A secure anonymous communication scheme in vehicular ad hoc networks from pairings

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Abstract

Security and efficiency are two crucial issues in vehicular ad hoc networks. Many researches have devoted to these issues. However, we found that most of the proposed protocols in this area are insecure and can't satisfy the anonymous property. Due to this observation, we propose a secure and anonymous method based on bilinear pairings to resolve the problems. After analysis, we conclude that our scheme is the most secure when compared with other protocols proposed so far.

Keywords: *Anonymous communication protocol*, *bilinear pairings*, *ID-based cryptosystem*, *man in the middle attack, ad hoc networks, KCI attack resistance, mutual authentication*

1. Introduction

For the rapid development in the hardware technology, vehicular networks would be widely deployed in the coming years and become the most important application of ad hoc networks. A vehicular ad hoc network (VANET) mainly consists of three components vehicles, roadside devices, and base stations. Vehicles should provide functions for accessing to the internet, communicating among themselves, and offering services such as, traffic monitoring, vehicle diagnostics, cooperative driving, and entertainment services. Among the functions provided, security and efficiency are the two most concerned issues. For example, it is essential to assure that life-critical traffic information cannot be modified or forged by an attacker. Also, it may require that the protocol needs possessing the anonymity property. A number of researches have investigated on the two issues, security and efficiency, [1, 4, 8, 9, 10, 11, 16, 17]. In 2005, Yang et al. [16] proposed a secure and efficient authentication protocol for anonymous channel in wireless communications. However, we found that their protocol not only suffers from the known plaintext attack but also violates the anonymous property. For, in their protocol, if an adversary E eavesdrops on the communication line between the two communicating parties (ID_{VN} and ID_{HN}) and knows ID_{VN} and $(ID_{VN}, T_2, D, E, F)_{k_{h,v}}$, he can launch an offline secret key, $k_{h,v,}$ guessing attack to decrypt the latter. If the secret key guessed is correct, E will find ID_{VN} in the decrypted $(ID_{VN}, T_2, D, E, F)_{k_{h,v}}$. In 2007, Raya et al. [12] proposed a “securing vehicular ad hoc networks”. However, in their scheme when vehicle A sends $\{B|K|T\}_{PuK_B}$ and $Sig_{PrK_A}[B|K|T]$ to vehicle B, we can easily use A’s public key to obtain the session key from $Sig_{PrK_A}[B|K|T]$. In 2008, Wang et al. [14] also proposed a novel secure communication scheme in vehicular ad hoc networks. Yet, we also found the same weakness in their scheme. Since in the scheme, when vehicle A sends $\{B|SK|T\}_{PuK_B}$ and $Sig_{PrK_A}[B|SK|T]$ to vehicle B, an attacker can easily use A’s public key to obtain the session key SK from $Sig_{PrK_A}[B|SK|T]$. Moreover, in both Raya et al.’s and Wang et al.’s schemes, when a member leaves the group, their protocols don’t involve an updating process for the group key. Therefore, a left member can use the old group key to decrypt the new group messages. In other words, their protocols don’t have the forward and backward secrecy. Also in 2008, Li et al. [4] proposed a secure and efficient communication scheme, they claimed their scheme is secure, but we found that it suffers from the parallel session attack and the leakage of each vehicle's secret key. We will describe this in Section 3.

The rest of this paper is organized as follows. The introduction of preliminary is shown in Section 2. In Section 3, we review Li et al.'s scheme [4] and show the weaknesses. After that, we present our protocol in Section 4 and analyze its security in Section5. In Section 6, we make security properties comparisons of our scheme with others; then, we show the discussion in Section7; Finally, a conclusion is given in Section 8.

2. Preliminary

In this section, we briefly introduce some background knowledge used in this paper.

2.1 Bilinear pairings

In 2001, bilinear pairings, namely the Weil pairing and the Tate pairing, defined on elliptic curves were proved and applied to cryptography by Boneh and Franklin [2]. Since then, many protocols in security issues have been designed based on the Weil pairing [2, 3, 5]. In the following, we briefly describe the definitions and properties of bilinear pairings.

Let P be a generator of G_1 that is a cyclic additive group whose order is a prime q, and G_2 be a cyclic multiplicative group of the same order. Then a bilinear pairing is defined as a map e: $G_1 \times G_1 \rightarrow G_2$ with the following conditions. It is assumed that the discrete logarithm problem (DLP) in both G_1 and G_2 is difficult.

(1) Bilinear: $e(aP,bQ) = e(P,Q)^{ab}$, for any $a,b \in Z_q^*$ and P, $Q \in G_1$.

(2) Computability: There is an efficient algorithm to compute $e(P, Q)$ for all, $P,Q \in G_1$.

(3) Non - degenerate: there exists $P \in G_1$ and $Q \in G_1$ such that $e(P,Q) \neq 1$ in G_2.

After showing what is a bilinear map. We introduce the following problems in G_1:

– **Discrete Logarithm Problem (DLP):** Given two group elements P and Q, finding an integer n, such that $Q = nP$, whenever such an integer exists.

– **Decision Diffie-Hellman Problem (DDHP):** For $a, b, c \in Z_q*$, given P, aP, bP, cP, deciding whether $c \equiv ab \bmod q$.

– **Computational Diffie-Hellman Problem (CDHP):** For $a, b \in Z_q*$, given P, aP, bP, compute abP.

– **Decision Bilinear Diffie–Hellman Problem (DBDHP)**: Given P, aP, bP, cP for $a, b, c \in Z_q^*$ and $z \in G_2$, deciding whether $z = e(P, P)^{abc}$.

2.2 Blind Signatures from Pairings

In 2002, Paterson [7] proposed an ID-based signature scheme from pairings. In 2003, Lu et al. [6] modified Paterson scheme to become a blind signature protocol. In the following, we briefly describe their modification.

Assume that Alice has a message m, and wants to ask Bob to sign on m blindly. Let Bob's public key be $Q_B=H_1(ID_B)$ and private key be $D_B=sQ_B$. They would perform the following three steps:

Step 1: Alice selects a random number $t_1 \in Z_q^*$, computes $m' = t_1 H_2(m)$, then sends m' to Bob.

Step 2: After receiving m', Bob selects a random number $k \in Z_q^*$. He computes $R_1 = kP$, $S_1 = k^{-1}m'P$, and $S_2 = k^{-1}D_B$, then sends back R_1, S_1, S_2 to Alice.

Step 3: After receiving R_1, S_1, S_2, Alice selects a random number $t_2 \in Z_q^*$ and computes the signature (R, S) of m, by computing $R = t_2R_1 = t_2kP$ and $S = t_2^{-1}(t_1^{-1}S_1+H_3(R)S_2) = t_2^{-1}(t_1^{-1}k^{-1}m'P+H_3(R)k^{-1}D_B) = t_2^{-1}(t_1^{-1}k^{-1}t_1H_2(m)P + H_3(R)k^{-1}D_B) = t_2^{-1}(k^{-1}(H_2(m)P + H_3(R)D_B)$.

To verify the signature (R, S) on message m, the verifier computes $e(R, S)$ and compares the result with the value of $e(P, P)^{H_2(m)} * e(P_{pub}, Q_B)^{H_3(R)}$. If the two values in G_2 match, the signature is accepted; otherwise, it is rejected. The verification process is shown as follows.

$e(R, S)=e(t_2kP, t_2^{-1}(k^{-1}(H_2(m)P+H_3(R)D_B)))= e(P, H_2(m)P+H_3(R)D_B) =$

$e(P, P)^{H_2(m)} \cdot e(P, D_B)^{H_3(R)} = e(P, P)^{H_2(m)} \cdot e(P_{Pub}, QB)^{H_3(R)}$

3. Review of Li et al.'s protocol

In 2008, Li et al. [4] proposed a secure and efficient scheme for vehicular ad hoc networks. However, we found some security flaws exit in their protocol. In the following, we first list the notations' definitions of Li et al.'s protocol in Section3.1. , then review the method in Section 3.2. After that , we present our attack in Section 3.3..

3.1 Definitions of used notations

In this section, we list the definitions of used notations in Li et al.'s protocol as follows which will also be used through this paper.

