

# ASAP-V: A Privacy-preserving Authentication and Sybil detection Protocol for VANETs

Thiago Melo de Sales<sup>a,\*</sup>, Angelo Perkusich<sup>a</sup>, Leandro Melo de Sales<sup>a</sup>, Hyggo Oliveira de Almeida<sup>a</sup>, Gustavo Soares<sup>a</sup>, Marcello de Sales<sup>b</sup>

<sup>a</sup>*Embedded Systems and Pervasive Computing Laboratory, Federal University of Campina Grande, Campina Grande, PB, Brazil*

<sup>b</sup>*Intuit, Inc. San Diego, C.A, USA*

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## Abstract

Security plays a key role in providing reliability in Vehicular Ad Hoc Networks (VANETs), which may include node authentication and non-repudiation. Moreover, users' privacy is also a key challenge and one of the main security threats in VANETs. On the other hand, there is a trade-off between authentication/non-repudiation and users' privacy, which may lead to a harmful type of network attack called *sybil* attack. In such attack, a malicious node behaves as if it is a large number of nodes. Therefore, it may decrease service reliability and significantly impact on network performance. Thus, the challenge is to provide node authentication and detect *sybil* attacks without compromising users' privacy. In this paper we propose a privacy-preserving authentication and *sybil* attack detection protocol for VANETs called *ASAP-V*. Our approach uses the group signature and the multiple-pseudonym schemes to allow authentication and non-repudiation, as well as the anonymity set concept to detect *sybil* attacks without compromising users' privacy. What is more, *ASAP-V* does not require a fixed infrastructure during *sybil* attack detection time. Experimental results suggest that *ASAP-V* is more robust against *sybil* attacks with lower average detection time, as well as lower false-positive rates and false-negative re-

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\*Corresponding author

Email addresses: thiago.sales@ee.ufcg.edu.br (Thiago Melo de Sales), perkusich@dee.ufcg.edu.br (Angelo Perkusich), leandro@embedded.ufcg.edu.br (Leandro Melo de Sales), hyggo@dsc.ufcg.edu.br (Hyggo Oliveira de Almeida), gsoares@computacao.ufcg.edu.br (Gustavo Soares), marcellodesales@gmail.com (Marcello de Sales)

silence compared to the state-of-art works.

*Keywords:*

VANET, Security, Authentication, Privacy, Sybil Attack

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## 1. Introduction

The Vehicular Ad Hoc Network (henceforth VANET) is an emerging type of Mobile Ad Hoc Network (MANET) that aims at providing vehicular safety applications, optimized vehicular traffic routing, and real-time applications for drivers and passengers, such as mobile infotainment [1]. Vehicles act as mobile nodes<sup>1</sup> that can send message to other vehicles and to roadside units (RSUs), which are fixed infrastructures along the roads that may provide vehicle connectivity in sparse or low density areas. The communication between vehicles is called V2V (Vehicle-to-Vehicle), while the communication between vehicle and RSU is called V2I (Vehicle-to-Infrastructure).

In VANET, vehicles communicate by means of the North American Dedicated Short-Range Communication (DSRC) standard, that employs the IEEE 802.11p [2] standard for wireless communication. Moreover, vehicles may send two types of messages: periodic (or beacon), and event-driven messages. The former allows a vehicle to announce its current position, speed, and direction to neighbors allowing other vehicles to perceive and predict the kinematics of the vehicle. The latter may inform sporadic events, such as road hazardous warnings (on-road obstacles, icy surfaces, weather conditions, to name a few).

The concepts behind VANET are bringing new challenges to a diverse of network research areas, including security [3]. Security has been considered a critical concern due to VANET's open wireless nature since there are no authentication and association procedures in 802.11p [4]. Thus, VANET requires fundamental security aspects in the application layer such as the vehicles' message authentication and non-repudiation. In this context, there have been a lot of new authentication approaches [5] for VANET, which basically may include the two common cryptography key models, such as symmetric and/or asymmetric keys [6], [7] and [8], as well as the group [9] and identity-based [10] signature schemes.

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<sup>1</sup>We use the terms vehicles, nodes and cars interchangeably.

However authentication and non-repudiation require a one-to-one correspondence between vehicle and identity (here represented as cryptography keys), which may allow a malicious entity to build a vehicle routing profile. This may potentially compromise users' privacy and lead to several user safety problems such as kidnapping, and undesirable tracking for mobile advertisement [11].

In order to secure users' location privacy, there are essentially three types of identity distribution: *i*) all vehicles share the same identity (same key); *ii*) each vehicle keeps multiple identities and certain groups of vehicles share a set of identities; and *iii*) each vehicle stores multiple identities (also called multiple *pseudonyms*), without sharing any identity, which are unique to each vehicle. Through a simple and secure, yet powerful mathematical and logical analysis, researchers identified that the more suitable identity assignment was the last one [12], which leads to a reasonable users' privacy and fast, yet secure revocation of cryptography keys.

