Delegating Authentication to Edge: A Decentralized Authentication Architecture for Vehicular Networks

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***Abstract*— Secure and efficient access authentication is one of the most important security requirements for vehicular networks, but it is difficult to fulfill due to potential security attacks and long authentication delay caused by high vehicle mobility, etc. Most of the existing authentication protocols, either do not consider attacks like single point of failure or do not focus on reducing authentication delay. To address these issues, we introduce an edge-assisted decentralized authentication (EADA) architecture, which provides secure and more communication-efficient authentication by enabling an authentication server to delegate its authentication capability to distributed edge nodes (ENs) such as roadside units (RSUs) and base stations (BSs). Under the architecture, we propose a threshold mutual authentication protocol that supports fast handover, which involves two scenarios, Auth-I and Auth-II. Auth-I only happens once when a vehicle tries to access the network for the first time, while Auth-II happens when a vehicle seamlessly roams between two ENs, i.e., handover. Specifically, for Auth-I, each vehicle can be cooperatively authenticated by t out of n ENs with identity-based signature techniques to obtain an authentication token and the involved ENs can be efficiently authenticated in a batch by the vehicle. For Auth-II, the vehicle can utilize the token as its private credential to achieve fast handover based on identity-based signature without interacting with multiple ENs, which further reduces the authentication delay significantly. In addition, we design a flexible method to support dynamic joining and leaving of ENs without the assistance of a trusted center. We demonstrate that the proposed protocol is secure and efficient through security analysis and performance evaluation.**

***Index Terms*— Vehicular networks, edge, mutual authentication, threshold signature.**

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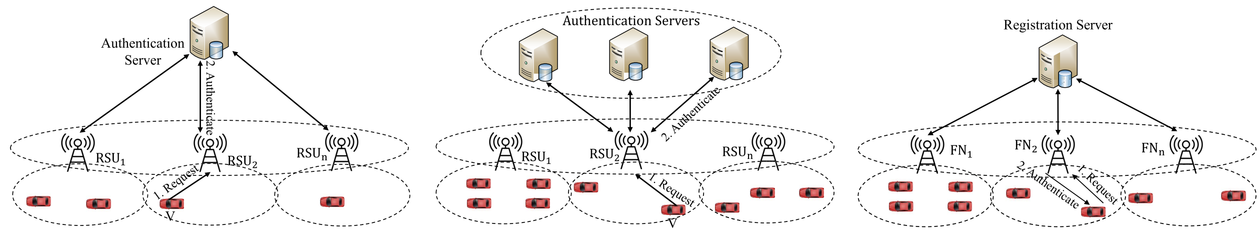
I. Introduction

The advanced sensing and communication technologies have been integrated into vehicles to make them more intelligent. Through dedicated short-range communication (DSRC) [1] or LTE V2X technology [2], [3], vehicles can interact with other vehicles or infrastructures to share and exchange information, which forms vehicular networks that have been well recognized as one of the potential components to achieve intelligent transportation systems (ITS). A typical vehicular network is composed of vehicles and infrastructures named roadside units (RSU) that are sparsely deployed over roads. With vehicular networks, RSUs can broadcast critical information such as traffic accidents and road conditions to surrounding vehicles which can improve the driving safety and the energy efficiency of road travel, while in the meantime vehicles can request services such as downloading navigation maps and automated valet parking upon driving through the communication area of a certain RSU. For example, a project in Europe called SCOOP [4] has been built for deploying cooperative intelligent transport systems based on vehicular networks in order to improve road safety. Especially, with the interconnection and accessibility problems of vehicular networks having been firstly addressed by Cheng *et al.* [5], it becomes more practical to deploy vehicular networks for ITS.

Similar to other wireless networks, in vehicular networks, data is transmitted directly over the air, which means the communication channel is vulnerable to adversaries and various security threats like impersonation, replay and man-in-the-middle attacks [6]–[8] could be launched. Security is an essential factor to ITS, since illegally accessing or tampering data may lead to severe consequences and threaten national security. Specifically, to ensure that only authorized vehicles



(a) Type 1: Vehicles are authenticated by a central authentication server.

(b) Type 2: Vehicles are authenticated by multiple authentication servers.

(c) Type 3: Vehicles are authenticated by fog nodes.

Fig. 1. Three existing authentication architectures in vehicular networks.

can request services (e.g., wireless network access), it is critical to verify the authenticity of vehicles. Due to the high mobility of vehicles and the limited communication range of RSUs (e.g., 300-500 meters) [9], a moving vehicle may stay within a specific RSU only for a short time and may need to reconnect to another RSU frequently, which means the vehicle is supposed to be authenticated. However, frequent authentication may severely degrade the quality of networking services for vehicles. As a consequence, designing an effective authentication scheme for vehicular networks confronts more challenges.

A common authentication method as shown in Figure 1(a) is to employ an authentication server (AS) (e.g., an AS is employed by the Department of Motor Vehicles in U.S.) to store some "secret information" about the vehicle during the registration, which can further be exploited to authenticate the vehicle by the AS later on. When a vehicle requests for some networking service, it needs to authenticate itself to AS through an RSU. However, when the number of vehicles becomes large, the burden of authenticating all the vehicles at the same time is extremely large for the single AS which turns out to be a bottleneck of the system and also leads to the single point of failure problem. To avoid these issues, an improved authentication architecture is shown as in Figure 1(b), which employs multiple ASs to authenticate vehicles. A proper protocol under this architecture can indeed amortize the authentication burden and mitigate the single point of failure issue, but it also inevitably poses delay because of the interaction between the RSU and the remote ASs. To avoid the authentication delay, some researchers [10], [11] proposed to delegate the authentication functionality to fog nodes (e.g., RSUs) which are close to vehicles compared with remote authentication servers. This kind of architecture as shown in Figure 1(c) indeed reduces the authentication latency, but it does not consider the fog node compromise attack. Once a fog node is controlled, the security of the system is broken.

To cope with all the above challenging issues, we propose a new edge-assisted decentralized authentication architecture (EADA) for vehicular networks. The architecture includes three types of parties, i.e., a registration server (RS), edge nodes (EN) (e.g., RSUs and BSs), and vehicles. Specifically, RS is in charge of registration and revocation for vehicles and ENs, while ENs cooperatively authenticate vehicles and each vehicle can authenticate the ENs as well. Within this architecture, a vehicle requesting services can be authenticated by ENs directly without the assistance of the remote RS. This can reduce the computation and communication overhead as well as the authentication delay compared with the traditional authentication architecture. Note that RS only takes care of the registration and management (e.g., update and revocation of a registered vehicle) and thus can be offline during the authentication phase, which makes it more difficult for attackers to compromise RS. Furthermore, to resist the single point of failure problem, we propose to employ threshold cryptosystems [12] where multiple ENs collaboratively authenticate a vehicle. In this case, even compromising a limited number of ENs will not disrupt the system. In summary, the contribution of this article is briefly summarized as follows.

- We propose an edge-assisted decentralized authentication architecture (EADA) for vehicular networks, where the authentication capability is delegated to distributed edge nodes (e.g., RSU and BS). This architecture can assist in providing more communication-efficient authentication since the ENs are introduced as middlewares between vehicles and the registration server.
- Under the authentication architecture, we propose a scalable threshold mutual authentication protocol supporting fast handover, which is divided into two cases: Auth-I and Auth-II. Auth-I only happens once when a vehicle tries to access the network for the first time, while Auth-II happens when a vehicle seamlessly roams between two ENs. Specifically, for Auth-I, each vehicle can be cooperatively authenticated by t out of n ENs with identity-based signature techniques to obtain an authentication token and the involved ENs can be efficiently authenticated in a batch by the vehicle. For Auth-II, the vehicle can precompute its authentication credentials based on the token that is regarded as its secret to achieve fast handover by its nearest EN based on identity-based signature without interacting with multiple ENs, which further reduces the authentication delay significantly.
- We propose a flexible method to support dynamic joining and leaving of ENs without the involvement of a trusted center.

Furthermore, we provide a comprehensive security analysis and evaluate the performance of the proposed protocol. We also conduct a series of comparison experiments and the experimental results show that our protocol is efficient in terms of both computation complexity and communication latency.

The remainder of this article is organized as follows. In Section II, we revisit existing works that are related to ours. Then we introduce preliminaries to be used in design of the proposed scheme in Section III. In the next section, system model, security model and design goals are defined. The proposed protocol is elaborated in Section V, followed by the security analysis and performance evaluation of the proposed protocol. Finally, we make a conclusion of this article in Section VIII.

II. Related Work

To provide secure communication for vehicular networks, Raya and Hubaux [6] proposed to utilize PKI as a building block for vehicle authentication where the certificates of vehicles were transmitted along with the credentials. After that, many different authentication protocols [5], [13]–[30] have been presented with focusing on distinct functionalities. For example, Jiang *et al.* [14] had concerns of the efficiency of vehicular authentication protocols that adopt certificate revocation lists (CRL), since it is necessary to query the CRL and the certificate of a vehicle in order to verify its authenticity, both of which are time consuming. Instead of the CRL method, they proposed to check the revocation status of a vehicle by a fast HMAC function which can reduce the authentication delay significantly. He *et al.* [16] and Azees *et al.* [17] dealt with the efficiency of conditional privacy-preserving authentication protocols. Zhang *et al.* [19] proposed a distributed aggregate authentication scheme for vehicular networks. They considered RSUs as lower-level trusted authorities which are enrolled by a root trusted authority. Vehicles can register to any of these RSUs and achieve the authentication based on their identities and public keys of the RSUs. Hao *et al.* [31] and Jo *et al.* [18] proposed cooperative message authentication where multiple vehicles collaboratively verify a message in order to reduce the authentication cost on individual vehicles. Zhang *et al.* [15] proposed a novel Chinese remainder theorem (CRT)-based conditional privacy-preserving authentication protocol, which only requires realistic TPDs instead of ideal TPD. This will greatly promote the deployment and application of the authentication protocol in VANETs. These message authentication protocols focus on guaranteeing the authenticity of the party who sends the messages and cannot be directly adapted to user authentication in service-oriented systems.