TTP: a trusted third party,
VID_i: the identity of vehicle i,
RID_i: the identity of roadside device i,
SID_i: the identity of service provider i,
V_i : vehicle i,
R_j : roadside device j,
S_i: service provider i,
(PK_{S_i}, SK_{S_i}): a public and private key pair for service provider S_i,
VK_i: V_i's secret key,
RK_j: R_j's secret key,
SPK_{S_i} : S_i's secret key,
tag#: an unique tag number for a request,

hop: the number of hops a message can be transmitted,
r_l: the identity of roadway section *l*,
ES_i: an emergency signal issued by vehicle *i*,
MAC: the message authentication code defined by $MAC = H(K, m)$, where *m* denotes the message and *K* is the protection key,
M_i: the receipt of a service access for user *i* to access the service that S_i provides,
AC: an authorized credential,
H(.): a collision-free one-way hash function,
$\oplus$: an exclusive OR operation,
t: an integer
T_i: a timestamp of vehicle or roadside device *i*,

$E_{PK_{S_i}}\{x\}$: message *x* is encrypted with service provider S_i's public key PK_{S_i} ,

$D_{SK_{S_i}}\{x\}$: message *x* is decrypted with service provider S_i's private key SK_{S_i} .

H(*SK*): the hash value of group secret key *SK* shared among all nodes in the network,
$H_t(m)$: an one-way hash chain represents that message m has been hashed t times,
$a \,||\, b$: the concatenation of messages *a* and *b*

3.2 Li et al.'s protocol

Li et al.'s non-interactive ID-based scheme takes use of members' identities to establish a secure trust relationship between communicating vehicles, and of a blind signature-based scheme for vehicle-to-roadside device communication which allows authorized vehicles to anonymously interact with their roadside devices. Their scheme includes: (A) a pre-deployment phase, and (B) three communication scenarios. The three scenarios are Scenario 1: secure communications between vehicles, Scenario 2: secure communications between vehicles and roadside devices, and Scenario 3: a secure and efficient communication scheme with privacy preservation (SECSPP). We briefly describe their protocol as follows:

(A) Pre-deployment phase

TTP first chooses four relatively prime numbers p_js such that $(p_j\text{-}1)/2$ is prime, for *j*=1 to 4. Let $n=p_1*p_2*p_3*p_4$ and *TTP*'s public/private key pair be (*e*, *d*) satisfying ed=1 mod $\phi(n)$. Then *TTP* performs some actions to deal with three cases: (a) handling new vehicles, (b) handling new roadside devices, and (c) handling new service providers. We describe each of them as follows.

(a) Handling new vehicles V_i

TTP sets V_i's identity as VID_i, the roadway section identity as r_l, the group's secret key $H^t(SK)$, and V_i's secret key $VK_i= e*log_g(VID_i^2)$ mod ϕ (n). Then, it sends them to V_i in the network through a secret channel.

(b) Handling new roadside devices R_i

TTP sets the length of t, R_i's identity as RID_i, the roadway location identity as r_l, the initial group secret key $H^t(SK)$, and R_i's secret key $RK_i=e*log_g(RID_i^2)$ mod ϕ (n). Then, TTP sends them to R_i in the network through a secret channel.

(c) Handling new service providers S_i

TTP issues (SID_i, $H^t(SK)$, r_l, $SPK_{Si}=e*log_g(SID_{Si}^2)$ mod ϕ (n)) and generates an asymmetric public/private key pair (PK_{S_i}, SK_{S_i}) for service provider S_i.

(B) The three scenarios

After the pre-deployment phase, Li et al.'s protocol performs the following three scenarios. Here, we only demonstrate each scenario's function. The details can be referred to the original article [4].

Scenario 1: Secure communications between vehicles

It is a secure communication mechanism with mutual authentication between vehicular nodes V_s and V_d. According to the phase of this scenario, V_s can discover the path to V_d and establish the session key.

Scenario 2: Secure communications between vehicle and roadside device

It is a secure communication mechanism with mutual authentication between vehicular nodes $\mathrm{V_s}$ and roadside device $\mathrm{R_j}$. According to the phase of this scenario, $\mathrm{V_s}$ can discover the path to $\mathrm{R_j}$ and establish the session key.

Scenario 3: A secure and efficient communication scheme with privacy preservation

In this scenario, when a vehicle wants to access pay-services, he must first obtain the authorized credential and then use it to access services anonymously. The service provider can not link the authorized credential to the user's identity. There are two phases in this scenario: (a) access authorization phase, and (b) access service phase. In the following, we only briefly describe and these two phases and depict them in figure1 and 2 respectively.

(a) Access authorization phase

When V_i wants to anonymously access pay-services from R_j, he must first get an authorized credential AC_i from S_i by presenting the receipt M_i as shown in Figure 1, where C=$(SID_{\mathrm{i}}{}^2)^{H(T_{Vi})*VK_i}$ and C'=$(VID_i{}^2)^{H(T_{Vi})*SPK_{Si}}$.

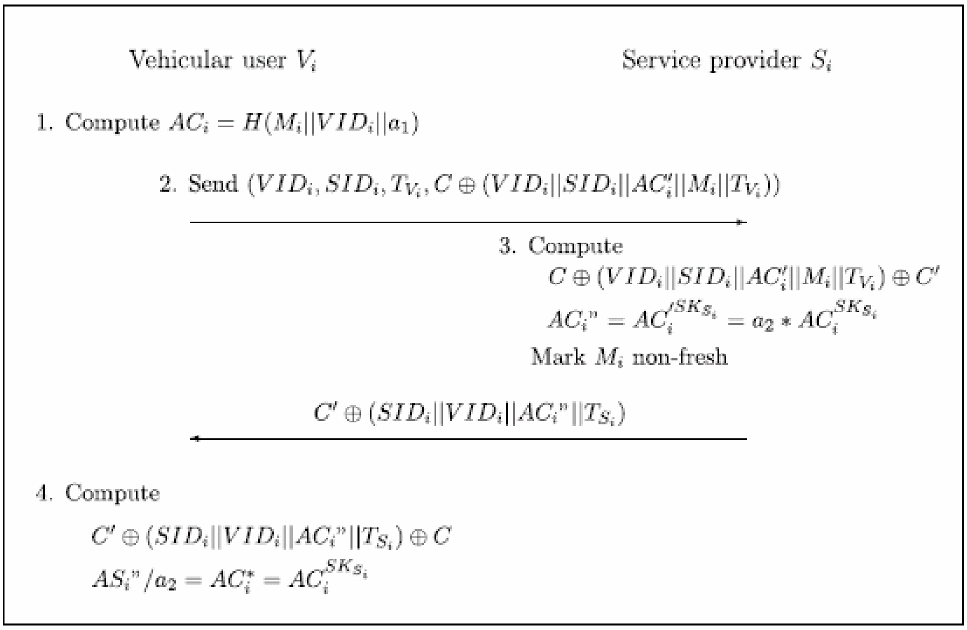

Vehicular user V_i
Service provider S_i
1. Compute $AC_i = H(M_i||VID_i||a_1)$
2. Send $(VID_i, SID_i, T_{V_i}, C \oplus (VID_i||SID_i||AC_i'||M_i||T_{V_i}))$
3. Compute
$C \oplus (VID_i||SID_i||AC_i'||M_i||T_{V_i}) \oplus C'$
$AC_i" = AC_i'^{SK_{S_i}} = a_2 * AC_i^{SK_{S_i}}$
Mark M_i non-fresh
$C' \oplus (SID_i||VID_i||AC_i"||T_{S_i})$
4. Compute
$C' \oplus (SID_i||VID_i||AC_i"||T_{S_i}) \oplus C$
$AS_i"/a_2 = AC_i^* = AC_i^{SK_{S_i}}$

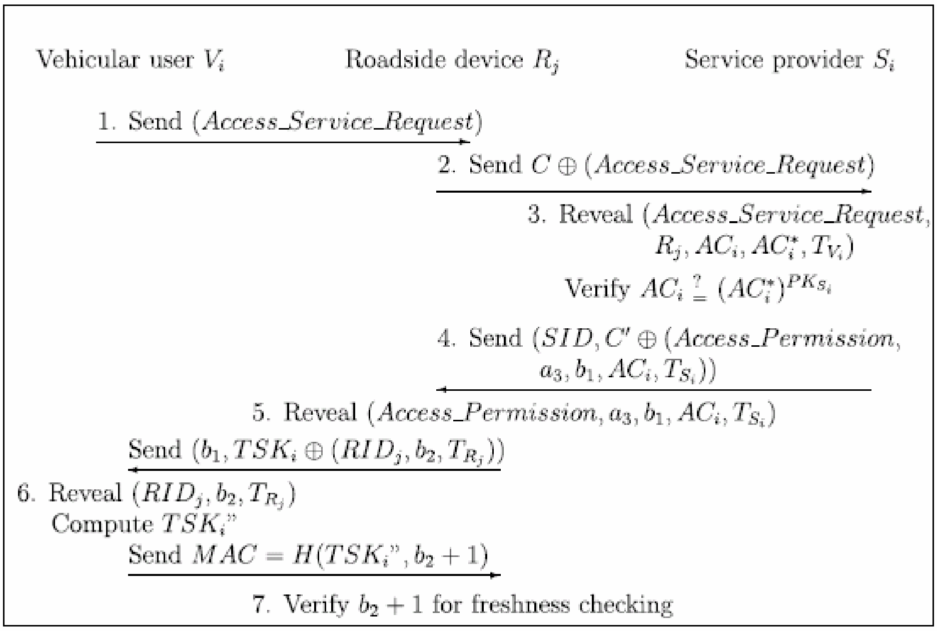
Figure 1.access authorization phase

(b)Access service phase

After phase (a), V_i uses the authorized credential to access the pay-services without disclosing any information about his identity VID_i as shown in Figure 2, where C=(SID_i^2)$^{H(T_{Rj})*RK_j}$ and C'=(RID_j^2)$^{H(T_{Vi})*SPK_{Si}}$.