Initially proposed by Raya et. al.[6], there have been many other multiple-pseudonym-based approaches for securing location privacy in VANET [7], [8], [13] and [14]. Furthermore, many researchers adopt the concept of Mix Zones [15] to prevent malicious entities from linking different vehicle's pseudonyms [16], [11], [17], [18], [19] and [20]. In this case, the main goal is to spatially and temporally build groups of vehicles in order to allow them to change their pseudonyms without compromising users' privacy.

Even so, the multiple-pseudonym approach leads to a simple yet harmful type of network attack called a *sybil* attack [21]. In *sybil* attacks, a malicious node behaves as if it is a large number of nodes. Since a vehicle may have multiple valid identities to control its privacy, a malicious vehicle can send multiple messages with different identities to inform false events in VANETs. Some examples may include false on-road obstacles and false emergency braking warning along a road, or creating an illusion of traffic congestion through beacon messages by claiming to be at different locations. The presence of a *sybil* node may also increase packet loss, as well as decrease the packet delivery ratio and the aggregated throughput due to incorrect routing paths [22], [23] and [24].

To avoid a vehicle from keeping, at the same time, multiple identities in multiple-pseudonym-based approaches, other works propose a single vehicle to store only one identity at a time [25], [26], [27], [28] and [29]. To change its identity, each vehicle requests from the RSUs along the road, one new identity which is valid only in the region where the RSU is responsible for.

These approaches lack flexibility though and they are highly dependable on the RSUs deployment methods [30], [31] and [32]. Other approaches explore the RSU and Central Authority (CA) to detect *sybil* attacks [33] and [34], as well as the relationship between time and space [35], [36] and [37] and the use of neighboring vehicles to filter malicious vehicles [38] and [39]. However, due to the tradeoff between *sybil* detection attacks and privacy-preserving authentication, these approaches suffer from *false-negative sybil* attack detections when a malicious vehicle is not detected as one.

Based on a deep investigation of the state of the art approach, this paper proposes a decentralized privacy-preserving authentication and *sybil* attack detection protocol for VANETs called *ASAP-V (Authentication and Sybil Attack detection Protocol for VANETs)*. The authentication process is based on the multiple-pseudonym approach in order to provide users' location privacy. Non-repudiation is also achieved through the Group Signature Scheme [40]. Moreover, our approach uses the anonymity set theory [41] in a multilevel fashion to detect and avoid *sybil* attacks, while still providing users' privacy control. The proposed solution does not require a fixed infrastructure during *sybil* attack detection time, nor does it require third-party services such as trust and reputation systems [42]. Instead, the *sybil* detection is coordinated through the vehicles in the vicinity. We evaluated our approach using the BAN logic [43] formal method, which proves that our multiple-pseudonym authentication approach is secure, and the *sybil* detection protocol through simulated experiments.

The contributions of this paper are summarized as follows:

- a new privacy-preserving authentication and *sybil* detection protocol;
- decentralization of the *sybil* detection approach, which does not require a fixed infrastructure during detection time;
- a resilient approach to false-negative *sybil* detection results without the support of an infrastructure. Hence, our *sybil* detection approach will always detect a malicious vehicle without compromising other's user privacy;
- it is able to detect *sybil* attacks from both beacon and event-driven messages;
- finally, our results suggest that the detection protocol provides lower average *sybil* attack detection time than the state-of-the-art approaches.

The remainder of the paper is organized as follows: Section 2 details the proposed privacy-preserving authentication and *sybil* detection approach. Section 3 discusses the experiments and results of the approach, while Section 4 briefly discusses the related works in the context of privacy-preserving *sybil* detection attacks. Finally, Section 5 presents the conclusions and future work.

## 2. A Privacy-preserving Authentication and Sybil Attack Detection Protocol for VANET

This section details the privacy-preserving authentication and *sybil* detection protocol for VANETs called *ASAP-V*. The goal is to provide strong privacy-preserving authentication and non-repudiation while detecting *sybil* attacks.

### 2.1. The Threat Model

Before detailing the main features of the *ASAP-V* protocol, it is important to point out which types of malicious users we are dealing with. Thus, it is possible to understand the main threats that they may launch in order to compromise the available services of a VANET. This information also helps us to understand what the malicious users' profiles are, how they operate during a given attack, and what are their advantages and limitations during such attack. Hence, it is possible to define and to build more reliable solutions to detect and avoid attacks.

In our case, there are two main threats to cope with: the *sybil* attack, and the potential violation of the driver's privacy. According to the Raya taxonomy [6], the former threat may be launched from malicious users classified as *insider* (users with authenticated vehicle), *malicious* or *rational* (users that aim to harm or just to seek personal profit, respectively), *active* (users that can generate authenticated packets), and *local* (users that are limited in scope). The other threat may be launched from a malicious entity classified as an *insider* or *outsider* (an intruder), *rational*, *passive* (users that only eavesdrop on the wireless channel), and *extended* (users that control several sensors that are scattered across the network).