Huang *et al.* [10] introduced the concept of vehicular fog computing that integrates vehicular networks with fog computing techniques. Specifically, RSUs are regarded as fog nodes which can help process requests from vehicles. Thakur and Malekian [32] employed fog computing based connected vehicles to handle vehicular congestion. Yao *et al.* [11] proposed a blockchain-based anonymous authentication for distributed vehicular fog services. In their protocol, only the fog node closest to the vehicle is required to authenticate vehicles, after which the fog node broadcasts the authentication result to other fog nodes and record the results to blockchain. Therefore, their protocol did not consider fog node compromise attack. Once a fog node is controlled or compromised, the reported result to the blockchain could be misleading. Cui *et al.* [33] introduced edge computing into authentication for vehicular networks, where parts of vehicles are considered as the edge nodes to assist RSUs to authenticate other nearby vehicles. After that, RSUs broadcast the authentication results for the messages through a cuckoo filter. The legitimacy of these messages is thus able to be quickly determined by querying the filter later. Ma *et al.* [13] proposed a secure authenticated key agreement protocol for fog-based vehicular networks which does not utilize bilinear pairing and thus becomes very computationally efficient. Nevertheless, they employ the remote cloud server (i.e., the authentication server) instead of fog nodes to authenticate vehicles and thus cannot avoid the delay between the cloud server and the fog nodes.

Shao *et al.* [34] designed a threshold authentication protocol for vehicular networks, in which a message should be accepted only after it has been verified by a threshold number of vehicles. Nevertheless, their work considered message authentication instead of user authentication and therefore cannot be applied to solve the problems defined in this article. Malik *et al.* [35] proposed to authenticate vehicles assisted with blockchain technology, which can avoid the single-point-of-failure problem. However, the authentication delay includes the time when RSUs query certificates from the blockchain which is not discussed in that paper. Park *et al.* [36] proposed an efficient RSU-based distributed group key management for vehicular networks, where the key distribution center takes charge of vehicles membership updates and each RSU is responsible for generating and managing keys for its serving vehicles. Different from their scenario, we consider that the fog nodes (e.g., RSUs) could be compromised by attackers and thus do not manage keys for vehicles in this article.

Except for normal authentication, handover is introduced to enable mobile devices to seamlessly and securely roam among multiple access points in mobile wireless networks. Likewise, in vehicular networks, when a vehicle moves to a new access point (the coverage of a new RSU), the handover authentication should allow the new access point to authenticate the vehicle as well. There have been a lot of handover authentication protocols designed in the literature [37]–[39]. As mentioned in the introduction part, all these authentication protocols require active participation of the authentication server, which will cause delay due to the interaction between the access point and the remote authentication server. As a contrast, our proposed architecture delegates the authentication to local edge nodes which thus eliminates the handoff delay across multiple RSUs.

III. Preliminary

A. Bilinear Pairing

Let G and G_T be an additive and multiplicative cyclic group respectively, both with order q (q is a large prime). Practically, G may be implemented utilizing a group of points on some elliptic curve over a finite field while G_T may be implemented utilizing a multiplicative subgroup of a finite field. A map $e : G \times G \to G_T$ is said to be an admissible bilinear pairing if it satisfies the following properties:

1) *Bilinear:* $e(aP, bQ) = e(P, bQ)^a = e(aP, Q)^b = e(P, Q)^{ab}$ for any $P, Q \in G$ and any $a, b \in Z_q^*$.

2) *Non-degenerate:* there exists $P \in G$, so that $e(P, P) \neq 1$ (i.e., $e(P, P)$ is a generator of G_T).
3) *Computable:* there exists an efficient algorithm to compute $e(P, Q)$ for any $P, Q \in G$.

B. Threshold Cryptography

First introduced by Shamir [40], a (t, n)-threshold scheme allows a dealer owning a secret $s \in Z_q^*$ to distribute its secret to n parties, so that any t or more out of the n shareholders are able to reconstruct s while less than t parties cannot reveal any information about s even they collude. This can be done with the following steps. The dealer selects a polynomial $f(x)$ over Z_q of degree $t-1$ so that $s = f(0)$ and sends each party an evaluation of $f(x)$ on points $i = 1, \cdots, n$ (i.e., $(f(i))$. Then given any subset of t pairs from the set of $\{(i, f(i))\}$, without loss of generality saying $(i_1, f(i_1)), \cdots, (i_t, f(i_t))$, the secret s can be recovered by $s = \sum_{j=1}^{t} f(i_j) \prod_{l \neq j} \frac{i_j}{i_j - i_l}$. Based on Shamir's work, various threshold signature schemes [41]–[45] have been constructed. A typical application is to use threshold signature for authentication purpose to prevent single point of failure [34], [46]–[48], which is also the usage purpose in this article.

C. Mathematical Assumptions

The security of the proposed protocol is based on the intractability of some mathematical assumptions which are described as follows.

1) Discrete Logarithm (DL) Assumption: Given a generator $P \in G$ and a random chosen element $X \in G$, there is no probabilistic polynomial adversary who can find an integer $a \in Z_q^*$ so that $X = aP$ with non-negligible probability.

2) Computational Diffie-Hellman (CDH) Assumption: Given a tuple of $(P, aP, bP) \in G^3$ with randomly selected a, b from Z_q^*, there is no probabilistic polynomial adversary who can compute $abP \in G$ with non-negligible probability.

3) Bilinear Diffie-Hellman (BDH) Assumption: Given a tuple of $(P, aP, bP, cP) \in G^4$ with randomly selected a, b, c from Z_q^*, there is no probabilistic polynomial adversary who can compute $e(P, P)^{abc} \in G_T$ with non-negligible probability.

IV. SYSTEM MODEL, THREAT MODEL, AND DESIGN GOALS

A. System Model

As shown in Figure 2, we consider an edge-assisted vehicular network which comprises a registration server, a number of edge nodes (acting as authentication servers) and vehicles. Edge nodes are connected with diverse service providers through secure high-bandwidth backbone networks and thus can provide various services to legitimate vehicles. The detail of each entity is elaborated as follows:

- **Registration Server (RS)**: it is a trusted party that initializes the whole system and takes care of the registration of vehicles and ENs. Upon registration, RS generates secret keys for vehicles and ENs that would be used in authentication phase. It is also responsible for notifying the update information of vehicles such as joining or revocation to ENs. Once the registration is done, RS could be offline since the authentication procedure can be finished by vehicles and ENs themselves.
- **Vehicle**: a vehicle is an end-user that wants to gain services from vehicular networks. Each vehicle is installed with on-board units that are used to communicate with ENs. In general, vehicles have adequate computational resource and storage capability to perform public cryptography operations, which is practical considering the powerful CPU that modern vehicles have.
- **Edge Node (EN)**: an EN(e.g., RSU or a BS) is located on the roadside and can interact with vehicles directly. The authentication capability is distributed to a set of ENs from traditional authentication servers. Namely, whenever an EN receives a request message from vehicles under its coverage, it will authenticate the vehicle, collaboratively with other ENs if necessary. The computational and storage capabilities of ENs should be far greater than vehicles.

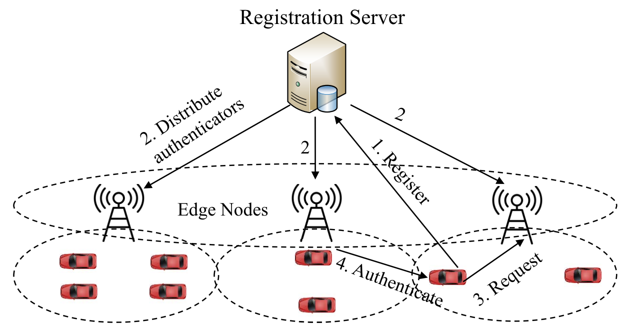


Fig. 2. The proposed edge-assisted decentralized authentication architecture for vehicular networks.

With the above entities, we briefly introduce how the system works from scratch as shown in Figure 2. First, all the vehicles and ENs register to RS with their identities to obtain their individual private keys. Then when a vehicle V enters the communication range of an EN, it can request for expected services through the EN. Before obtaining the access permission, V should be authenticated. If it is V's first request without a valid token, V will be authenticated by a set of ENs together and meanwhile these ENs could also be authenticated by V. If all parties pass the authentication, these ENs will collaboratively generate a valid token with an expiry time to V. If V has already a valid token, it can be fast authenticated by its nearest EN based on this token.

B. Threat Model

The registration server RS is assumed to be a trusted party and cannot be compromised. Thus, it will honestly follow the protocol to provide registration and membership updates services. Vehicles are considered to be malicious in sense that they may try to forge valid tokens to pass the authentication. Similarly, ENs could be malicious or compromised by attackers. However, to ensure the system security, we assume that attackers can only compromise a limited number of ENs, where the value of the number is defined according to the system parameter. The communication channel between vehicles and ENs is vulnerable to attackers. Namely, attackers can eavesdrop, inject, send and even modify messages transmitted on the channel. The communication channel among different ENs is assumed to be secure against the adversary by utilizing existing techniques like Transport Layer Security protocol (TLS). With the above assumption, we consider a probabilistic polynomial adversary which may launch the following attacks:

1) *Replay attack:* an attacker eavesdrops and records previous transaction transcripts between vehicles and ENs and then disguises as a legitimate vehicle using the recorded transcripts in order to pass a new authentication with the ENs.
2) *Impersonation attack:* an attacker impersonates a legitimate vehicle to convince the ENs to accept it as the legitimate vehicle so that it can obtain the access permission.
3) *EN compromise attack:* an attacker could compromise a set of ENs, aiming to break down the authentication mechanism so that it can abuse the services. Namely, it can grant access permissions to any vehicles no matter they are legal or not.
4) *Wasting network resources attack:* an attacker can flood a large number of requests to a specific EN which will forward these requests to other ENs for collaborative authentication, with the purpose to waste the network resources.
5) *Token forgery attack:* an attacker may forge an authentication token without secret keys in order to pass the authentication.