3.3 Security Analysis of Li et al.'s protocol

Although, Li et al. claimed that their protocol can achieve secure communication between any two parties. However, we found that some flaws exists in their scheme. We describe them as follows.



Vehicular user V_i
Roadside device R_j
Service provider S_i
1. Send $(Access\_Service\_Request)$
2. Send $C \oplus (Access\_Service\_Request)$
3. Reveal $(Access\_Service\_Request, R_j, AC_i, AC_i^*, T_{V_i})$
Verify $AC_i \overset{?}{=} (AC_i^*)^{PK_{S_i}}$
4. Send $(SID, C' \oplus (Access\_Permission, a_3, b_1, AC_i, T_{S_i}))$
5. Reveal $(Access\_Permission, a_3, b_1, AC_i, T_{S_i})$
Send $(b_1, TSK_i \oplus (RID_j, b_2, T_{R_j}))$
6. Reveal (RID_j, b_2, T_{R_j})
Compute TSK_i"
Send $MAC = H(TSK_i", b_2 + 1)$
7. Verify $b_2 + 1$ for freshness checking

Figure 2.access service phase

(a) Violation of anonymous property and unsafty of secret keys

In case (a) of the pre-deployment phase for handling new vehicle V_i in, *TTP* sets V_i's secret key and the initial group secret key as VK_i=e*log_g(VID_i^2) mod Ø (n). A malicious group member can obtain VID_i by using the group secret key $H^t(SK)$ to XOR the message $H^t(SK) \oplus (tag\#, VID_s, VID_d, hop, T_{Vs}, r_l, C \oplus (tag\# \parallel VID_s \parallel VID_d \parallel T_{Vs} \parallel a))$ broadcast by V_i in Scenario 1, or the message $H^t(SK) \oplus (ES_i, VID_i, RID_j, T_{Vi}, r_l, C \oplus (ES_i \parallel VID_i \parallel RID_j \parallel T_{Vi} \parallel a)$ also broadcast by V_i in

Scenario 2. This violates the anonymous property. Moreover, if two malicious group members, V_a and V_b, collude and share their secret keys, VK_a *and* VK_b, they can break the system. Because $VK_a=e*log_g(VID_a^2) + k_1 Ø(n)$ and $K_b=e*log_g(VID_b^2) + k_2 Ø (n)$, they can compute $(VK_a-VK_b)=(e*log_g(VID_a^2)-e*log_g(VID_b^2))+(k_1-k_2) Ø (n)$, where k_1 and k_2 are two integers. Let $k_3=(k_1-k_2)$. Since that e is the signer's public key, and (VK_a-VK_b) and $(e*log_g(VID_a^2)-e*log_g(VID_b^2))$ are two known fixed values. If we let the difference of these two values be df, then $df = k_3 Ø (n)$. Accordingly they can figure out $Ø(n)$ by setting k_3 to a proper value. This makes the secret keys in the system insecure. Thus, the system is broken.

4. Our proposed protocol

For there still lacks a secure scheme in VANETs, in this section, we propose a novel secure VANET protocol based on bilinear pairings. We present the scheme in Section 4.2.

4.1 Definitions of used notations

In the following, we only list the definitions of used notations which are not listed in Section 3.1.

G_1, G_2: the cyclic additive group with order q and a cyclic multiplicative group respectively, both order q

G_2: a cyclic multiplicative group with order q

P: a generator of G_1

e: $G_1 \times G_1 \rightarrow G_2$ be a bilinear pairing

$P_{pub}(=sP)$: the private/public key pair of *TTP*

$H_1 : G_1 \rightarrow \{0,1\}^*$

$H : G_2 \rightarrow \{0,1\}^*$

f : a public one-way hash function with arbitrary input length and the same fixed output length as H_1 and H

X$_{or}$: an exclusive OR operation

$Q_{V_i}(=H(VID_i))/S_{V_i}(=sQ_{V_i})$: the public/private key pair of V_i

$Q_{S_i}(=H(SID_i))$: the public key of S_i

$S_{S_i}(=sQ_{S_i})$: the private key of S_i

$Q_{R_i}(=H(RID_i))$: the public key of R_i,

$S_{R_i}(=sQ_{R_i})$: the private key of R_i,

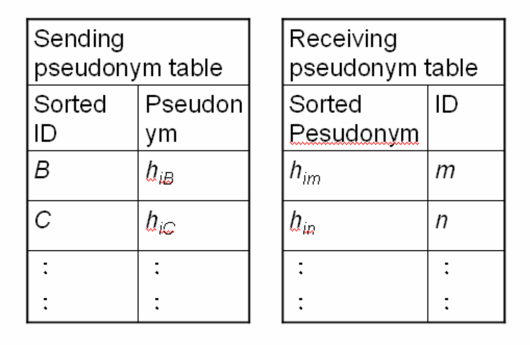
$h_{V_iV_j}(=H(e(S_i,Q_j))=H(e(Q_i,S_j)))$: a common secrecy shared between node V_i and node V_j.

4.2 The proposed scheme

As in Li et al.s' protocol, our scheme also contains: (a) pre-deployment phase, and (b) three communication scenarios.

(a) Pre-deployment phase

TTP selects *P* as a generator of G_1 and *s* as his secret key, and computes $P_{pub} = sP$ as his public key. When a new vehicle V_i and service provider S_i joins, *TTP* computes their public/private key pairs as $Q_{V_i}(=H(VID_i))/S_{V_i}(=sQ_{V_i})$ and $Q_{S_i}(=H(SID_i))/$ $S_{S_i}(=sQ_{S_i})$, correspondingly. Vehicle V_i can then use his private key to calculate the pseudonym shared with Vehicle/Node j as $h_{ij} = H(e(S_i, Q_j))$, for $i \neq j$ and builds up two pseudonym tables as shown in Figure 3.



Sending pseudonym table	
Sorted ID	Pseudonym
B	h_{iB}
C	h_{iC}
: :	: :

Receiving pseudonym table	
Sorted Pesudonym	ID
h_{im}	*m*
h_{in}	*n*
: :	: :

Figure 3. The two pseudonym tables of vehicle V_i

(b) Three communication scenarios

After pre-deployment phase, our scheme performs following three scenarios.

(1) Scenario 1: Secure Communications between Vehicles

For this scenario (V_s wants to anonymously communicate with another vehicle node V_d) , V_s and V_d together perform the following steps. We also depict them in figure 4.

Step 1: For initiating a route discovery process to establish a route to V_d, V_s generates a unique $tag\#$ and a random number *a,* and finds h_{sd} from his sending pseudonym table. He computes $C = H(e(S_{V_s}, aQ_{V_d}))$ and $C_s = h_{sd} \oplus C \oplus f(tag\# \| T_{V_s})$, where T_{V_s} is V_s system timestamp. Then, V_s broadcasts the route discovery message $(tag\#, hop, T_{V_s}, r_l, C_s, aQ_{V_s})$.

Step 2: After receiving the message, V_d checks to see if $(hop--) \le 0$, if so, V_d drops the message; otherwise, it decrypts C_s by computing $C' = H(e(a)Q_{V_s}, S_{V_d}))$ and $C_s \oplus C' \oplus f(tag\# \| \; T_{V_s})$ to obtain h_{sd}'. V_d uses h_{sd}' to search his receiving pseudonym table. If he finds the item, he is the destination node. V_d then selects a random number *b* and computes $\delta = H(e(aQ_{V_s}, bf(bIP_{V_d})S_{V_d}))$, $C_d = h_{ds} \oplus \delta \oplus f(tag\# \| T_{V_d})$, and the session key $sk = f(\delta \| 0)$, where h_{ds=}h_{sd}. He then sends $(tag\#, hop, f(bIP_{V_d}),\ T_{V_d}, r_l, C_d, bQ_{V_d})$ to V_s along the backward path. Else, he forwards the message $(tag\#, hop--, T_{V_s}, r_l, C_s, aQ_{V_s})$ to its neighboring nodes and goes to step 2.