### 2.2. The *ASAP-V* protocol description

The *ASAP-V* uses the concepts of pseudonyms and the anonymity set theory for protecting users' privacy, as well as the group signature scheme

for providing non-repudiation. To detect *sybil* attacks while preserving users' privacy, the *ASAP-V* divides the vehicles into multiple anonymity sets organized in a multilevel architecture. Therefore, each vehicle shares a set of attributes with other vehicles, but it must have at least one attribute that differs from other vehicles in a given time period.

The *ASAP-V* protocol is divided into four phases: the registration phase (Phase 1), the temporary identity (pseudonym) assignment phase (Phase 2), the *sybil* detection phase (Phase 3), and the prosecution phase (Phase 4). The next sections describe each phase, while Table 1 summarizes the notations for the protocol description.

Table 1: Notations.

Symbol	Description
$v_c$	Vehicle $c$ .
$RSU_n$	The $n^{th}$ RSU along the road.
$cert_a$	Digital certificate of an entity $a$ .
$k_{a,n}^+$	The $a$ 's $n^{th}$ public key.
$k_{a,n}^-$	The $a$ 's $n^{th}$ private key.
$cert_{a,n}$	The $a$ 's $n^{th}$ public key digital certificate.
$TK_a$	$a$ 's set of temporary public/private key pairs (pseudonyms).
$gsk_c$	Group signing key of vehicle $c$ .
$gpk$	A group public key.
$grt_c$	Group revocation token of vehicle $c$ .
$RL$	List of revoked <i>group revocation tokens</i> .
$Sign(\bullet)$	A digital signature function.
$Signed_a^m$	Entity $a$ signed message $m$ .
$a \Rightarrow b : m$	Entity $a$ sends message $m$ to $b$ .
$E(\bullet)$	An encryption function.
$sybil_{v_c}$	Vehicle $v_c$ is a <i>sybil</i> node

### 2.3. Vehicle Registration and Authentication (Phase 1)

Figure 1 summarizes the process of vehicle registration and authentication as the first step of the execution of the *ASAP-V* protocol. A CA is responsible for managing the unique identities of the vehicles by using the group signature scheme. Each vehicle has its own group sign key ( $gsk_c$ ) and also shares the group public key ( $gpk$ ) with others. Vehicles also store the digital certificate of the CA ( $cert_{CA}$ ) and the digital certificate of the roadside

units ( $cert_{RSU}$ ). Moreover, each vehicle receives one temporary (pseudonym) asymmetric key pair and its certificate ( $k_{c,1}^+, k_{c,1}^-, cert_{c,1}$ ). In case of judicial disputes, the CA is the only entity that can trace the original vehicle identity from a given message using its group manager secret key ( $gmsk$ ).

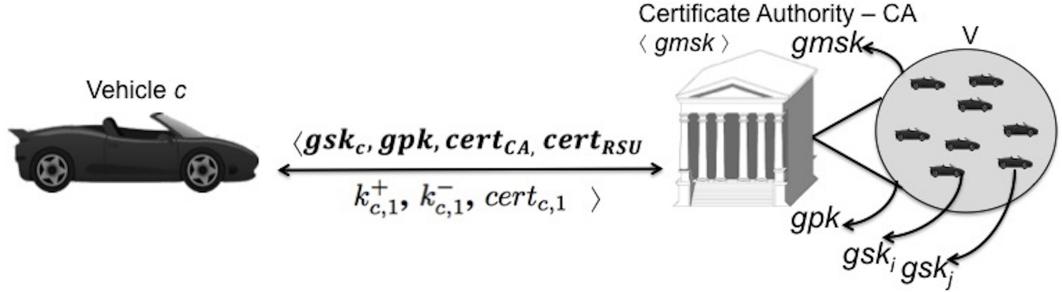


Figure 1: Vehicle registration and authentication.

The second step of the registration phase aims to cluster each vehicle into multiple sets of vehicles  $AS_{i,j}$  ( $i, j \in \mathbb{N}^*; 1 \leq i \leq m, 1 \leq j \leq n$ ). Each set  $AS_{i,j}$  has all of the properties of the anonymity set theory. According to Figure 2, the anonymity sets  $AS_{m,n}$  are organized in  $m$  levels, where each level has  $n$  anonymity sets. The proposed multilevel anonymity set architecture has the following properties:

1. Let  $V = \{v_1, v_2, \dots, v_p\}$  the set of all vehicles registered.  $p = |V|$  is the total number of vehicles and  $K\text{-AS} = \{AS_{1,1}, AS_{1,2}, \dots, AS_{1,n}, \dots, AS_{2,1}, AS_{2,2}, \dots, AS_{2,n}, \dots, AS_{m,n}\}$  is the set of all anonymity sets;
2. Each vehicle must belong to at least  $k$  sets ( $1 < k < n$ ) in each level.  $AS_c$  denotes the set of all anonymity sets that vehicle  $v_c$  belongs to ( $AS_c \subseteq K\text{-AS}$ ). For instance,  $AS_c = \{AS_{1,1}, AS_{1,3}, AS_{1,12}, AS_{1,22}, AS_{1,35}, AS_{2,5}, AS_{2,9}, \dots, AS_{m,n}\}$  if it belongs to anonymity sets  $AS_{1,1}, AS_{1,3}$  etc.;
3. Each anonymity set  $AS_{i,j}$  has a digital certificate  $cert_{AS_{i,j}}$ . Thus, if vehicle  $v_c$  belongs to  $AS_{i,j}$ , then  $v_c$  must store  $cert_{AS_{i,j}}$ . Formally,  $v_c \in AS_{i,j} \rightarrow cert_{AS_{i,j}} \in CERT_{AS_c}$ , where:
  - (a)  $CERT_{AS_c}$  is the set of all anonymity sets' digital certificates in which the vehicle  $v_c$  belongs to; and,
  - (b) for a given time interval  $t$ , a vehicle  $v_c$  must choose a subset  $CERT_{AS_c}^t$  of anonymity set digital certificates ( $CERT_{AS_c}^t \subseteq CERT_{AS_c}$ ) that comprises only one digital certificate per level.

4. Any two vehicles  $v_c$  and  $v_{c'}$  in  $AS_{1,j}$  must not belong to the same anonymity set of some lower level. Formally,  $v_c, v_{c'} \in AS_{1,j} \rightarrow \exists AS_{i,r} \in K\text{-AS} | v_c \in AS_{i,r} \oplus v_{c'} \in AS_{i,r} \{i, j, r \in \mathbb{N}^* : i > 1, 1 \leq j \leq n, 1 \leq r \leq n\}$ . Therefore,  $CERT_{AS_c} - CERT_{AS_{c'}} \neq \emptyset$ .

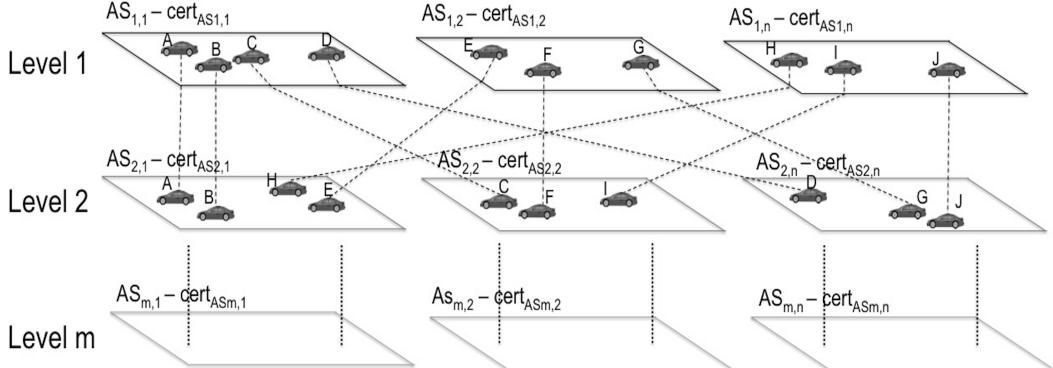


Figure 2: The Multilevel *ASAP-V* Architecture.

#### 2.4. Temporary Key Assignment (Phase 2)

In order to protect users' privacy, the multiple-pseudonym-based approach is used, and the second phase is responsible for managing pseudonym assignments to vehicles. In the *ASAP-V* protocol, cryptography asymmetric key pairs represent vehicle pseudonyms. For instance, the key pair  $k_{c,i}^+ / k_{c,i}^-$  and its certificate  $cert_{c,i}$  is the  $i^{th}$  pseudonym of the vehicle  $v_c$ . Vehicles obtain temporary keys from authenticated RSUs available along the roads. Listing 1 shows the temporary key assignment protocol, which is detailed as follows:

Listing 1: Pseudonym renewal protocol.