C. Design Goals

Based on the system model and security threats elaborated above, we define a series of design goals for the proposed threshold authentication protocol in terms of three aspects: efficiency, security, and scalability, elaborated as the following.

1) Efficiency: The communication delay caused by authenticating vehicles should be reduced as much as possible. The protocol should also be efficient in terms of computation complexity.

2) Security: The proposed protocol should satisfy the following security requirements.

- Mutual Authentication: It should achieve mutual authentication between vehicles and ENs. Namely, vehicles can authenticate ENs and vice versa.
- Secure Token Generation: The final composite token should only be able to be generated by an authenticated vehicle through aggregating the pieces of token shares from multiple ENs. Note that ENs themselves cannot produce a final token even $t-1$ of them collude with each other.
- Attacks Resistance: It should be secure against the above five attacks.

3) Scalability: Scalability means that the proposed protocol should support dynamic property in terms of update of vehicles and ENs.

- Update of Vehicles: It should support secure and efficient update of vehicles including joining and revocation. In particular, a newly joined vehicle should be authenticated by ENs as normally as existing ones, while revocation of a vehicle requires that the vehicle cannot request for services anymore even with its previous private keys.
- Update of ENs: It should support secure and efficient update of ENs including joining and revocation. Specifically, a newly joined EN should be able to authenticate any vehicle together with other ENs, while a revoked EN cannot be exploited by any adversary to authenticate vehicle uers jointly with other ENs.

V. The Proposed Threshold Mutual Authentication Protocol

A. Design Challenges and Our Ideas

Putting forward a specific protocol that can achieve all the security goals is not trivial. Several design challenges are supposed to be carefully addressed.

- First, the property of multiple ENs verifying a single vehicle provides a natural environment for attackers to launch a flooding attack. Specifically, an attacker could simply flood a large number of requests, each of which will be checked by multiple ENs. This flooding attack will definitely waste the whole network resources. In order to prevent this attack, we propose to set up a leader EN (e.g., the first EN which receives the vehicle's request) and requires the leader EN to verify the request first before forwarding it to other ENs. If the request is not valid, the leader EN rejects the vehicle immediately and will not forward it. One possible vulnerability of this method is that if the leader EN is compromised then it could be controlled by the attacker to intentionally reject legitimate vehicles' requests. Fortunately, since vehicles are usually highly moving from one place to another, the duration of service interruption caused by a compromised EN is quite limited. Namely, once the vehicle enters another EN's communication range, it can request services from the new leader EN.
- In addition, it is also subtle to provide certificateless mutual authentication between vehicles and ENs. In particular, ENs need to authenticate vehicles before providing services, while vehicles also need to ensure that they are requesting services from legitimate ENs. A naive way to achieve this is to employ PKI-based signatures, but the large number of vehicles makes it impractical for each EN to query the certificates of vehicles whenever authenticating them. To address this issue, we adapt identity-based signatures for ENs to authenticate vehicles. On the other hand, for vehicles authenticating ENs, it is acceptable to require vehicles to query for ENs' certificates since the number of ENs is fractional to that of vehicles.
- Finally, the proposed protocol should also support secure update of vehicles and ENs such as joining or revocation. For example, a revoked vehicle should not be able to utilize its previous secrets to generate a valid token, while

a revoked EN should not be able to have the power to cooperate with other ENs to authenticate any vehicle. We associate a state with each vehicle in order to manage the update of vehicles, while we propose a distributed method to securely update the authentication information stored on ENs in terms of joining or leaving of the ENs, respectively.

B. Protocol Design

We elaborate the proposed authentication protocol which contains setup phase, registration phase, and authentication phase. We divide the authentication phase into two cases: Auth-I which is the first authentication with token generation phase and Auth-II which is the second and future authentication phase due to the requirement of fast handover authentication when a vehicle moves from the radiation coverage of one EN to another. Intuitively, in Auth-I a vehicle V is collectively authenticated by at least t out of n ENs from the set $\{F_1, \cdots, F_n\}$, while in Auth-II, V can be efficiently authenticated with the token by its nearest EN.

1) Setup Phase: In the system setup, a bilinear map $e : G \times G \rightarrow G_T$ is created by RS, where G is an additive cyclic group with order q and P is a generator of G, and G_T is a multiplicative cyclic group with order q. Four cryptographic hash functions H, H_1, H_2 and H_3 are selected, where H is defined as $H : \{0,1\}^* \rightarrow G$, H_1 is defined as $H_1 : \{0,1\}^* \times G \rightarrow G$, H_2 is defined as $H_2 : G_T \rightarrow G$, and H_3 is defined as $H_3 : G_T \rightarrow \{0,1\}^*$. Then, RS chooses a random element x from Z_q^* as its master secret key and thus the master public key is $P_{pub} = xP$.

In addition, RS chooses another random element s from Z_q^* and divides it into n shares $s_i (1 \leq i \leq n)$ with a (t, n)-secret sharing scheme, so that any t or more shares of s_i can be combined to recover the secret s. Note that s is the composite secret key that will be used to compute the composite token and the corresponding public verification key is $P_S = sP$. To distribute the secret key s, RS selects a random polynomial function with degree of $t-1$ as Equation 1.

$$f(x) = s + a_1 x + a_2 x^2 + \cdots + a_{t-1} x^{t-1} \mod q \quad (1)$$

where $a_1, \cdots, a_{t-1} \in Z_q^*$ are randomly chosen polynomial coefficients. RS sets $s_i = f(i)$ as the secret key of EN $F_i (i \in [1, n])$ and sends s_i to F_i through a secure channel. The corresponding public key of F_i becomes $PK_{F_i} = s_i P$. RS then publishes these public keys: P_{pub}, P_S and $PK_{F_i} (i \in [1, n])$.

2) Registration Phase: In this phase, a vehicle V sends its identity ID_V to RS which computes the corresponding private key for V as $sk_V = xH(ID_V)$. In practice, ID_V could be the VIN (vehicle identification number) that is a unique code used to identify individual vehicles. In addition, for each vehicle, there is a one-bit state $st \in \{0, 1\}$ which indicates the registration state. Namely, $st = 1$ means that it is registered as a legitimate vehicle while $st = 0$ means it has been revoked. Once the registration is successful, RS will set the vehicle's state to be 1 and send all pairs of (ID_V, st_V) to each of the ENs.

3) Auth-I Phase: This phase includes two steps: a vehicle is firstly authenticated by a set of ENs which then collaboratively generate a valid token that can be used as the authentication credential for Auth-II phase. The proposed protocol achieves mutual authentication, i.e., vehicles and ENs can authenticate each other. A vehicle V is authenticated collectively by $T(|T| = t)$ ENs. Since V could be only in the communication range of certain EN(w.l.o.g., say F_i) at any time, it is necessary to require F_i to forward V's request information to other ENs. F_i thus becomes the leader EN. Specifically, the procedure of Auth-I is elaborated as follows.

1) A vehicle V that requests a service selects a random element r_1 from Z_q^*, and computes $R_1 = r_1 \; H(ID_V)$, $R_2 = r_1 \; P$, and $Y = r_1(sk_V + H_1(ID_V||TS||R_1))$, where TS is a timestamp, and "$||''$ means a concatenation operation. We assume that all the entities including vehicles and ENs can loosely synchronize their time clocks with some existing time synchronization techniques like GPS. Then V sends a request $req = (ID_V, Y, R_1, R_2, TS)$ to the leader EN F_i whose communication range covers V.
2) Upon receiving the request information, F_i will perform the following actions.
   a) It first checks whether the difference between the timestamp TS and the current time is within a given threshold in order to prevent replay attacks. In addition, it also checks the registration state st_V of the corresponding vehicle V by searching from its database. If $st_V = 1$, then it goes on with the sequential steps.
   b) It authenticates V by checking Equation 2. If the checking does not pass, it rejects V immediately.
   $$e(Y, P) \stackrel{?}{=} e(R_1, P_{pub}) \cdot e(H_1(ID_V||TS||R_1), R_2) \quad (2)$$
   c) It generates a composed string EXP which may include V's identity/attribute information ID_V, the expiration time and a policy that would control the nature of access. Then it computes a signature σ_i on EXP by $\sigma_i = s_i \cdot H(EXP)$. Typically, σ_i is the partial token generated by F_i. Finally, F_i forwards V's request information req together with EXP to the other ENs.
   d) It selects a random element r_2^i from Z_q^* and computes $U_i = e(H(ID_V), P_{pub})^{r_2^i}$, $W_i = \sigma_i \oplus H_2(U_i)$, $C = EXP \oplus H_3(U_i)$ and $V_i = r_2^i \; P$.
   e) Meanwhile, for the other ENs $F_j (j \in [1, n], j \neq i)$, we assume a set of at least $t-1$ ENs are ready to collaboratively authenticate V and generate a valid token together with F_i. They do the same actions as F_i to authenticate V and accept the legitimacy of EXP. Then they generate and return their individual V_j and W_j to F_i. By far, F_i and the other cooperative ENs constitute a set $T(|T| \geq t)$.
   f) It sends all the pairs of $(V_k, W_k)(k \in T)$ and C to V. It also computes $K = H_3(Y||U_i)$ which is the session key that will be used between it and V for secure communication purpose.