Step 3: V_s computes $\delta' = H(e(aS_{V_s}, b)Q_{V_d}))$ and $C_d \oplus \delta' \oplus f(tag\# \|\ \ T_{V_d})$, obtaining h_{ds}'. He then uses h_{ds}' to search his receiving pseudonym table to decide whether he is the source node V_s. If he can find the item h_{ds}' in the table, he is the source node V_s. He then computes the session key $sk = f(\delta' \| 0)$. V_s and V_d can then use this session key to communicate with each other.

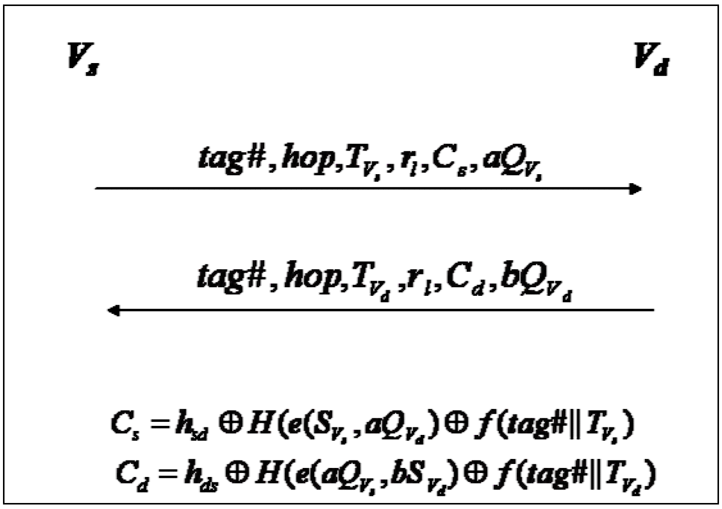

V_s
V_d
$tag\#, hop, T_{V_s}, r_l, C_s, aQ_{V_s}$
$tag\#, hop, T_{V_d}, r_l, C_d, bQ_{V_d}$
$C_s = h_{sd} \oplus H(e(S_{V_s}, aQ_{V_d}) \oplus f(tag\# \| T_{V_s})$
$C_d = h_{ds} \oplus H(e(aQ_{V_s}, bS_{V_d}) \oplus f(tag\# \| T_{V_d})$

Figure 4. Secure communications between vehicles

(2) Scenario 2: Secure communications between vehicle and roadside device

For this scenario (V_i wants to anonymously communicate with road device R_j), V_i and R_j together performs the following steps. We also depict it in figure 5.

Step 1: V_i selects a random number *a*, computes $C = H(e(S_{V_i}, aQ_{R_j}))$ and $C_i = h_{VR} \oplus C \oplus f(ES_i \| T_{V_i} \| r_l \| aQ_{V_i})$. He then sends

$(ES_i, T_{V_i}, r_l, C_i, aQ_{V_i})$ to R_j, where $h_{VR} = H(e(S_{V_i}, Q_{R_j}))$ is searched from his sending Pseudonym table and ES_i is an emergency signal issued by vehicle V_i.

Step 2: After receiving the message from V_i, R_j first checks the validity of T_{V_i} to see if it is in time. If it is, R_j compute $C' = H(e(aQ_{V_i}, S_{R_j}))$ and $C_i \oplus C' \oplus f(ES_i \| T_{V_i} \| r_l \|_a Q_{r_a})$ to obtain h_{VR}'. R_j uses h_{VR}' to search his receiving pseudonym table. If he finds the item, he is the destination node. Then R_j selects a random number b and computes $\delta = H(e(aQ_{V_i}, bS_{R_j}))$, $C_j = h_{RV} \oplus \delta \oplus f(ES_i \| T_{R_j} \| r_l \| bQ_{R_j})$, and the session key $sk = f(\delta \| 0)$. Then, R_j sends $(ES_i, T_{R_j}, r_l, C_j, bQ_{R_j})$ to V_i, where $h_{RV} = H(e(Q_{V_i}, S_{R_j}))$ is searched from his sending Pseudonym table.

Step 3: After receiving the message from R_j, V_i first checks the validity of T_{R_j} to see if it is in time. If it is, V_i computes $\delta' = H(e(aS_{V_i}, bQ_{R_j}))$ and $C_j \oplus \delta' \oplus f(ES_i \| T_{R_j} \| r_l \| bQ_{R_j})$ to obtain h_{RV}'. Then he uses h_{RV}' to search his receiving pseudonym table. If he can find such item in the table, he is the destination node R_j. He then computes the common session key as $sk = f(\delta' \| 0)$. V_i and R_j can then use this session key to communicate with each other.

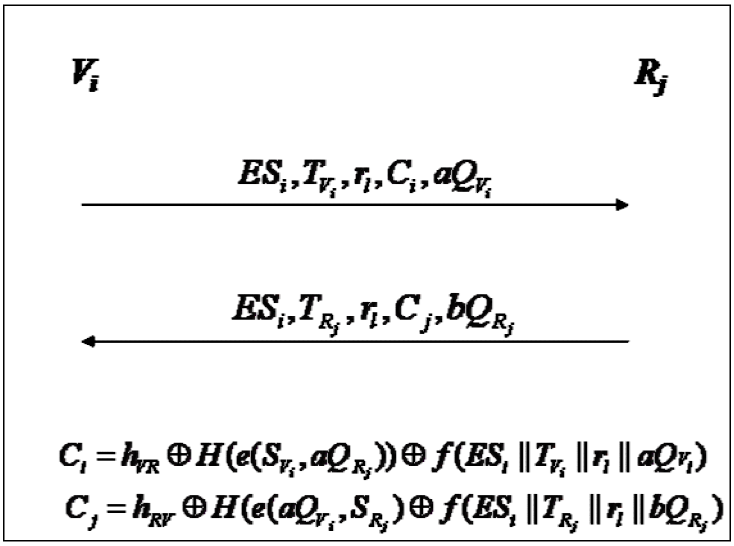

V_i
R_j
$ES_i, T_{V_i}, r_l, C_i, aQ_{V_i}$
$ES_i, T_{R_j}, r_l, C_j, bQ_{R_j}$
$C_i = h_{VR} \oplus H(e(S_{V_i}, aQ_{R_j})) \oplus f(ES_i \| T_{V_i} \| r_l \| aQ_{V_i})$
$C_j = h_{RV} \oplus H(e(aQ_{V_i}, S_{R_j}) \oplus f(ES_i \| T_{R_j} \| r_l \| bQ_{R_j})$

Figure 5. Secure communications between vehicle and roadside device

(3) Scenario 3: A secure and efficient communication scheme with privacy preservation

This scenario consists of two phases: (a) Access authorization phase: V_i wants to anonymously obtain an authorized access credential AC_i from S_i, without S_i knowing AC_i's content, and (b) Access service phase: V_i uses the credential to anonymously access service provided by S_i. We now describe these two phases as follows and also depict them in figure 6 and figure 7 respectively.

(a) Access an authorized credential phase:

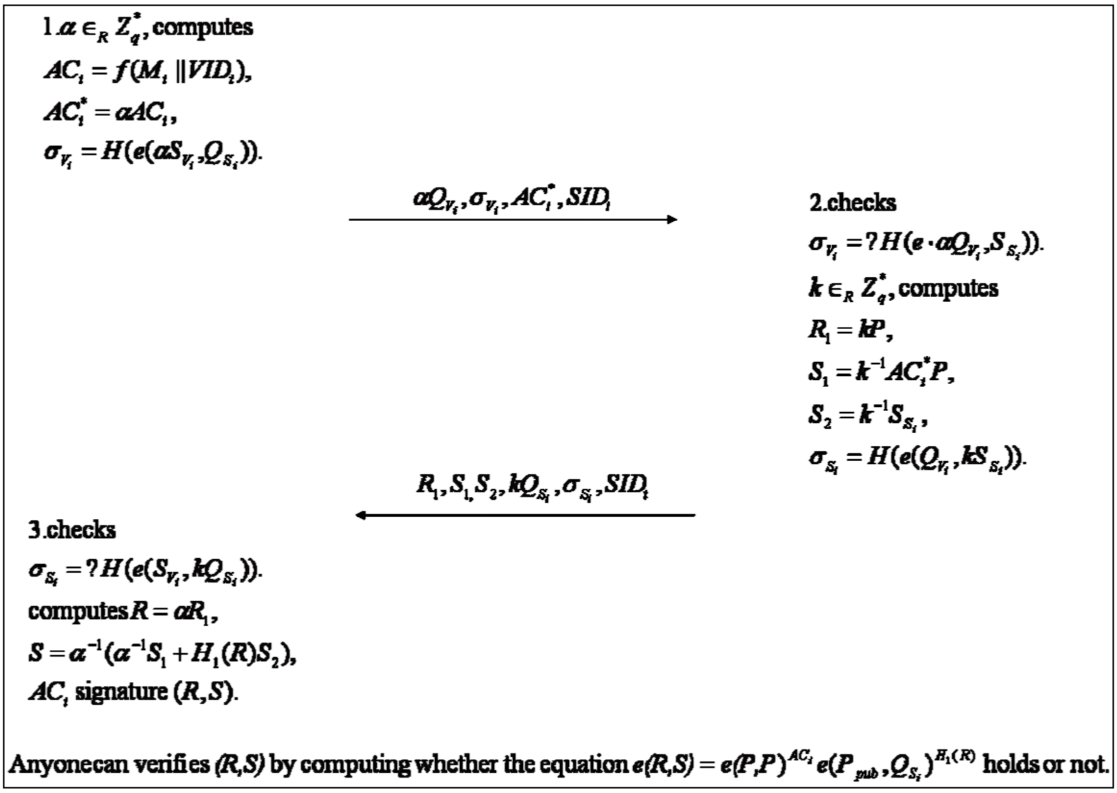
For this phase, V_i and S_i perform the following steps.