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- 1 Step (1):  $v_c \Rightarrow RSU_n: \sigma = \text{Sign}(gpk, gsk_c, m), cert_{c,i}, cert_{c,TPD}$   
 2 Step (2):  $RSU_n:$   
 3 Step (2.1): Verify  $(gpk, \sigma, m)$   
 4 Step (2.2): Generates the set  $TK_c$  of w temporary key pairs  
 5 and authenticates (signs) each key pair  
 6 Step (3):  $RSU_n \Rightarrow v_c: E(k_{c,i}^+, TK_c, cert_{c,TPD})$
- 

- In Step 1, a vehicle  $v_c$  requests the set of temporary keys from a given  $RSU_n$ . This step includes the request message  $m$  digitally signed using group signature, as well as one temporary  $v_c$ 's digital certificate

$(cert_{c,i})$ , and a tamper-proof device's digital certificate  $(cert_{c,TPD})$ , which is deeply discussed later;

- In Step 2, the  $RSU_n$  checks two parameters: first, it verifies if the group revocation token  $(grt_c)$  of vehicle  $v_c$  is not in the Revocation List (RL) and if the message's timestamp (the time that  $v_c$  signed  $\sigma$ ) is within a reasonable threshold in order to avoid replay attacks [44] (Step 2.1). The *Verify* function represents this process and is formally described in the Equation 1. The CA is responsible for periodically sharing an updated version of RL and is detailed in Section 2.6.

$$\begin{aligned} Verify(gpk, \sigma, m) = valid \leftrightarrow grt_c \notin RL \wedge \\ (current\ timestamp - timestamp(\sigma) \leq threshold) \end{aligned} \quad (1)$$

If valid, the  $RSU_n$  generates the new set of keys  $TK_c = \{(k_{c,1}^+ / k_{c,1}^-), (k_{c,2}^+ / k_{c,2}^-), (k_{c,3}^+ / k_{c,3}^-) \dots, (k_{c,w}^+ / k_{c,w}^-)\}$  for vehicle  $v_c$  and authenticates each key (Step 2.2), which is formally represented as follows:

$$\forall k_{c,i}^+ \in TK_c (1 \leq i \leq w), Sign(k_{RSU}^-, k_{c,i}^+) = cert_{c,i}. \quad (2)$$

- In Step 3, the  $RSU_n$  returns the new set of temporary keys to the vehicle  $v_c$  by encrypting the message with the  $i^{th}$   $v_c$ 's temporary public key received in Step 1 ( $k_{c,i}^+$  is extracted from  $cert_{c,i}$ ). This procedure avoids malicious users from eavesdropping on the wireless channel to take the new set of temporary key pairs  $TK_c$ .

Vehicles must store all anonymity set digital certificates and temporary keys in a tamper-resistant Hardware Security Module (HSM), also known as tamper-proof device (TPD - see Figure 3). This avoids malicious users from copying keying material that belongs to other vehicles. Moreover, the digital certificate  $cert_{c,TPD}$  (Step 1) avoids the vehicle  $v_c$  from installing the keys on another TPD. A TPD is also responsible for signing messages on behalf of the vehicle's applications, as well as to check message authenticity received from other vehicles and to manage the change of pseudonyms. It is important to point out that IEEE 1609.2, which describes all security aspects of the Wireless Access for Vehicular Environment (WAVE) architecture, also

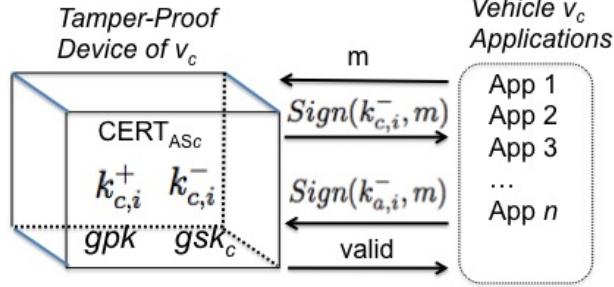


Figure 3: A tamper-proof device (TPD), which goes inside of a vehicle, stores key materials, while applications request message digital signatures, digital signature authenticity checking and decryption, as well as pseudonym management.

emphasizes that whenever practical, keying material must be protected from exposure in a TPD.

From now on, a legitimate vehicle  $v_c$  may send messages to the network. Figure 4 depicts the message format and its field goals. Each message is digitally signed with the  $i^{th}$   $v_c$ 's temporary private key ( $k_{c,i}^-$ ), which aims at providing message authenticity and integrity; the *event* field is the message's event type (e.g., beacon, accident warning etc.);  $cert_{AS1,j}$  is the (current) first level anonymity set digital certificate ( $cert_{AS1,j} \in CERT_{AS_c}^t$ ) that the vehicle  $v_c$  belongs to (this field allows one or more anonymity set digital certificates, as discussed in Section 2.5);  $\sigma$  is the group signature of data  $d$ , which allows privacy-preserving non-repudiation;  $cert_{c,i}$  is the  $i^{th}$   $v_c$ 's public key digital certificate which also allows other vehicles to evaluate the correctness of the message's digital signature; and *timestamp* is the time in which the vehicle  $v_c$  signs the message, which aims to detect replay attacks.