3) Upon receiving the messages from F_i, V will do the following actions.
   a) It recovers EXP by $EXP = C \oplus H_3(e(sk_V, V_i))$. Note that this holds because $e(sk_V, V_i) = e(xH(ID_V), r_2^i\ P) = e(H(ID_V), P_{pub})^{r_2^i} = U_i$.
   b) For all $k \in T$, V recovers $\sigma_k = W_k \oplus H_2(e(sk_V, V_k))$. Then, it checks whether Equation 3 holds which allows V to efficiently authenticate multiple ENs in a batch instead of authenticating them individually. If the batch verification fails, we can employ the "divide-and-conquer" method to identify the invalid signatures. The basic idea is to divide the set of signatures into two subsets and do the batch verification respectively. This procedure is iteratively exceeded until all the invalid signatures are found out. If for some $\ell \in T$, the signature σ_ℓ is invalid, then it means F_ℓ is illegitimate and thus is rejected. Then V reports this error to F_i so that F_i can ask for another EN for cooperation.

$$e(\sum_{k \in T} \sigma_k, P) \stackrel{?}{=} e(H(EXP), \sum_{k \in T} PK_{F_k}) \quad (3)$$

   c) It computes $\sigma = \sum_{k \in T} \omega_k \sigma_k = \sum_{k \in T} \omega_k s_k H(EXP) = sH(EXP)$ where $\omega_k = \prod_{\ell \in T, \ell \neq k} \frac{\ell}{\ell - k}$. If σ_k is valid, then σ must be valid as well since σ is computed based on σ_k using polynomial interpolation. σ is essentially the token that are generated by aggregating t shares of the token from multiple ENs collaboratively. It also computes the session key with $K = H_3(Y|| e(sk_V, V_i))$. This finishes the session key establishment since $H_3(Y||e(sk_V, V_i)) = H_3(Y|| e(xH(ID_V), r_2^i\ P)) = H_3(Y||e((H(ID_V), P_{pub}))^{r_2^i}) = H_3(Y||U_i)$.

   Note that in our scheme, only the vehicle V itself can do the aggregation since each partial token is encrypted with V's public key. This can avoid the attack in which an adversary compromises only one EN and pretends to be a leading EN to collect $t-1$ pieces of partial tokens from other ENs and consequently obtain the composite token. Actually, even $t-1$ ENs are compromised, the attacker still cannot generate a valid token.

4) Auth-II Phase: Once a vehicle V finishes the first authentication, it will obtain a token σ together with the string EXP for its future authentication before the expiry date indicated in EXP. Actually, we can consider σ as V's secret credential that can be used for future fast authentication purpose while EXP is the auxiliary information. In the Auth-II phase, V just needs to show that it holds a valid token to its nearby EN upon requesting services. Suppose V that holds a valid token σ and EXP moves into the communication area of a new edge node F_k and requests to connect to the vehicular networks. Then the mutual authentication between V and F_k is elaborated as follows.

1) V selects a random element r_3 from Z_q^*, and computes $R_3 = r_3\ H(EXP)$, $R_4 = r_3\ P$, and $Y_2 = r_3(\sigma + H_1(EXP||TS||r_3\ PK_{F_k}))$, where TS is a timestamp, and "$||$" means a concatenation operation. Then V sends a request $req = (ID_V, EXP, Y_2, R_3, R_4, TS)$ to F_k. Meanwhile, V also computes the session key as $K = H_3(r_3\ PK_{F_k})$.
2) Upon receiving the request information, F_k first checks the validity of TS and the registration state st_V of V by searching from its database. If both are valid, it authenticates V by checking Equation 4 with its secret key s_k. If the check does not pass, it rejects V immediately. Otherwise, it calculates the session key as $K = H_3(s_k R_4)$.

$$e(Y_2, P) \stackrel{?}{=} e(R_3, P_S) \cdot e(H_1(EXP||TS||s_k R_4), R_4) \quad (4)$$

If everything goes smoothly, V can communicate with F_k securely with the session key K, since $K = H_3(r_3\ PK_{F_k}) = H_3(r_3\ s_k P) = H_3(s_k R_4)$. Note that V can pre-compute the request information just before moving into the new area so that the authentication delay can be further reduced.

C. Correctness Proofs of the Equations

We will prove the correctness of equation 2, equation 3 and equation 4. Namely, ENs can indeed authenticate a vehicle through Equation 2 while each vehicle can aggregately authenticate a bunch of ENs at the same time by Equation 3. On the other hand, in Auth-II phase, V can be fast authenticated by any edge node F_k.

First, we have:

$$\begin{aligned} e(Y, P) &= e(r_1(sk_V + H_1(ID_V||TS||R_1)), P) \\ &= e(r_1\ xH(ID_V), P) \cdot e(r_1\ H_1(ID_V||TS||R_1), P) \\ &= e((r_1\ H(ID_V), xP) \cdot e(H_1(ID_V||TS||R_1), r_1\ P) \\ &= e(R_1, P_{pub}) \cdot e(H_1(ID_V||TS||R_1), R_2) \end{aligned}$$

which indicates the correctness of Equation 2.

Then, for the correctness of Equation 3, we have

$$\begin{aligned} e(\sum_{k \in T} \sigma_k, P) &= e(\sum_{k \in T} s_k H(EXP), P) \\ &= e(H(EXP), \sum_{k \in T} s_k P) \\ &= e(H(EXP), \sum_{k \in T} PK_{F_k}). \end{aligned}$$

Finally, for the correctness of Equation 4, we have

$$\begin{aligned} &e(Y_2, P) \\ &= e(r_3(\sigma + H_1(EXP||TS||r_3\ PK_{F_k})), P) \\ &= e(r_3\ sH(EXP) + r_3\ H_1(EXP||TS||r_3\ PK_{F_k}), P) \\ &= e(r_3\ sH(EXP), P) \cdot e(r_3\ H_1(EXP||TS||r_3\ PK_{F_k}), P) \\ &= e(r_3\ H(EXP), sP) \cdot e(H_1(EXP||TS||r_3\ s_k P), r_3\ P) \\ &= e(R_3, P_S) \cdot e(H_1(EXP||TS||s_k R_4), R_4) \end{aligned}$$

D. Enabling Update of Vehicles and ENs

The proposed protocol supports secure update of vehicles and ENs where update includes a new entity joining and a current entity revocation. Note that achieving update functionality is not trivial since an improper design could occur security issues. We will elaborate how our protocol can support the update of both vehicles and ENs, and at the same time can avoid potential attacks.

1) Update of Vehicles:

a) Joining of a Vehicle: Whenever a new vehicle V hopes to join in the system, it can first register with its ID_V to RS and obtain the corresponding secret key $xH(ID_V)$. RS sets its registration state $st_V = 1$ and sends (ID_V, st_V) to all the n ENs. By far, V joins in the system successfully.

b) Revocation of a Vehicle: In case that a vehicle V is scrapped or stolen, the owner should notify RS which will set the corresponding registration state st_V to be 0 and sends (ID_V, st_V) to all the ENs. Upon receiving the record, each EN replaces the value of st_V with the new one. By doing this, if there is a request sent from the same ID_V, it will be rejected immediately. To avoid infinite growth of the table size on the EN side, we can optionally require RS to associate an expiration time for the revocation list. For example, if the fact that $st_V = 0$ has lasted more than half a year, ENs can remove the related records about V from the database.

2) Update of ENs:

a) Joining of an EN: When a new EN requests to join in the authentication server group, it needs to obtain its secret share of s. The total number of ENs becomes $n+1$ and the threshold value becomes t', which results in a $(t', n+1)$-secret sharing. We will show how the secret s can be redistributed from original n shares to new $n+1$ shares (from (t, n)-sharing to $(t', n+1)$-sharing) without the involvement of RS.

- First, all of the $n+1$ ENs interact with each other to negotiate a common set $T(|T| = t)$ from original n ENs.
- Each EN F_i in T divides its secret share s_i into $n+1$ pieces $s_{ij}\,(j \in [1, n+1])$ with the following polynomial function
$$f(x) = s_i + b_{i1}x + b_{i2}x^2 + \cdots + b_{i(t'-1)}x^{t'-1} \mod q \quad (5)$$
where $b_{i1}, \cdots, b_{i(t'-1)} \in Z_q^*$ are randomly chosen coefficients. Then F_i sends $s_{ij} = f(j)$ to EN $F_j (j \in [1, n+1], j \neq i)$.
- When F_j receives s_{ij} from all the ENs in the set of T, it can reconstruct a new secret share s'_j of s by Equation 6.
$$s'_j = \sum_{i \in T} \prod_{\ell \in T, \ell \neq i} \frac{\ell}{\ell - i} s_{ij} \quad (6)$$

By far, all the ENs in the new authentication group constitute a $(t', n+1)$-sharing structure, where any t' out of $n+1$ ENs can collaborate to authenticate a vehicle and generate a valid token.

b) Revocation of an EN: When an EN is revoked with some reason, the secret keys should also be redistributed among the rest ENs so that the revoked EN cannot take participation in authenticating vehicles anymore. In this case, the total number of ENs becomes $n-1$ and the threshold value becomes t'', which results in a $(t'', n-1)$-secret sharing. We will show how the secret s can be redistributed from original n shares to new $n-1$ shares (from (t, n)-sharing to $(t'', n-1)$-sharing).

