$   | Time for one point multiplication in $\mathcal{G}$ | 0.6 ms |
| $T_{pair}$   | Time for one pairing operation                     | 4.5 ms |

In our proposed protocol, verifying a message, requires $4T_{pair}$ as shown in section IV-C. Let $T_{PRSB}$ be the required time cost in our protocol, then we have:

$$T_{PRSB} = 4T_{pair} = 4 \times 4.5 = 18\text{(ms)}$$

In the RSUB protocol, to verify a message, it requires $3T_{pair} + 11T_{pmul}$. Let $T_{RSUB}$ be the required time cost in RSUB’s protocol, then we have:

$$T_{RSUB} = 3T_{pair} + 11T_{pmul} = 3 \times 4.5 + 11 \times 0.6 = 20.1\text{(ms)}$$

In the GSB protocol [6], the time cost to verify a message is related to the number of revoked OBUs in the revocation list. Thus the required time is demonstrated as follows:

$$T_{GSB} = 6T_{pmul} + (4 + m)T_{pair} = 6 \times 0.6 + (4 + m) \times 4.5\text{(ms)}$$

Let

$$T_{PG} = \frac{T_{PRSB}}{T_{GSB}} = \frac{4 \times 4.5}{3.6 + (4 + m) \times 4.5}$$

$$T_{RG} = \frac{T_{RSUB}}{T_{GSB}} = \frac{3 \times 4.5 + 11 \times 0.6}{3.6 + (4 + m) \times 4.5}$$

be the cost ratio between the PRSB and the GSB protocol, and between the RSUB and the GSB protocol, respectively. Fig. 5 plots the time cost ratio $T_{PG}$ and $T_{RG}$ when $m$ OBUs are revoked, as $m$ ranges from 1 to 100. We observe that both of the time cost ratios decreases as $m$ increases, which demonstrates the much better efficiency of our proposed protocol and RSUB protocol than the GSB protocol especially when the revocation list is large. We also observe that our proposed protocol is a little more efficient than RSUB protocol.

**VII. SUMMARY**

We have presented an efficient conditional privacy preserving protocol with trustworthy based on the proxy re-signature and aimed for secure vehicular communications. We demonstrate that proposed protocol is not only provides conditional privacy, a critical requirement in VANETs, but also able to improve the confidence of message receiver. By this way, our protocol achieves both *priori* and *posteriori* countermeasures simultaneously. Through extensive performance evaluation, we have demonstrated that the proposed protocol can achieve much better efficiency than previously reported counterparts in terms of the number of keys stored at each vehicle, communication overhead and, message verification.
Saving Lives Through Advanced Vehicle Safety Technology: Dedicated Short Range Communications (5.9 GHz DSRC), [Online]. Available: http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS/PR/14153_files/iwv.pdf

Fig. 5. Time efficiency ratio $T_{RG} = T_{RSSB}/T_{GSB}$ when varying the number of revoked OBUs, $m$, from 1 to 100.

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The number of vehicles

Transmission overhead (MBytes)

GSB Protocol
RSUB Protocol
RRSB Protocol with n=5
RRSB Protocol with n=10

The number of vehicles