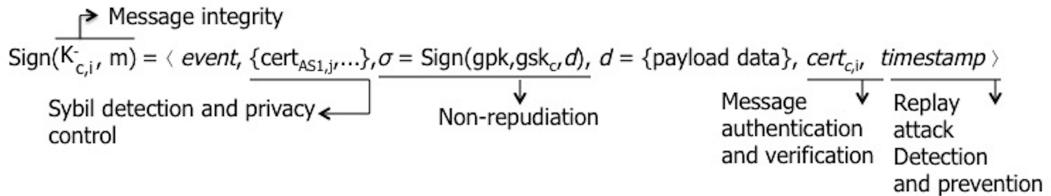


Figure 4: The format of beacon or event-driven messages and the field goals.

The multiple-pseudonym approach proposed herein may use any of the pseudonym change approaches available in the literature [16], [11], [17], [18], [19] and [20]. However, the change of pseudonyms may imply a change on the current anonymity set digital certificates  $CERT_{AS_c}^t$  that the vehicle  $v_c$  must use. For instance, suppose that  $v_c$  belongs to the following anonymity sets of 5 levels ( $m = 5$ ):  $AS_c = \{AS_{1,1}, AS_{1,3}, AS_{1,12}, AS_{1,22}, AS_{1,35}, AS_{2,5}, AS_{2,9}, AS_{2,18}, AS_{2,23}, AS_{3,6}, AS_{3,15}, AS_{3,21}, AS_{4,9}, AS_{4,27}, AS_{4,32}, AS_{5,2}, AS_{5,11}, AS_{5,23}, AS_{5,43}\}$ . If  $v_c$  is currently sending messages with pseudonym  $cert_{c,3} \in TK_c$  and its current anonymity set digital certificates is  $CERT_{AS_c}^{t_1} = \{cert_{AS_{1,3}}, cert_{AS_{2,18}}, cert_{AS_{3,6}}, cert_{AS_{4,32}}, cert_{AS_{5,23}}\}$ , then the change from the pseudonym  $cert_{c,3}$  to  $cert_{c,4} \in TK_c$  requires a new subset  $CERT_{AS_c}^{t_2}$  of anonymity set digital certificates. This approach aims to avoid pseudonym linkage, in which an eavesdropper is able to associate two or more pseudonyms that belong to the same vehicle in different time intervals.

For instance, suppose that two vehicles  $v_A$  and  $v_B$  belong to the first level anonymity sets  $AS_{1,2}$  and  $AS_{1,3}$ , respectively. Hence, their messages must include at least the digital certificates  $cert_{AS_{1,2}} \in CERT_{AS_A}^{t_1}$  and  $cert_{AS_{1,3}} \in CERT_{AS_B}^{t_1}$ , respectively. Now consider the following scenario depicted in Figure 5: both vehicles form a mix zone and start a pseudonym change process at time  $t_1$ . If vehicle  $v_A$  changes the pseudonym  $cert_{A,1} \in TK_A$  to  $cert_{A,2} \in TK_A$ ,  $v_B$  changes from  $cert_{B,1} \in TK_B$  to  $cert_{B,2} \in TK_B$ , but they also keep their current anonymity set digital certificates as  $cert_{AS_{1,2}}$  and  $cert_{AS_{1,3}}$  at time  $t_2$  (i.e.:  $CERT_{AS_A}^{t_2} = CERT_{AS_A}^{t_1}$  and  $CERT_{AS_B}^{t_2} = CERT_{AS_B}^{t_1}$ ), then an eavesdropper may link both changes by analyzing the first level anonymity set digital certificates (i.e.:  $cert_{AS_{1,2}}$  and  $cert_{AS_{1,3}}$ ). On the other hand, if both vehicles also change their current anonymity set digital certificates at time  $t_2$  ( $CERT_{AS_A}^{t_1} \neq CERT_{AS_A}^{t_2}$  and  $CERT_{AS_B}^{t_1} \neq CERT_{AS_B}^{t_2}$ ), then it is difficult to link new and previous pseudonyms.

The TPD will not change the current subset from  $CERT_{AS_c}^t$  to  $CERT_{AS_c}^{t+1}$  if the last change occurred in a time less than  $\tau$  units of time. This decision helps to avoid *sybil* attacks, which comprise the third phase of the ASAP-V protocol and is discussed on the next section.