- First, all of the $n-1$ ENs interact with each other to negotiate a common set $T(|T| = t)$ of ENs.
- Each EN F_i in T divides its secret share s_i into $n-1$ pieces $s_{ij}\,(j \in [1, n-1])$ with the following polynomial function
$$f(x) = s_i + c_{i1}x + c_{i2}x^2 + \cdots + c_{i(t''-1)}x^{t''-1} \mod q \quad (7)$$
where $c_{i1}, \cdots, c_{i(t''-1)} \in Z_q^*$ are randomly chosen coefficients. Then F_i sends $s_{ij} = f(j)$ to EN $F_j (j \in [1, n-1], j \neq i)$.
- When F_j receives s_{ij} from all the ENs in the set of T, it can reconstruct a new secret share s''_j of s by Equation 8.
$$s''_j = \sum_{i \in T} \prod_{\ell \in T, \ell \neq i} \frac{\ell}{\ell - i} s_{ij} \quad (8)$$

By far, all the ENs in the new authentication group constitute a $(t'', n-1)$-sharing structure, where any t'' out of $n-1$ ENs can collaborate to authenticate a vehicle and generate a valid token.

c) Update of ENs' Keys: Although we assume that the number of compromised ENs is up to $t-1$, an empirical attacker could compromise more than t ENs gradually in the sense that it can break one EN at this time and break another later on. As a consequence, the attacker can finally corrupt more than t ENs and break the system security over time. Although it is beyond the security model defined in this article, this is a very practical issue. To avoid this issue, the ENs should redistribute their secret keys periodically so that breaking $t-1$ ENs provides no advantages for the attacker to break a new one. The update of keys of ENs can be simply achieved using the similar decentralized key redistribution technique employed to achieve the update of ENs as shown in V-D.2 and is thus omitted for simplicity.

E. Discussion

In the proposed protocol, we assume that the registration server RS is a trusted party for simplicity. However, in practice, RS could represent a single point of failure. We discuss why we make this assumption and explain how to remove it. On one hand, RS is in charge of registration and revocation for vehicles and edge nodes, and thus it can be offline during the authentication phase which happens most frequently. Less time when connected with the networks provides attackers less transaction records which makes it more difficult for attackers to compromise RS. On the other hand, the single-point-of-failure issue could also be mitigated with a threshold cryptosystem. Namely, RS could be split into multiple sub-registration servers (Sub-RSs) which collaboratively take charge of the registration and revocation jobs. The master secret key can be distributed to these Sub-RSs with secret sharing schemes without a trusted party, where each Sub-RS can select its own secret key share and a threshold number of shares can be aggregated into a composite secret that serves as the master secret key. The key distribution of a secret sharing scheme without a trusted dealer has been well studied for many years and is not the highlight of this article, so we neglect the details and assume that RS is a trusted party.

VI. Security Analysis

In this section, we analyze the security of the proposed threshold mutual authentication protocol. In particular, we will discuss how the proposed protocol under the edge-assisted decentralized architecture can achieve all the security goals listed in section IV-C.

A. Mutual Authentication

The proposed protocol can achieve mutual authentication, i.e., vehicles and ENs can authenticate each other. We will discuss the details separately.

1) Authentication of Vehicles: In Auth-I phase, to authenticate a vehicle V, an EN first computes $H_1(ID_V||TS||R_1)$ upon receiving req and then checks whether Equation 2 holds. Only a legitimate vehicle with a valid secret key $sk_V = xH(ID_V)$ can generate a valid verifiable proof Y. An adversary without sk_V has to forge a valid $Y^* = xr^*H(ID_V) + r^*H_1(ID_V||TS||R_1^*)$ as well as $R_1^* = r^*H(ID_V)$ and $R_2^* = r^*P$ so that the proof can satisfy Equation 2. Even with the ability to eavesdrop previous transactions such as req that includes (Y, R_1, R_2), it cannot recover sk_V since r_1 is impossible to be recovered due to the intractability of the DL assumption. This essentially requires the adversary to construct a valid $xr^*H(ID_V)$ without knowing $xH(ID_V)$, the probability of which is obvious negligible. Thus, the authentication of vehicles can be achieved. Similarly, in Auth-II phase, the adversary has to construct a valid $sr_3^*\ H(EXP)$ without knowing $sH(EXP)$ in order to pass Equation 4, which again violates the DL assumption. Thus, the authentication of vehicles can be achieved.

2) Authentication of ENs: In Auth-I phase, to authenticate an EN F_i, a vehicle checks whether Equation 3 holds. Specifically, σ_i is a signature generated by F_i. Only a legitimate EN with the corresponding private key s_i can produce a valid signature. Since the signature algorithm is based on the BLS short signature [49], the security analysis of it can also be reduced to that of the BLS signature which has been formally provided in [49]. Thus, the authentication of each EN can be achieved. In Auth-II phase, the EN is implicitly authenticated during the session key establishment. Indeed, only a legitimate EN with the corresponding private key s_k can generate the correct s_kR_4 and thus the session key K.

B. Secure Token Generation

In the proposed protocol, a final composite token σ is generated by combing at least t pieces of token shares σ_i from the corresponding EN F_i $(i \in T)$ with threshold signature technique, i.e., $\sigma = \sum_{i\in T} \omega_i\sigma_i$. Each of the piece of token σ_i is encrypted upon sent to the vehicle V, i.e., $W_i = \sigma_i \oplus H_2(U_i)$ where $U_i = e(H(ID_V), P_{pub})^{r_2^i}$. Since σ_i is encrypted with the public key of V, only V with the valid private key sk_V can decrypt the message by $\sigma_i = W_i \oplus H_2(e(sk_V, V_i))$. If the BDH assumption holds, the encryption algorithm is secure. Thus, only the authenticated V can obtain all the t pieces of token shares which are further aggregated into the final composite token. Note that even up to $t-1$ ENs collude with each other, they cannot generate the composite token if the (t, n) threshold signature is secure which will be proven in Section VI-C.3.

C. Attacks Resistance

The proposed protocol can mitigate all the five attacks defined in Section IV-B. The detailed analysis is given as follows.

1) Replay Attack: To launch a replay attack, an attacker eavesdrops previous transcripts and tries to pass a new authentication session with the recorded transcripts. In particular, it records (ID_V, Y, R_1, R_2, TS) and sends the tuple to an EN F_i. Note that the proof (Y, R_1, R_2) cannot pass the authentication since Y includes the timestamp TS which has already expired. Thus, the proposed protocol is resistant to replay attack.

2) Impersonation Attack: To impersonate a legitimate vehicle V, an attacker has to generate a valid tuple of proof (ID_V, Y, R_1, R_2, TS). Without the secret key sk_V, it cannot produce a valid Y though. On the other hand, it could also forge a Y' based on previous Y such as $Y' = r'Y = r'r_1(sk_V + H_1(ID_V||TS||R_1))$. However, in this case, Y' includes an expired timestamp TS that can be detected by the ENs. Therefore, the attacker has no way to forge a valid proof. Namely, the impersonation attack can be effectively prevented.

3) EN Compromise Attack: If the (t, n) threshold signature is secure, then the proposed protocol can tolerate compromise of up to $t-1$ ENs. Namely, the attacker has secret keys of these ENs and tries to collaboratively authenticate a vehicle V and generate a valid access token σ for V. We will prove that even with this secret keys, the attacker cannot forge a valid token.

Without loss of generality, we assume that the $t-1$ compromised ENs are $(F_1, \cdots, F_{t-1})$ with secret keys $(s_1, \cdots, s_{t-1})$. The attacker can thus produce $t-1$ pieces of tokens $\sigma_i = s_i \cdot H(EXP)(1 \le i \le t-1)$. If the attacker can produce a valid token $\sigma = \sum_{i=1}^{t} \omega_i\sigma_i$, then it can compute $\sigma_t = (\omega_t)^{-1} \cdot (\sigma - \sum_{i=1}^{t-1} \omega_i\sigma_i) = (\prod_{j=1}^{t-1} \frac{j}{j-t})^{-1} \cdot (\sigma - \sum_{i=1}^{t-1} \prod_{j=1, j\neq i}^{t} \frac{j}{j-i}\sigma_i)$. This means that the attacker can compute the valid σ_t which should actually be $s_t \cdot H(EXP)$ without s_t. Namely, given $H(EXP) \in G$, P, s_tP, the attacker can compute $s_t \cdot H(EXP)$, which contradicts with the CDH assumption. Therefore, the attacker cannot produce a valid token with up to $t-1$ compromised ENs, i.e., our protocol is still secure even up to $t-1$ ENs are compromised.

TABLE I
COMPARISON BETWEEN THE PROPOSED PROTOCOL AND EXISTING PROTOCOLS

Scheme	Computational Cost		Authentication Delay	SPF Resistance*	F/ENCA Resistance**
	Vehicle	Fog/Edge/AS			
Azees *et al.* [17]	$2mt_p + (6\ell + 2)mt_{sm}$	$2mt_p + 7mt_{sm}$	$m(t_V + t_R + T_{VR})$	×	×
Cui *et al.* [33]	$4mt_{sm}$	$6mt_{sm}$	$m(t_V + t_R + T_{VR})$	×	×
Ma *et al.* [13]	$3mt_{sm}$	$12mt_{sm}$	$m(t_V + t_R + t_S) + m(T_{VR} + T_{RS})$	×	√
Our protocol	$(t+2)t_p + (4m-1)t_{sm} + (m+t+2)t_h$	$(3m+1)t_p + (m+2)t_{sm} + (m+3)t_h$	$t_V + t_R + m(t'_R + T_{VR})$	√	√

* SPF: single point of failure
** F/ENCA: Fog/Edge Node Compromise Attack
m: the number of authentication execution
ℓ, t: system parameters (constant)

4) Wasting Network Resources Attack: To launch a wasting network resources attack, an attacker keeps sending a large number of illegal requests to a specific EN which will forward the requests to other ENs for collaborative authentication. This will definitely waste the network resources. In the proposed protocol, whenever an EN receives a request from a vehicle, it first authenticates the request information before forwarding it to other ENs. If the authentication fails, it will rejects the vehicle immediately without forwarding. This can effectively mitigate the wasting network resources attack.

5) Token Forgery Attack: To launch a token forgery attack, an attacker tries to forge a token. In the proposed protocol, a token is generated based on threshold signature technique. To generate a valid token, the attacker needs to obtain the secret keys of at least t ENs. However, due to the hardness of the DL problem, it is computationally infeasible to reveal the secret key s_i from $PK_{F_i} = s_i P$. Thus, the proposed protocol can prevent token forgery attack.