Step 1: V_i selects a random number α and computes the authorized credential $AC_i = f(M_i \| VID_i)$. Then, he computes $AC_i^* = \alpha \cdot AC_i$ and $\sigma_{V_i} = H(e(\alpha S_{V_i}, Q_{S_i}))$, and sends $(\alpha Q_{V_i}, \sigma_{V_i}, AC_i^*, SID_i)$ to S_i.

Step 2: After receiving the message from V_i, S_i checks to see whether $\sigma_{V_i} = H(e \cdot \alpha Q_{V_i}, S_{S_i}))$. If it holds, S_i selects a random number $k \in Z_q^*$, computes $R_1 = kP$, $S_1 = k^{-1}AC_i{}^*P$, $S_2 = k^{-1}S_{S_i}$, and σ_{S_i} = $H(eQ_{V_i}, kS_{S_i}))$. S_i then sends R_1, S_1, S_2, kQ_{S_i}, σ_{S_i} and SID$_i$ to V_i.

Step 3: After receiving the message from S_i, V_i checks to see whether σ_{S_i} = $H(eS_{V_i}, kQ_{S_i}))$ holds or not. If it holds, he computes the signature of AC_i as (R, S), where $R = \alpha R_1$ and $S = \alpha^{-1}(\alpha^{-1}S_1 + \quad H_1(R)S_2)$. Everyone can verify (R, S) by computing whether the equation $e(R, S)$ = $e(P,P)^{AC_i} e(P_{pub}, Q_{S_i})^{H_1(R)}$ holds. Here, we give the correctness of this equation by using the following deduction.

$$
\begin{aligned}
& e(R,S) \\
& = e(\alpha R_1, \alpha^{-1}(\alpha^{-1}S_1 + H_1(R)S_2)) \\
& = e(kP, \alpha^{-1}S_1)e(kP, H_1(R)S_2) \\
& = e(kP, \alpha^{-1}k^{-1}AC_i{}^*P)e(kP, H_1(R)k^{-1}S_{S_i}) \\
& = e(P,P)^{AC_i} e(P_{pub}, Q_{S_i})^{H_1(R)}
\end{aligned}
$$



1.$\alpha \in_R Z_q^*$, computes

$AC_i = f(M_i \| VID_i)$,

$AC_i^* = \alpha AC_i$,

$\sigma_{V_i} = H(e(\alpha S_{V_i}, Q_{S_i}))$.

$\alpha Q_{V_i}, \sigma_{V_i}, AC_i^*, SID_i$

2.checks

$\sigma_{V_i} = ?H(e\cdot\alpha Q_{V_i}, S_{S_i}))$.

$k \in_R Z_q^*$, computes

$R_1 = kP$,

$S_1 = k^{-1}AC_i^*P$,

$S_2 = k^{-1}S_{S_i}$,

$\sigma_{S_i} = H(e(Q_{V_i}, kS_{S_i}))$.

$R_1, S_{1,} S_2, kQ_{S_i}, \sigma_{S_i}, SID_i$

3.checks

$\sigma_{S_i} = ?H(e(S_{V_i}, kQ_{S_i}))$.

computes $R = \alpha R_1$,

$S = \alpha^{-1}(\alpha^{-1}S_1 + H_1(R)S_2)$,

AC_i signature (R,S).

Anyonecan verifies (R,S) by computing whether the equation $e(R,S) = e(P,P)^{AC_i} e(P_{pub}, Q_{S_i})^{H_1(R)}$ holds or not.

Figure 6. Access credential phase

(b) Access service phase

In this phase, V_i must use the authorized credential to anonymously access the service provide by S_i via R_j . They together perform the following steps (as depicted in figure 7).

Step 1: When V_i wants to access the pay-service from the roadside device R_j, he selects a random number a, computes $h_{V_iS_i} = H(e(aS_{V_i}, Q_{S_i}))$, $k_{V_iS_i} = H(e(aS_{V_i}, Q_{S_i}))$, $E = (request \parallel T_{V_i} \parallel aQ_{V_i})$, $A = h_{V_iS_i} \oplus k_{V_iS_i} \oplus f(E \parallel AC_i \parallel R \parallel S)$, $B = E_{k_{V_iS_i}}(AC_i, R, S)$. Then, he sends the request message $(A, B, requestaQ_{V_i}, T_{V_i})$ to R_j.

Step 2: After receiving the message from V_i, R_j forms E=($request \parallel T_{V_{i_i}} \parallel f(a^2 P_{v_i}) \parallel aQ_{v_i}$)and selects a random number b , and computes $D = H(e(bS_{R_j}, Q_{S_i}))$ and $\alpha_j = h_{RS} \oplus D \oplus f(E \parallel T_{R_j} \parallel bQ_{R_j})$. He forwards $D \oplus A$, B, α_j, $request, aQ_{V_i}, T_{V_i}, f(aIP_{V_i})$, aQ_{V_i}, T_{R_j}, and bQ_{R_j} to S_i.

Step 3: After receiving the message from R_j, S_i forms E’= $request \parallel T_{V_{i_i}} \parallel f(a^2 P_{v_i}) \parallel aQ_{v_i}$) ,and uses bQ_{R_j} to compute $D' = H(e(bQ_{R_j}, S_{S_i}))$ and $h_{RS}' = \alpha_j \oplus D' \oplus f(E \parallel T_{R_j} \parallel bQ_{R_j})$. He then uses h_{RS}' to search his receiving pseudonym table. If he finds the item, he is the destination node. He computes $k_{V_iS_i} = H(e(aQ_{V_i}, S_{S_i}))$ to decrypt B, obtaining (AC_i, R, S). He then verifies the validity of the authorized credential by checking whether the equation

$e(R,S) = e(P,P)^{AC_i} e(P_{pub},Q_{S_i})^{H_1(R)}$ holds or not(see Figure 8_continued). If it holds, *S* S_i selects a random $c \in_R Z_q^*$ and computes $U_{S_iR_j} = H(e(bQ_{R_j}, cS_{S_i}))$. Then, S_i computes $\delta_{S_iV_i} = H(e(aQ_{V_i}, cS_{S_i}))$, $\beta_{S_iR_j} = h_{SR} \oplus f(U_{S_iR_j} \| T_{S_i} \| \ cQ_{S_i})$, and $h_{S_iV_i} = H(e(aQ_{V_i}, S_{S_i}))(= h_{V_iS_i})$, and sends *permission*, aQ_{V_i}, caQ_{V_i}, T_{S_i}, cQ_{S_i}, $\delta_{S_iV_i}$, $\beta_{S_iR_j}$, $h_{S_iV_i} \oplus bcQ_{R_j}$ to R_j.

Step 4: After receiving the message from S_i, R_j computes $U_{S_iR_j}' = H(e(bS_{R_j},$ $cQ_{S_i})$ to form $f(U_{S_iR_j} \| T_{S_i} \| cQ_{s_i})$ to X_{or} $\beta_{S_iR_j}$, obtaining $h_{RS}(= h_{SR})$. He then uses h_{RS} to search his receiving pseudonym table to check whether he is the destination node and T_{S_i} is in time. If so, he can obtain the temporary service key by computing $k_{V_iR_j} = f(H(e(caQ_{V_i}, bS_{R_i})))$. After that, he selects a random number b_2 and sends *permission*, aQ_{V_i}, cQ_{S_i}, $\delta_{S_iV_i}$, $h_{S_iV_i} \oplus bcQ_{R_j}$, $E_{k_{V_iR_j}}(RID_j, b_2, T_{R_j})$ to V_i.