### 2.5. The Sybil Attack Detection (Phase 3)

The third phase of the ASAP-V protocol is the *sybil* attack detection itself. A *sybil* attack may be explored from malicious users that modify their vehicles to launch the attack. The *sybil* attack is defined as follows:

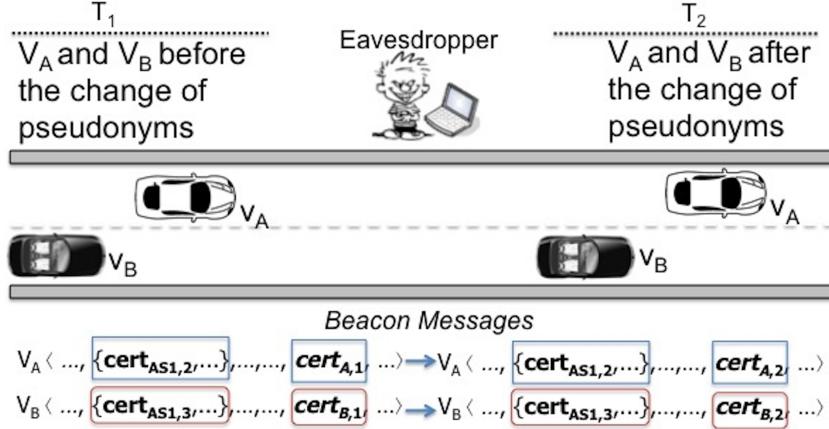


Figure 5: An eavesdropper may link old and new pseudonyms if vehicles do not change their current anonymity set digital certificates during the change of pseudonyms.

**Definition 1.** *In the sybil attack, a vehicle uses multiple identities to disseminate the same false event. This vehicle is so called the sybil vehicle or the sybil node.*

In VANETs, vehicles disseminate events in order to provide vehicular safety applications. Examples may include accident reporting, an approaching safety vehicle, and electronic emergency braking warnings, to name a few. These events are classified as sporadic events. Beacon messages, which allow vehicles to perceive and predict the kinematics of other vehicles, may also be an event and are classified as periodic events. An event is defined as follows:

**Definition 2.** *An event, as defined in [33], is represented as a tuple  $\langle \text{evt}, l, t \rangle$ , where evt is the event type, l and t are the location and the time interval in which the event occurred, respectively.*

The privacy-preserving *sybil* detection phase explores the multilevel anonymity set architecture (described in Section 2.3) to detect *sybil* attacks from beacon and event-driven messages. In short, the properties 1 to 3 provide privacy control, while property 4 allows the *sybil* detection process. The basic detection concept is as follows: any two or more messages with different pseudonyms, which disseminate the same event, cannot include the same

subset of anonymity set digital certificates. Hence, during a *sybil* attack, the system must evaluate the Equation 3, where  $V_l$  is the set of vehicles in the transmission range in a given location  $l$ .

$$\forall v_i \in V_l, \bigcap_{i=0}^{|V_l|} CERT_{AS_{v_i}}^t = \emptyset \quad (3)$$

In beaconing-like messages, as long as a vehicle  $v_c$  receives messages from other vehicles  $v_i$  in a given location  $l$  ( $v_i, v_c \in V_l, 0 \leq i \leq |V_l|$ ),  $v_c$  must check if these messages have different sets of anonymity set digital certificates. On the other hand, if any vehicle  $v_d$  ( $v_d \in V_l$ ) receives beacon messages from vehicles  $v_i$  that include the same  $v_d$ 's subset of anonymity set digital certificates, then vehicles  $v_d$  and  $v_i$  gradually attach, into the beacon messages, the digital certificate of the next deeper anonymity set until the Equation 3 is satisfied where all messages are distinguishable among each other.

For instance, consider that vehicles  $v_a$ ,  $v_b$  and  $v_e$  belong, among other anonymity sets, to the following anonymity sets for 5 levels ( $m = 5$ ), respectively:  $AS_a = \{AS_{1,2}, AS_{2,4}, AS_{3,2}, AS_{4,4}, AS_{5,1}\}$ ,  $AS_b = \{AS_{1,3}, AS_{2,4}, AS_{3,7}, AS_{4,6}, AS_{5,2}\}$  and  $AS_e = \{AS_{1,3}, AS_{2,4}, AS_{3,5}, AS_{4,6}, AS_{5,8}\}$ . Thus, each vehicle also stores its current anonymity set digital certificates as  $CERT_{AS_a}^t = \{cert_{AS_{1,2}}, cert_{AS_{2,4}}, cert_{AS_{3,2}}, cert_{AS_{4,4}}, cert_{AS_{5,1}}\}$ ,  $CERT_{AS_b}^t = \{cert_{AS_{1,3}}, cert_{AS_{2,4}}, cert_{AS_{3,7}}, cert_{AS_{4,6}}, cert_{AS_{5,2}}\}$ ,  $CERT_{AS_e}^t = \{cert_{AS_{1,3}}, cert_{AS_{2,4}}, cert_{AS_{3,5}}, cert_{AS_{4,6}}, cert_{AS_{5,8}}\}$ . Moreover, suppose that the vehicles also store  $w$  temporary key pairs  $TK_a$ ,  $TK_b$  and  $TK_e$ .

Consider the scenario depicted in Figure 6 and also suppose that vehicles  $v_a$  and  $v_b$  periodically send beacon messages with identities  $cert_{a,1} \in TK_a$  and  $cert_{b,1} \in TK_b$ . Listing 2 describes the beacon messages, where  $sp_v$ ,  $pos_v$  and  $dir_v$  are the current speed, position, and direction of vehicle  $v$ .