D. Secure Update of Vehicles

Secure update of vehicles can be achieved by associating each vehicle with a one-bit state st_V. When a new vehicle V joins the system, upon registration, $st_V = 1$ is sent together with the identifier ID_V to all the n ENs. When a vehicle V is revoked (e.g., because of being scrapped or stolen), the owner notifies RS which will set $st_V = 0$ and send the updated state to all the ENs. Note that the communication between RS and ENs is based on a secure channel, so no attacker can obtain or modify the transcripts.

E. Secure Update of ENs

Secure update of ENs can be achieved by a distributed threshold key management which does not require the involvement of RS. First, we prove that in the case of a new EN joining the system, the constructed $(t', n+1)$-sharing is still a sharing of the secret key s as follows.

According to the construction, $s = \sum_{i\in T} \omega_i s_i$ and $s'_j = \sum_{i\in T} \omega_i s_{ij}$ where $\omega_i = \prod_{\ell\in T,\ell\neq i} \frac{\ell}{\ell - i}$. Since each s_i is divided into $n+1$ pieces by F_i, we can obtain that $s_i = \sum_{j\in T'} \omega'_j s_{ij}$ where $\omega'_j = \prod_{\ell\in T',\ell\neq j} \frac{\ell}{\ell - j}$. Therefore, we have

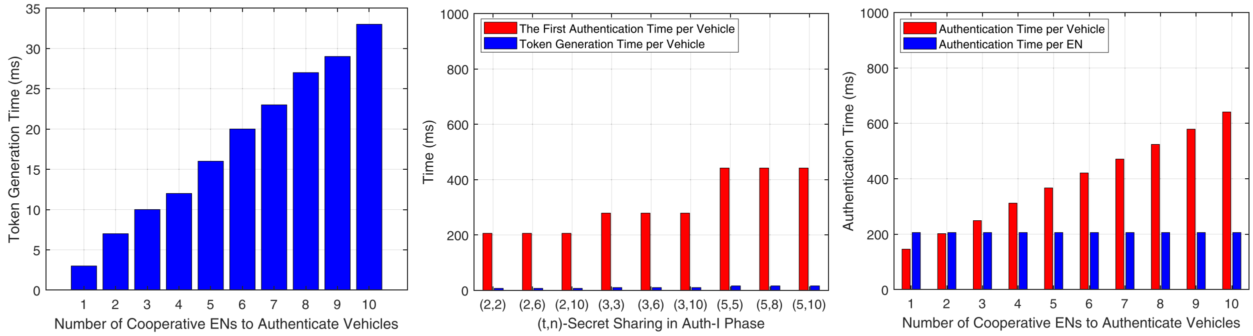
$$\begin{aligned}\sum_{j\in T'} \omega'_j s'_j &= \sum_{j\in T'} \omega'_j \Big(\sum_{i\in T} \omega_i s_{ij}\Big)\\ &= \sum_{i\in T} \omega_i \Big(\sum_{j\in T'} \omega'_j s_{ij}\Big)\\ &= \sum_{i\in T} \omega_i s_i\\ &= s\end{aligned}$$

As a consequence, any t' out of $n+1$ ENs can reconstruct s. On the other hand, any set of less than t' ENs cannot reconstruct s since s_i is divided into a $(t', n+1)$-sharing and any set of less than t' partial keys s_{ij} cannot reconstruct s_i. Thus, $(t', n+1)$-sharing is still a sharing of the secret key s. Any subset of t' out of $n+1$ ENs including the newly joined one can authenticate vehicles collaboratively.

For the case of an EN F_i being revoked, the constructed $(t'', n-1)$-sharing can be proved to be a sharing of the secret key s similarly. Since each of the secret shares of s has been replaced with new share, F_i's old secret share s_i will be invalid and thus F_i cannot be exploited by attackers to authenticate vehicles jointly with other ENs. That is, the proposed protocol supports secure revocation of ENs as well.

VII. PERFORMANCE EVALUATION

In this section, we analyze and evaluate the performance of the proposed protocol in terms of computation cost and latency induced by the cooperation of ENs. We also compare the performance of the proposed protocol with existing related works. As shown in Table I, we compare the performance of our proposed protocol with existing protocols from several aspects: the computational cost, the authentication delay, and the security functionalities. Let t_p, t_{sm}, and t_h represent the time required to perform a pairing, a scalar multiplication, and a map-to-point hash, respectively, which dominate the computational costs in these protocols. Let t_V, t_R, t_S be the delay introduced by computation time on vehicle, edge/fog, and AS side respectively, and T_{VR}, T_{RS} be the communication latency caused by message propagating between the vehicle and edge/fog node, and between the edge/fog node and AS, respectively. In the proposed protocol, the authentication cost in two scenarios is different, i.e., the cost in Auth-I phase is bigger than that if Auth-II phase. However, before the token



(a) The Time Cost to Generate a Token. (b) The Time Cost in Auth-I Phase with Different Security Parameters (c) The First Authentication Cost of Vehicles and ENs.

Fig. 3. Computation cost in Auth-I phase.

EXP expires, the Auth-I phase is only performed once. Thus, with the number of authentication execution (m) increasing, the average cost decreases. Table I shows the computational cost on both vehicle and fog/edge/AS side for a number of m authentication execution. It indicates that the proposed protocol does not have to be the most computationally efficient one. Nevertheless, our protocol stands out in the authentication delay and security aspects. Namely, with m increasing, the authentication delay increases much more slowly than the other protocols. In addition, our protocol can prevent both single point of failure and edge node compromise attack. We will give detailed analysis and performance evaluation subsequently.

The experiment is conducted with a Laptop owning a 2.8GHz Intel(R) Core(TM) i7-7700HQ CPU and 16 GB of RAM. We use Java language to write the programming code which invokes the Java Pairing-Based Cryptography Library (JPBC) with version of 2.0.0. The Type-A pairing built on the curve $y^2 = x^3 + x$ with the embedding degree of 2 is chosen. The corresponding group $|G|$ has order of q with $\log q = 160$ and the size of a group element is 512 bits. In order to increase the accuracy, we run each of the evaluation 50 times and take the averaged values as the final results.

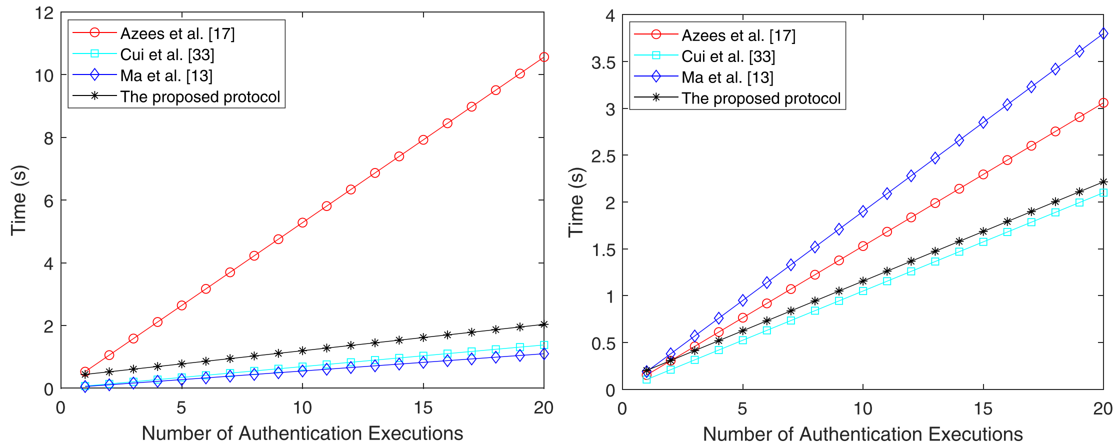
A. Computation Cost

We evaluate the time cost required to do the authentication on both vehicles and ENs' sides. For the (t, n)-threshold signature, we evaluate the scenarios of t up to 10. This is reasonable, since it is really hard for an attacker to compromise more than 10 ENs within a short period (in practice we can require the ENs to update their private keys daily or weekly.)

1) Cost in Auth-I Phase: First, we evaluate the performance of Auth-I phase, where a vehicle needs to authenticates a set of ENs and aggregate at least t partial tokens into the composite token. The vehicle needs to perform $(t+2)$ bilinear pairing operations, 3 scalar multiplications, and $(t+3)$ map-to-point hashes, while an edge node needs to perform 4 bilinear pairing operations, 3 scalar multiplications, and 4 map-to-point hashes, respectively. To evaluate the time to generate a token on the vehicle side, we conduct experiments with different number of cooperative ENs that authenticate the vehicle, that is, we consider a (t, n)-secret sharing scheme with $t \in [1, 10]$ and a fixed $n = 10$. The result is shown in Figure 3(a). Even in the case of $t = 10$, it only costs 33ms to generate a valid token. In addition, we also explore the impact of the t and n on the computation cost in Auth-I phase. As shown in Figure 3(b), with the same threshold t, distinct values of n result in similar runtime, which is aligned with our design. Namely, for a given t, the vehicle only needs to authenticate t ENs and combine t pieces of partial tokens, and thus the authentication time should be roughly the same. With a higher t, the computation cost increases as well which is also reasonable. Finally, we evaluate the authentication cost of both vehicles and ENs. As shown in Figure 3(c), the authentication time for vehicles is different when the number of cooperative ENs (i.e., t) required to authenticate vehicles changes, since vehicles need to authenticate all t ENs. However, since our scheme supports batch verification for the vehicle to authenticate multiple ENs, the number of time-consuming pairing operations does not increase with the growth of t. Even when $t = 10$, the authentication time per vehicle is still less than one second (641 ms). On the other hand, the authentication cost of each EN keeps constant because it only needs to verify one vehicle per request.