Step 5: After receiving the message from R_j, V_i checks to see whether $\sigma_{S_iV_i} = H(e(aS_{V_i}, cQ_{S_i}))$ holds or not. If it holds, he uses $h_{V_iS_i}$ to XOR $h_{v_is_i}' \oplus bcQ_{R_j}$, obtaining bcQ_{R_j} . He then computes $k_{V_iR_j}'(= f(H(e(aS_{V_i}, bcQ_{R_j})) = k_{V_iR_j})$ to decrypt $E_{k_{V_iR_j}}(RID_j, b_2, T_{R_j})$, obtaining (RID_j, b_2, T_{R_j}). Then, he computes $MAC = f(k_{V_iR_j}', \ b_2 + 1)$ and sends it to R_j.

Step 6: After receiving the message from V_i, R_j checks to see whether *MAC*= $f(k_{V_iR_j}, \ b_2 + 1)$. If it holds, V_i and R_j can use $k_{V_iR_j} = f(H(e(aS_{V_i},$

bcQ_{R_j}) to secure the subsequent data transfer in the access service phase.

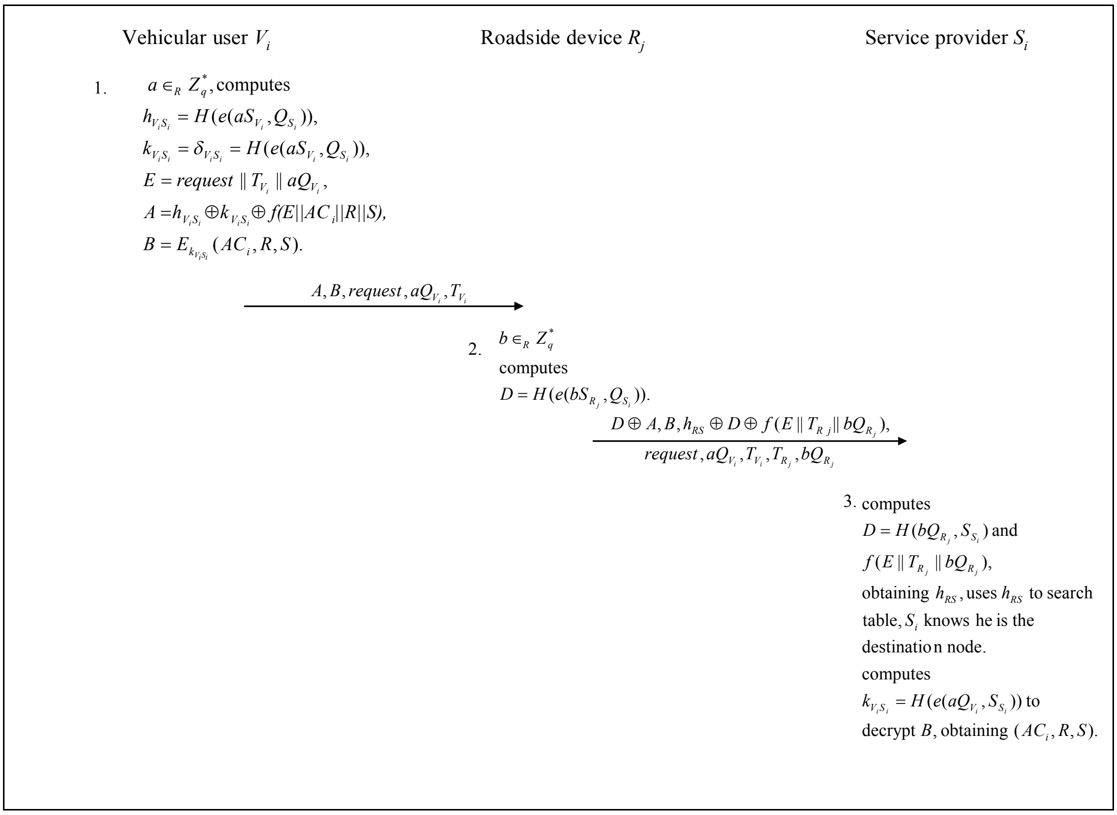

Vehicular user V_i
Roadside device R_j
Service provider S_i
1. $a \in_R Z_q^*$, computes
$h_{V_iS_i} = H(e(aS_{V_i}, Q_{S_i}))$,
$k_{V_iS_i} = \delta_{V_iS_i} = H(e(aS_{V_i}, Q_{S_i}))$,
$E = request \parallel T_{V_i} \parallel aQ_{V_i}$,
$A = h_{V_iS_i} \oplus k_{V_iS_i} \oplus f(E||AC_i||R||S)$,
$B = E_{k_{V_iS_i}}(AC_i, R, S)$.
$A, B, request, aQ_{V_i}, T_{V_i}$
2. $b \in_R Z_q^*$
computes
$D = H(e(bS_{R_j}, Q_{S_i}))$.
$D \oplus A, B, h_{RS} \oplus D \oplus f(E \parallel T_{R\ j} \parallel bQ_{R_j})$,
$request, aQ_{V_i}, T_{V_i}, T_{R_j}, bQ_{R_j}$
3. computes
$D = H(bQ_{R_j}, S_{S_i})$ and
$f(E \parallel T_{R_j} \parallel bQ_{R_j})$,
obtaining h_{RS}, uses h_{RS} to search
table, S_i knows he is the
destinatio n node.
computes
$k_{V_iS_i} = H(e(aQ_{V_i}, S_{S_i}))$ to
decrypt B, obtaining (AC_i, R, S).

Figure 7. Access service phase

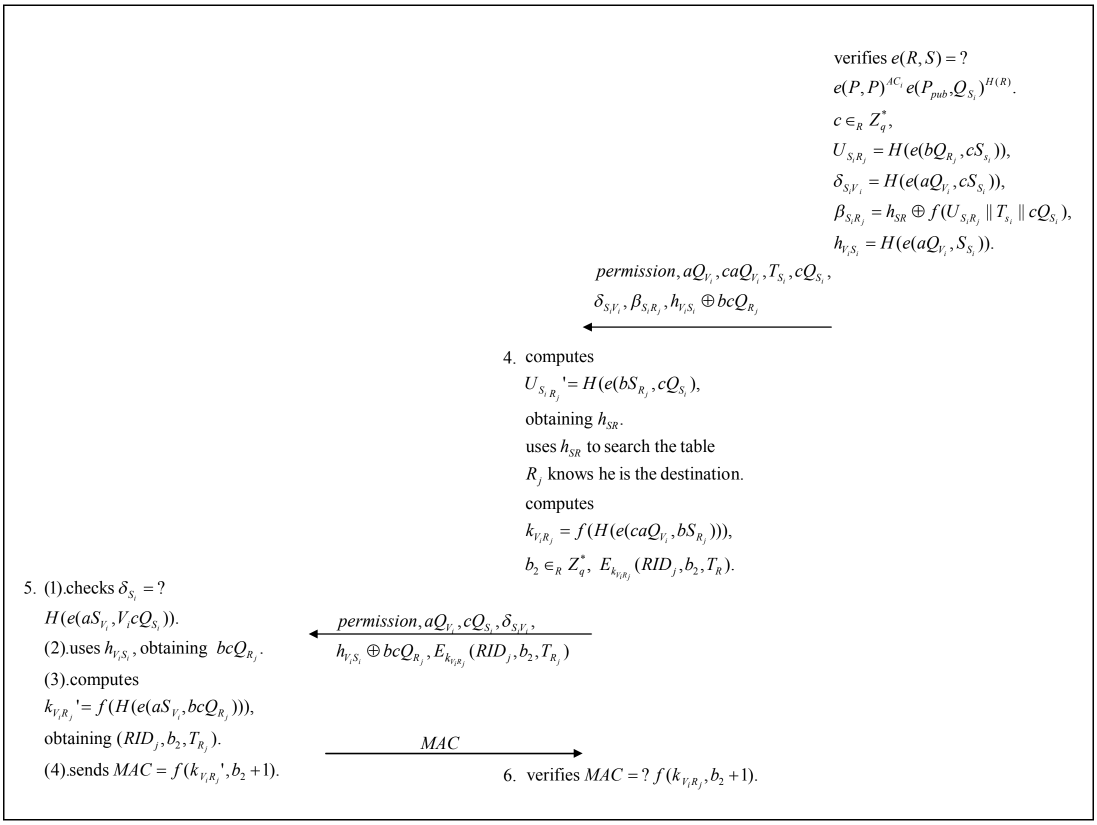

verifies $e(R,S)=?$
$e(P,P)^{AC_i}e(P_{pub},Q_{S_i})^{H(R)}$.
$c\in_R Z_q^*$,
$U_{S_iR_j}=H(e(bQ_{R_j},cS_{s_i}))$,
$\delta_{S_iV_i}=H(e(aQ_{V_i},cS_{S_i}))$,
$\beta_{S_iR_j}=h_{SR}\oplus f(U_{S_iR_j}\|T_{s_i}\|cQ_{S_i})$,
$h_{V_iS_i}=H(e(aQ_{V_i},S_{S_i}))$.
$permission, aQ_{V_i}, caQ_{V_i}, T_{S_i}, cQ_{S_i}$,
$\delta_{S_iV_i}, \beta_{S_iR_j}, h_{V_iS_i}\oplus bcQ_{R_j}$
4. computes
$U_{S_iR_j}'=H(e(bS_{R_j},cQ_{S_i})$,
obtaining h_{SR}.
uses h_{SR} to search the table
R_j knows he is the destination.
computes
$k_{V_iR_j}=f(H(e(caQ_{V_i},bS_{R_j})))$,
$b_2\in_R Z_q^*$, $E_{k_{V_iR_j}}(RID_j,b_2,T_R)$.
5. (1).checks $\delta_{S_i}=?$
$H(e(aS_{V_i},V_icQ_{S_i}))$.
(2).uses $h_{V_iS_i}$, obtaining bcQ_{R_j}.
(3).computes
$k_{V_iR_j}'=f(H(e(aS_{V_i},bcQ_{R_j})))$,
obtaining (RID_j,b_2,T_{R_j}).
(4).sends $MAC=f(k_{V_iR_j}',b_2+1)$.
$permission, aQ_{V_i}, cQ_{S_i}, \delta_{S_iV_i}$,
$h_{V_iS_i}\oplus bcQ_{R_j}, E_{k_{V_iR_j}}(RID_j,b_2,T_{R_j})$
MAC
6. verifies $MAC=?f(k_{V_iR_j},b_2+1)$.

Figure 7-continued. Access service Phase

5. Security analysis

In this session, we analyze the security of our protocol by using the following security features: (1) mutual authentication and replay attack prevention, (2) KCI attack resistance, (3) man-in-middle attack resistance, (4) anonymity. We describe them as follows.

(1) Mutual authentication and replay attack prevention

Our protocol can achieve mutual authentication in the case of, (a): secure communications between vehicles, (b): secure communications between vehicle and roadside device, and (c): a secure and efficient communication scheme with privacy preservation. We describe them respectively below.

(a). Secure communications between vehicles

In this case, as indicated in figure 5, after receiving the message from V_s, V_d decrypts C_s to obtain h_{sd}. If he is the destination node, he can find this items in his receiving pseudonym table and thus implicitly authenticate that the sending party as V_s. Conversely, after receiving the message from V_d, V_s decrypts C_d to obtain h_{ds}. If he is the destination node, he can find this items in his receiving pseudonym table and thus implicitly authenticate that the sending party as V_d. Hence, they can implicitly achieve mutual authentication. Since that if they either are not the correct nodes, they can't compute the shared secrecy $h_{sd=}h_{ds}$ between them. In addition, V_d and V_s compute the common session key sk as $f(H(e(aQ_{V_s}, bS_{V_d}))\|0)$ and $f(H(e(aS_{V_s}, bQ_{V_d}))\|0)$, respectively. If they can use sk to communicate, they go a step further to authenticate each other implicitly except for the authentication through using the pseudonym table search. Besides in our protocol a and b are two random numbers chosen by V_s and V_d respectively, which are used to assure the freshness of each session key. This can prevent our scheme from replay attack.

(b).Secure communications between vehicle and roadside device

In this case, as indicated in figure 6, after receiving the message from V_i , R_j computes $H(e(aQ_{V_i}, \quad f(aIP_{V_i})S_{R_j}))\oplus \; f(ES_i \| T_{V_i} \|r_{|l}\| aQ_a)$ to decrypt C_i , obtaining $h_{VR}'(=h_{VR})$. He can find the item from his receiving Pseudonym table and know that V_i wants to communicate with him. Similarly, after receiving the message from R_j, V_i computes $H(e(aS_{V_i}, bQ_{R_j})) \oplus \quad f(ES_i \| \quad T_{R_j} \| r_l \| bQ_{k_j})$ to X_{or} C_j, obtaining $h_{RV}'(=h_{RV}=h_{VR})$. If he is the right node, he can find the item from his receiving Pseudonym table and know that it is his intended party R_j responding to him. Hence, they both can achieve mutual authentication. In addition, R_j and V_i compute the common session key as sk =

f(H(e(aQ$_{Vi}$,bS$_{Rj}$)||0)) and *sk = f(H(e(aS$_{Vi}$,bQ$_{Rj}$)*||0)), respectively. If they can use *sk* to communicate, then this means they go a step further to authenticate each other except for the authentication through using the pseudonym table search.As for the replay attack prevention , since in our protocol, *a* is a random number chosen by V_i and *b* is a random number chosen by R_j, both are used to assure the freshness of every session key . This can prevent our scheme from replay attack.

(c). Secure and efficient communication scheme with privacy preservation

In this case, when V_i wants to access the pay-service from the roadside device R_j as indicated in figure 7 and figure 7_continued,after receiving and decrypting, the request message in from R_j step 2 $\mathrm{S_i}$ computes $D'\oplus f(E \,||\, T_{R_j} \,||\, bQ_{R_j})$ to $\mathrm{X_{or,}}$ obtaining $\mathrm{h_{r's}}$. If he is the destination node, he can find $\mathrm{h_{r's}}$ in the receiving pseudonym table. If it is valued, he computes and sends the *permission* message to R_j. If $\mathrm{R_j}$ is the destination node, he can compute $U_{s_i}R_j$ to $\mathrm{X_{or}}$ $B_{s_i}R_j$, obtaining $\mathrm{h_{rs.}}$ Hence, R_j and S_i can implicitly achieve mutual authentication. Similarly, R_j uses his secret key S_{R_j} to compute the session key. $k_{V_iR_j} = (H(e(acQ_{V_i}, bS_{R_j})))$, shared with V_i. and randomly chooses b_2 to compute $E_{k_{V_iR_j}}(RID_j, b_2, T_{R_j})$ he then sends the *permission* message to V_i. If V_i can decrypt $h_{V_iS_i} \oplus bcQ_{R_j}$ to obtain bcQ_{R_j}. He can compute the session key $k_{V_iR_j}' = H(e(aS_{V_i}, bcQ_{R_j}))$.

Hence, V_i and R_j can achieve mutual authentication If their session keys are the same. Moreover, in our protocol, *a*, *b*, and *c* are three random numbers chosen by V_i, R_j and S_i respectively, to assure every session key, used between V_i, and R_j, being fresh for each session. This prevents our scheme from replay attack.

(2) KCI attack resistance

KCI means that when a node's secret key has been compromised, an adversary can impersonate any other node to communicate with the compromised node using a common session key. We describe how our protocol can resist against such an attack in the three cases. In each case, there are two cases needed to be discussed for a communicating pair (*A*, *B*); either *A*'s private key is compromised by *E*, *E* can pretend anybody to communicate with *A*, or *B*'s private key is compromised by E, *E* can pretend anyone to communicate with *B*. Since in our protocol, each entity in a pair contributes a randomly chosen number to establish the session key. Hence, once we have analyzed one case, the other can be easily seen. Therefore, in the following, we only analyze one of the two cases.

(a). Secure communications between vehicles

Here, we assume that the private key S_{V_d} of V_d had been compromised by an adversary *E*. *E* can easily forge a valid route discovery message by computing $h_{sd} = H(e(Q_{V_S}, S_{V_d}))$ and $C_s = h_{sd} \oplus H(e(aQ_{V_s}, S_{V_d})) \oplus f(tag\#\| \quad T_{V_s})$. But he can not compute the valid session key $sk = f(e(aS_{V_s}, Q_{V_d})) \| 0)$ since he needs to know value b to compute $e(aQ_{V_s}, S_{V_d})$. However, he can not figure out *b* from bQ_{V_d}. It is an ECDLP problem. Therefore, E fails to generate a session key shared with V_d and thus can not successfully launch such a KCI attack.