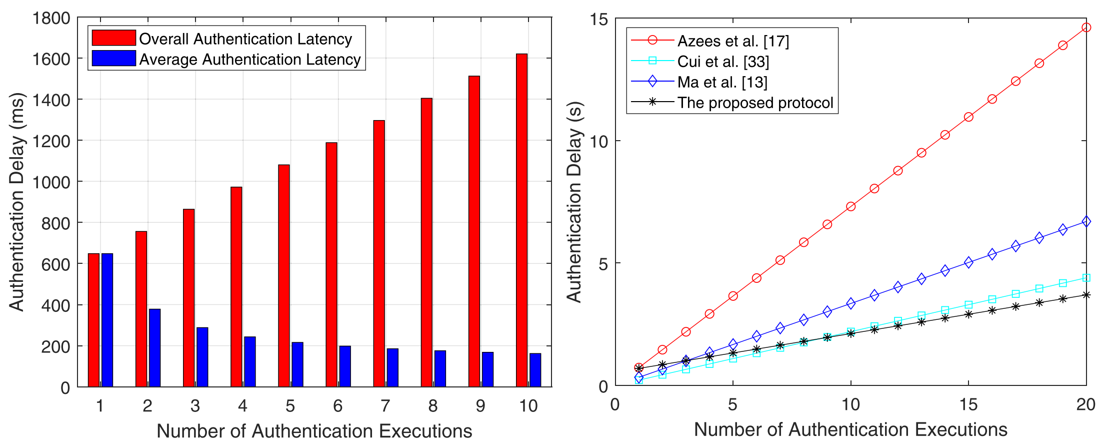
2) Cost in Auth-II Phase: As mentioned before, in the proposed protocol, once the vehicle obtains a token, it can hold and utilize this token for its future authentication purpose before the token expires. Thus, for the second-and-later authentication, only the vehicle and its nearest EN run the protocol, which significantly alleviates the computational burden of both vehicles and ENs. The vehicle needs to perform 4 scalar multiplications, and 1 map-to-point hash, while an edge node needs to perform 3 bilinear pairing operations, 1 scalar multiplications, and 1 map-to-point hash, respectively.

3) Overall Computation Cost: According to the above analysis, the overall computation cost can be simply derived. Moreover, since our protocol support fast handover authentication, we will evaluate the overall computation cost over multiple authentication executions. Let m be the number of authentication executions, then the overall computation cost of our protocol on vehicle and EN side is $(t+2)t_p + (4m-1)t_{sm} + (m+t+2)t_h$, and $(3m+1)t_p + (m+2)t_{sm} + (m+3)t_h$, respectively. Without loss of generality, we consider $t = 5$, i.e., at



(a) Overall Computation Cost on Vehicle. (b) Overall Computation Cost on Edge/Fog/AS.

Fig. 4. Comparison of Overall Computation Cost. Without loss of generality, we consider $t = 5$, i.e., at least 5 ENs cooperatively authenticate a vehicle. We set the parameter $\ell = 5$ in [17].



(a) Authentication Latency of the Proposed Protocol. (b) Comparison of the Authention Latency.

Fig. 5. Performance evaluation and comparison of the authentication latency.

least 5 ENs cooperatively authenticate a vehicle. We evaluate the overall computation cost including the vehicle and the EN authentication of our protocol and existing protocols, respectively. Figure 4 shows the result which demonstrates that the computational efficiency of our protocol approximates to that of the most efficient one [33].

B. Authentication Latency

Authentication latency means the delay caused by the mutual authentication, which contains the computation time (as mentioned before, may include t_V, t_R, t_S) and message propagation time (may include T_{VR}, T_{RS}). Due to the distinguished operations in different authentication phases, the latency also varies. In Auth-I phase, since authenticating a vehicle requires the cooperation of at least t ENs at different locations, it may induce latency including the computation time on the ENs side (denoted as t_R) and the vehicle side (denoted as t_V). For simplicity, we assume all the cooperative ENs can simultaneously deal with requests that are transmitted by the leader EN. Then the latency becomes $t_V + 2t_R$, which contains t_R caused by the leader EN and t_R caused by the cooperative ENs.

In Auth-II phase, the vehicle can pre-compute the credentials based on its token before it moves to the communication area of a new EN and thus the authentication latency caused on the vehicle side t'_V could be ignored (i.e., $t'_V = 0$). Likewise, ENs do not need to generate partial tokens either in this phase and thus the latency t'_R is also reduced. Thus, for a number of m authentication executions, the overall authentication delay of our protocol becomes $t_V + t_R + m(t'_R + T_{VR})$. The overall authentication delay of existing protocols can be found in Table I. Although Ma *et al.*'s protocol [13] requires least computation resources on vehicles, its authentication architecture belongs to Type 1. That is, in their protocol, vehicles are authenticated by a remote authentication server, which increases the authentication delay.

To evaluate the authentication latency, we assume that $T_{VR} = 100$ ms and $T_{RS} = 40$ ms, which represents the communication latency of a typical V2I communication [50] and a typical service provider, respectively. We consider the parameters $t = \ell = 5$. We first evaluate the performance of our protocol, as shown in Figure 5(a). Except for the overall authentication latency, we also compute the average authentication latency. It can be found that the average authentication latency is gradually reduced with m. Moreover, we compare the authentication latency of our protocol with existing protocols as shown in Figure 5(b). The result indicates that when m becomes larger than 9, the overall authentication latency of our protocol is the smallest, mainly because of the fast handover authentication of our protocol. In practice, the number of m is easily larger than 100. Considering the coverage range of an RSU is within 500 meters, suppose the velocity of a vehicle is 80Km/h, then the time that the vehicle connects to the RSU is less than 20 seconds. Thus, a vehicle will roam to new RSUs for about 180 times per hour if it hopes to enjoy seamless network services. Note that the evaluated authentication latency varies on different devices with distinct running environment. Specifically, in our simulated experiment, we use Java language to implement the code. The execution time of one bilinear pairing operation t_p, one scalar multiplication t_{sm}, and one map-to-point hash t_h is about 24 ms, 15 ms and 25 ms, respectively. In other papers which use similar personal computer to implement the code with C language [33], the corresponding execution time of these operations is 4.211 ms, 1.709 ms, and 4.406 ms, respectively. Therefore, if implementing with their code, the authentication latency will be further reduced. For instance, with $t = 5$, the authentication latency for Auth-I scenario is about 200 ms, while the authentication latency for Auth-II scenario is about 130 ms. As a result, our protocol caters for highly mobile scenarios like vehicular networks.

VIII. Conclusion

In this article, we have investigated the access authentication issues for vehicular networks and proposed an edge-assisted decentralized mutual authentication protocol, in which vehicles and edge nodes can efficiently authenticate each other with only one-round interaction. In the first authentication, each vehicle can be collaboratively authenticated by multiple edge nodes which then generate an access token all together based on (t, n) threshold signature for the vehicle that can be used for fast handover authentication later on. We have evaluated the performance of the protocol and the results show that our protocol can reduce the authentication delay to a big extent, and the fast handover authentication further reduces the authentication latency significantly. For instance, after executing the authentication for ten times, the overall authentication latency is less than 2 seconds and the average latency is reduced to less than 0.2 second. These advantages should expedite the deployment of intelligent transportation systems. Future work of this article includes but not limited to proposing new authentication protocol under the proposed authentication architecture with much more computational efficiency, and exploring privacy-preserving edge-assisted decentralized authentication protocols for vehicular networks.

References

[1] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, "Design of 5.9 GHz DSRC-based vehicular safety communication," *IEEE Wireless Commun.*, vol. 13, no. 5, pp. 36–43, Oct. 2006.

[2] S. Chen *et al.*, "Vehicle-to-everything (V2X) services supported by LTE-based systems and 5G," *IEEE Commun. Standards Mag.*, vol. 1, no. 2, pp. 70–76, 2017.

[3] X. Shen *et al.*, "AI-assisted network-slicing based next-generation wireless networks," *IEEE Open J. Veh. Technol.*, vol. 1, pp. 45–66, 2020.

[4] (2018). *SCOOP: General Presentation*. [Online]. Available: http://www.scoop.developpement-durable.gouv.fr/en/general-presentation-a9.html

[5] J. Cheng *et al.*, "Accessibility analysis and modeling for IoV in an urban scene," *IEEE Trans. Veh. Technol.*, vol. 69, no. 4, pp. 4246–4256, Apr. 2020.

[6] M. Raya and J.-P. Hubaux, "Securing vehicular ad hoc networks," *J. Comput. Secur.*, vol. 15, no. 1, pp. 39–68, 2007.

[7] Z. Lu, G. Qu, and Z. Liu, "A survey on recent advances in vehicular network security, trust, and privacy," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 2, pp. 760–776, Feb. 2019.

[8] Y. Li, Q. Luo, J. Liu, H. Guo, and N. Kato, "TSP security in intelligent and connected vehicles: Challenges and solutions," *IEEE Wireless Commun.*, vol. 26, no. 3, pp. 125–131, Jun. 2019.

[9] J. J. Blum, A. Eskandarian, and L. J. Hoffman, "Challenges of intervehicle ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 5, no. 4, pp. 347–351, Dec. 2004.

[10] C. Huang, R. Lu, and K.-K.-R. Choo, "Vehicular fog computing: Architecture, use case, and security and forensic challenges," *IEEE Commun. Mag.*, vol. 55, no. 11, pp. 105–111, Nov. 2017.

[11] Y. Yao, X. Chang, J. Mišić, V. B. Mišić, and L. Li, "BLA: blockchain-assisted lightweight anonymous authentication for distributed vehicular fog services," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 3775–3784, Apr. 2019.

[12] Y. Desmedt and Y. Frankel, "Threshold cryptosystems," in *Proc. Adv. Cryptol. CRYPTO*. New York, NY, USA: Springer, 1989, pp. 307–315.

[13] M. Ma, D. He, H. Wang, N. Kumar, and K.-K.-R. Choo, "An efficient and provably secure authenticated key agreement protocol for fog-based vehicular ad-hoc networks," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 8065–8075, Oct. 2019.