(b). Secure communications between vehicle and roadside device

We assume that the private key S_{Rj} of R_j had been compromised by an adversary *E*. For impersonating V_i, *E* forgs a valid route discovery message by computing h_{VR} = $H(e(Q_{Vi}, S_{Rj}))$ and $C_s = h_{VR} \oplus H(e(aQ_{V_i}, S_{R_j})) \oplus f(ES_i \| T_{V_i} \| r_l) \oplus (C \| tag\# \| T_{V_i})$. But E still can’t compute the valid session key since he needs to know value b to compute S’=$e(aQ_{Vi}, bS_{Rj})$. However, extricating *b* from bQ_{Rj} is an ECDLP problem. Therefore, *E* fails to generate a session key shared with R_j and thus can not launch a KCI attack.

(c). Secure and efficient communication scheme with privacy preservation

There are two oases in this scenario, case (a): access credential phase and (b): access secure phase. In case (a), V_i and S_i doesn’t negotiate any session key. Hence uses ignore it.

In case (b), we assume that the private key S_{Si} of S_i had been compromised to an adversary *E* who wants to impersonate V_i to access the pay-service from R_j. Although E can easily computes h_{ViSi}’ = $H(e(aQ_{Vi}, S_{Si}))$, where $a \in Z_q$ is his randomly chosen number, he can not compute the common session key *sk* shared between V_i and R_j for he needs to compute $sk = f(H(e(aS_{Vi}, bcQ_{Rj})))$ or $sk = f(H(e(caQ_{Vi}, bS_{Rj})))$, where *a*, *b*, *c* are random numbers chosen by *E*, R_j, S_i, respectively. However, *E* can know neither S_{Vi} nor bS_{Rj}. Therefore, *E* fails to generate a session key shared between with V_i and R_j, and thus can not launch a KCI attack. Even if *E* had compromised S_{Rj} and want to impersonate V_i to communicate with R_j .However, without the technology of b in computing $K_{v_i}R_j = f(H(e(aQ_{v_i}, bS_{R_j})))$ and c in computing $K_{v_i}R_j = f(H(e(aS_{v_i}, bQ_{R_j})))(= f(H(e(aQ_{v_i}, b(S_{R_j}))),$ he still can not impersonate V_i to communicate with R_j.

(3) man-in-middle attack (MIMA) resistance

This attack means that an adversary *E* who eavesdrops on the communication line between two communicating parties can make them believe that they each one talking to the intended party. But indeed, they each is talking to *E*. In scenario 1, assume that *E* replaces aQ_{V_s} with $a'Q_{V_s}$ and replaces bQ_{v_d} with $b'Q_{v_d}$ to compute, intending to compute the session key $f(H(e(a'Q_{V_s},bS_{V_d}))\|0)$ shared with V_d and to compute the session key $f(H(e(aS_{V_s},b'Q_{V_d}))\|\ 0)$ shared with V_s. However, without the knowledge of S_{V_d} and S_{V_s}. *E* can not successfully launch such a MIMA attack on our scheme. Not to mention, our scheme is anonymous. For more clear, we demonstrate the replacement in figure 8. The failure's of MIMA's on scenario 2 and scenario 3, can be reasoned in a similar way. We omit them here.

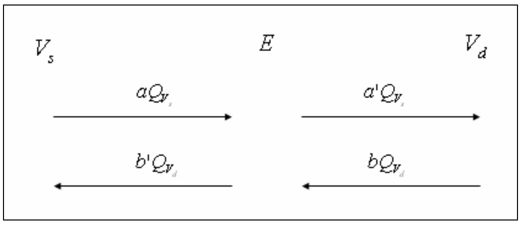


Figure 8. *E* launches an MIMA

(4) Anonymity

In Li et al.'s protocol, scenarios 1, 2, and the access authorization phase in scenario 3 have anonymous property. In the access service phase of scenario 3, only V_i communicate with R_j has anonymous property. In our scheme, the sender and receiver in all scenarios, scenario1, 2, and 3, don't send any information about their identities. They use their sending and receiving pseudonym tables to implicitly identify the communicating party's identity. For example, in the access authorization phase of scenario 3 as depicted in figure 6, V_i's identity VID_i and M_i are hashed together to from the authorized credential AC_i which is then protected by a blind factor α to form AC^*. After receiving (R_1, S_1, S_2) from S_i, V_i computes (R,S), the signature of AC_i, as

(R=αR_1, S=$\alpha^{-1}(\alpha^{-1}S_1+H(R)S_2)$). This can let S_i verify (AC_i, R, S), in the access service phase , by checking whether $e(R,S)=e(P,P)^{ACi}e(P_{Pub},Q_{Si})^{H(R)}$ holds or not without using the identity of V_i. In the access service phase, V_i sends a request message, A, B, r*equest, $aQ_{Vi,}$ T_{Vi}*,, to R_j which doesn't disclose any information about its identity. Only the right service provider S_i can compute k_{ViSi} to decrypt B to examine the validity of its signature (R, S) on AC_i. Moreover, for AC_i=H(M_i || VID_i) and R_1, S_i, S_2 transmitted from $\mathrm{S_i}$ in the access authorization phase are blinded by V_i to form (R, S), the service provider S_i can not link the user identity to the authorized credential AC_i in the access service phase. Thus, our scheme has the anonymity property.

6. Security properties and computational cost comparisons

In this session, we compare the security properties and computational cost with other related work and show the result in Table 1 and Table 2, respectively. In the following, we first list the definitions of used notations.

T_{Exp}: the time of a modular exponentiation,1 T_{Exp} ≅ 240 T_{Mul} [13]

T_{Mul}: the time of a modular multiplication

T_{XOR}: the time of a modular bit-XOR

T_{EC_Mul}: the time of a multiplication on an elliptic curve Z_p;1 T_{EC_Mul} ≅ 29 T_{Mul} [13]

T_{bp} : the computation time of a bilinear pairing

T_{hash}: the computation time of a hash function

T_{asym}: the time for an asymmetric encryption/decryption operation

T_{sym}: the time for an symmetric encryption/decryption operation

Security protocol	MIMA resistance	KCI attack resistance	mutual authentication	Anonymous property
Our scheme	Yes	Yes	Yes	Yes
Li et al.'s scheme[4]	Yes	No	Yes	No
Yang et al.'s scheme[16]	No	No	Yes	Yes
He et al.'s scheme[15]	Yes	No	Yes	No

Table 1: security comparisons

For in access authorization phase of our scheme, V_i can pre-compute $AC_i = H(M_i \| VID_i)$, $AC_i^* = \alpha * AC_i$,$\sigma_{Vi} = H(e(H(\alpha IP_{Vi})S_{Vi}, Q_{Si})$ and in the access service phase, V_i can pre-compute $h_{ViSi}' = H(e(aS_{Vi,}Q_{Si}))$, $\sigma_{Vi} = H(e(H(aIP_{Vi})S_{Vi}, Q_{Si})$, R_j can pre-compute$\alpha = H(e(bS_{Rj}, Q_{Si}))$, $\alpha_j = h_{RS} \oplus (\alpha || T_{Rj} || bQ_{Rj})$ before the communication taking place, we omit the count of these pre-computed computations in table 2.

scheme phase	Our scheme	Li et al.'s scheme[4]	Yang et al.'s scheme[16]	He et al.'s scheme[15]
Authorization Phase	$3T_{hash} + 4 T_{EC\_Mul} + 3T_{bp}$	$4 T_{XOR} + 3 T_{hash} + 3 T_{Exp} + 2 T_{asym}$	$4 T_{XOR} + 4 T_{sym} + 13 T_{Exp}$	$2 T_{asym} + T_{hash}$
Access Service Phase	$9T_{XOR} + 11 T_{hash} + 10T_{bp} + 4 T_{EC\_Mul}$	$5 T_{XOR} + 6 T_{hash} + 3 T_{Exp} + 3 T_{asym} + 2 T_{Mul}$	$4 T_{Exp} + 4 T_{sym}$	$4 T_{asym} + 4 T_{hash} + 2 T_{sym}$

Table 2: computational cost comparison

From Tables 1 and 2, we can see that our scheme is the first scheme that can resist against all known attacks and make all sender and receiver pairs anonymous. If it is not necessary in an application, for example, their R_j and S_i needs not to be anonymous in the access service phase, it can be seen that our scheme can be adapted for the situation easily. Although, our scheme has more computation overhead than others whereas it is more secure than all of the other proposed protocols in this aspect nowadays.

7. Conclusion

In this paper, we propose a secure communication scheme in vehicular ad hoc networks based on bilinear pairings. According to our analyses in Section 5 and Section 6, our scheme is the first scheme which not only has the anonymous property but also can resist against man-in-middle attack, KCI attack, and can achieve mutual authentication. That is, up to now to our knowledge, our scheme is the must robust scheme in VANETs.

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