[14] S. Jiang, X. Zhu, and L. Wang, "An efficient anonymous batch authentication scheme based on HMAC for VANETs," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 8, pp. 2193–2204, Aug. 2016.

[15] J. Zhang, J. Cui, H. Zhong, Z. Chen, and L. Liu, "PA-CRT: Chinese remainder theorem based conditional privacy-preserving authentication scheme in vehicular ad-hoc networks," *IEEE Trans. Dependable Secure Comput.*, early access, Mar. 11, 2019, doi: 10.1109/TDSC.2019.2904274.

[16] D. He, S. Zeadally, B. Xu, and X. Huang, "An efficient identity-based conditional privacy-preserving authentication scheme for vehicular ad hoc networks," *IEEE Trans. Inf. Forensics Security*, vol. 10, no. 12, pp. 2681–2691, Dec. 2015.

[17] M. Azees, P. Vijayakumar, and L. J. Deboarh, "EAAP: Efficient anonymous authentication with conditional privacy-preserving scheme for vehicular ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 9, pp. 2467–2476, Sep. 2017.

[18] H. J. Jo, I. S. Kim, and D. H. Lee, "Reliable cooperative authentication for vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 4, pp. 1065–1079, Apr. 2018.

[19] L. Zhang, Q. Wu, J. Domingo-Ferrer, B. Qin, and C. Hu, "Distributed aggregate privacy-preserving authentication in VANETs," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 3, pp. 516–526, Mar. 2017.

[20] J. Cui, J. Zhang, H. Zhong, and Y. Xu, "SPACF: A secure privacy-preserving authentication scheme for VANET with cuckoo filter," *IEEE Trans. Veh. Technol.*, vol. 66, no. 11, pp. 10283–10295, Nov. 2017.

[21] C. Zhang, L. Zhu, C. Xu, X. Liu, and K. Sharif, "Reliable and privacy-preserving truth discovery for mobile crowdsensing systems," *IEEE Trans. Dependable Secure Comput.*, early access, May 28, 2019, doi: 10.1109/TDSC.2019.2919517.

[22] A. Yang, J. Xu, J. Weng, J. Zhou, and D. S. Wong, "Lightweight and privacy-preserving delegatable proofs of storage with data dynamics in cloud storage," *IEEE Trans. Cloud Comput.*, early access, Jun. 28, 2018, doi: 10.1109/TCC.2018.2851256.

[23] H. Yang, Q. Zhou, M. Yao, R. Lu, H. Li, and X. Zhang, "A practical and compatible cryptographic solution to ADS-B security," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 3322–3334, Apr. 2019.

[24] C. Huang, R. Lu, X. Lin, and X. Shen, "Secure automated valet parking: A privacy-preserving reservation scheme for autonomous vehicles," *IEEE Trans. Veh. Technol.*, vol. 67, no. 11, pp. 11169–11180, Nov. 2018.

[25] A. Yang, X. Tan, J. Baek, and D. S. Wong, "A new ADS-B authentication framework based on efficient hierarchical identity-based signature with batch verification," *IEEE Trans. Services Comput.*, vol. 10, no. 2, pp. 165–175, Mar. 2017.

[26] C. Zhang *et al.*, "TPPR: A trust-based and privacy-preserving platoon recommendation scheme in VANET," *IEEE Trans. Services Comput.*, early access, Dec. 24, 2019, doi: 10.1109/TSC.2019.2961992.

[27] Y. Wang, Y. Ding, Q. Wu, Y. Wei, B. Qin, and H. Wang, "Privacy-preserving cloud-based road condition monitoring with source authentication in VANETs," *IEEE Trans. Inf. Forensics Security*, vol. 14, no. 7, pp. 1779–1790, Jul. 2019.

[28] J. Liang, Z. Qin, S. Xiao, L. Ou, and X. Lin, "Efficient and secure decision tree classification for cloud-assisted online diagnosis services," *IEEE Trans. Dependable Secure Comput.*, early access, Jun. 14, 2019, doi: 10.1109/TDSC.2019.2922958.

[29] S.-F. Tzeng, S.-J. Horng, T. Li, X. Wang, P.-H. Huang, and M. K. Khan, "Enhancing security and privacy for identity-based batch verification scheme in VANETs," *IEEE Trans. Veh. Technol.*, vol. 66, no. 4, pp. 3235–3248, Apr. 2017.

[30] A. Yang, J. Weng, N. Cheng, J. Ni, X. Lin, and X. Shen, "DeQoS attack: Degrading quality of service in VANETs and its mitigation," *IEEE Trans. Veh. Technol.*, vol. 68, no. 5, pp. 4834–4845, May 2019.

[31] Y. Hao, Y. Cheng, C. Zhou, and W. Song, "A distributed key management framework with cooperative message authentication in VANETs," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 3, pp. 616–629, Mar. 2011.

[32] A. Thakur and R. Malekian, "Fog computing for detecting vehicular congestion, an Internet of vehicles based approach: A review," *IEEE Intell. Transp. Syst. Mag.*, vol. 11, no. 2, pp. 8–16, Summer 2019.

[33] J. Cui, L. Wei, J. Zhang, Y. Xu, and H. Zhong, "An efficient message-authentication scheme based on edge computing for vehicular ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 5, pp. 1621–1632, May 2019.

[34] J. Shao, X. Lin, R. Lu, and C. Zuo, "A threshold anonymous authentication protocol for VANETs," *IEEE Trans. Veh. Technol.*, vol. 65, no. 3, pp. 1711–1720, Mar. 2016.

[35] N. Malik, P. Nanda, A. Arora, X. He, and D. Puthal, "Blockchain based secured identity authentication and expeditious revocation framework for vehicular networks," in *Proc. 17th IEEE Int. Conf. Trust, Secur. Privacy Comput. Commun., 12th IEEE Int. Conf. Big Data Sci. Eng. (TrustCom/BigDataSE)*, Aug. 2018, pp. 674–679.

[36] M.-H. Park, G.-P. Gwon, S.-W. Seo, and H.-Y. Jeong, "RSU-based distributed key management (RDKM) for secure vehicular multicast communications," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 3, pp. 644–658, Mar. 2011.

[37] D. He, S. Chan, and M. Guizani, "Handover authentication for mobile networks: Security and efficiency aspects," *IEEE Netw.*, vol. 29, no. 3, pp. 96–103, May 2015.

[38] Y. Xie, L. Wu, N. Kumar, and J. Shen, "Analysis and improvement of a privacy-aware handover authentication scheme for wireless network," *Wireless Pers. Commun.*, vol. 93, no. 2, pp. 523–541, Mar. 2017.

[39] D. He, S. Zeadally, L. Wu, and H. Wang, "Analysis of handover authentication protocols for mobile wireless networks using identity-based public key cryptography," *Comput. Netw.*, vol. 128, pp. 154–163, Dec. 2017.

[40] A. Shamir, "How to share a secret," *Commun. ACM*, vol. 22, no. 11, pp. 612–613, Nov. 1979.

[41] Y. Zhang, C. Xu, H. Li, K. Yang, N. Cheng, and X. Shen, "Protect: Efficient password-based threshold single-sign-on authentication for mobile users against perpetual leakage," *IEEE Trans. Mobile Comput.*, early access, Feb. 24, 2020, doi: 10.1109/TMC.2020.2975792.

[42] A. Boldyreva, "Threshold signatures, multisignatures and blind signatures based on the gap-diffie-hellman-group signature scheme," in *Public Key Cryptography—PKC*. Berlin, Germany: Springer, 2002, pp. 31–46.

[43] L. Harn and F. Wang, "Threshold signature scheme without using polynomial interpolation," *Int. J. Netw. Secur.*, vol. 18, pp. 710–717, Jul. 2016.

[44] K. Yang, X. Jia, B. Zhang, and Z. Zheng, "Threshold key redistribution for dynamic change of authentication group in wireless mesh networks," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Dec. 2010, pp. 1–5.

[45] W. Yang, W. Luo, X. Luo, J. Weng, and A. Yang, "Fully distributed certificateless threshold signature without random oracles," *Sci. China Inf. Sci.*, vol. 61, no. 9, pp. 1–3, Sep. 2018.

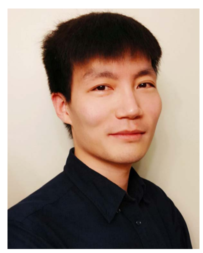
[46] S. Lee, K. Han, S.-K. Kang, K. Kim, and S. R. Ine, "Threshold password-based authentication using bilinear pairings," in *Public Key Infrastructure*. Berlin, Germany: Springer, 2004, pp. 350–363.

[47] Y. Zhang, C. Xu, J. Ni, H. Li, and X. S. Shen, "Blockchain-assisted public-key encryption with keyword search against keyword guessing attacks for cloud storage," *IEEE Trans. Cloud Comput.*, early access, Jun. 17, 2019, doi: 10.1109/TCC.2019.2923222.

[48] S. Agrawal, P. Miao, P. Mohassel, and P. Mukherjee, "Pasta: Password-based threshold authentication," in *Proc. 2018 ACM SIGSAC Conf. Comput. Commun. Secur. (CCS)*. New York, NY, USA: ACM, 2018, pp. 2042–2059.

[49] D. Boneh, B. Lynn, and H. Shacham, "Short signatures from the Weil pairing," in *Proc. 7th Int. Conf. Theory Appl. Cryptol. Inf. Secur., Adv. Cryptol. (ASIACRYPT)*. Berlin, Germany: Springer-Verlag, 2001, pp. 514–532.

[50] M. M. K. Tareq, O. Semiari, M. A. Salehi, and W. Saad, "Ultra reliable, low latency vehicle-to-infrastructure wireless communications with edge computing," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–7.



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