**Listing 2:** Vehicles  $v_a$  and  $v_b$  send beacon messages.

- 
- 1 A:  $Sign(k_{a,1}^-, m) = \langle \text{beacon}, (cert_{AS_{1,2}}), \sigma = Sign(gpk, gsk_a, d), d = \{sp_a, pos_a, dir_a\}, cert_{a,1} \rangle$   
 2 B:  $Sign(k_{b,1}^-, m) = \langle \text{beacon}, (cert_{AS_{1,3}}), \sigma = Sign(gpk, gsk_b, d), d = \{sp_b, pos_b, dir_b\}, cert_{b,1} \rangle$
- 

Now suppose that vehicle  $v_e$  is a *sybil* node and alternately also keeps sending the following beacon messages with 3 different identities  $cert_{e,1}$ ,  $cert_{e,2}$ ,  $cert_{e,3} \in TK_e$ :

**Listing 3:** *Sybil* vehicle  $v_e$  sends beacon messages with multiple identities.

- 
- 1 E:  $Sign(k_{e,1}^-, m) = \langle \text{beacon}, (cert_{AS_{1,3}}), \sigma = Sign(gpk, gsk_e, d), d = \{sp_e, pos_e, dir_e\}, cert_{e,1} \rangle$

$$\begin{aligned}
2 \ E_1 : \ Sign(k_{e,2}^-, m) &= \langle \text{beacon}, \ (cert_{AS_{1,3}}), \ \sigma = Sign(gpk, gsk_e, d), \ d = \{sp_e, pos_e, dir_e\}, cert_{e,2} \rangle \\
3 \ E_2 : \ Sign(k_{e,3}^-, m) &= \langle \text{beacon}, \ (cert_{AS_{1,3}}), \ \sigma = Sign(gpk, gsk_e, d), \ d = \{sp_e, pos_e, dir_e\}, cert_{e,3} \rangle
\end{aligned}$$


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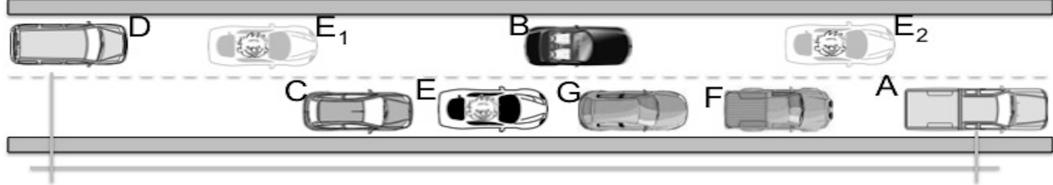


Figure 6: Sybil vehicle E sends three different beacon messages with three identities.

So, all other vehicles around cannot distinguish if messages with identities  $cert_{e,1}$ ,  $cert_{e,2}$  and  $cert_{e,3}$  are from different vehicles that belong to the same first level anonymity set ( $AS_{1,3}$ ), or from a *sybil* node. In addition, from the  $v_a$ 's perspective, the messages from  $v_b$  are also suspected, since they also include the same first level anonymity set digital certificate ( $cert_{AS_{1,3}}$ ) of  $v_e$ . After receiving the first beacon messages from  $v_e$ ,  $v_b$  sends the next beacon messages with the second level anonymity set digital certificate, that is,  $cert_{AS_{2,4}}$ . Thus,  $v_b$  sends the message as follows:  $Sign(k_{b,1}^-, m) = \langle \text{beacon}, (cert_{AS_{1,3}}, cert_{AS_{2,4}}), \sigma = \dots, d = \dots, cert_{b,1} \rangle$ .

Likewise,  $v_e$  also sends the next messages including the next anonymity set digital certificate. In this case, since  $v_e$  knows that it also belongs to anonymity set  $AS_{2,4}$ , it also must include the third anonymity set digital certificate otherwise vehicles in the vicinity will only drop the messages and the *sybil* attack has no effect. Therefore, the messages are as follows:  $Sign(k_{e,1}^-, m) = \langle \text{beacon}, (cert_{AS_{1,3}}, cert_{AS_{2,4}}, cert_{AS_{3,5}}), \sigma = \dots, d = \dots, cert_{e,1} \rangle$ ,  $Sign(k_{e,2}^-, m) = \langle \text{beacon}, (cert_{AS_{1,3}}, cert_{AS_{2,4}}, cert_{AS_{3,5}}), \sigma = \dots, d = \dots, cert_{e,2} \rangle$  and  $Sign(k_{e,3}^-, m) = \langle \text{beacon}, (cert_{AS_{1,3}}, cert_{AS_{2,4}}, cert_{AS_{3,5}}), \sigma = \dots, d = \dots, cert_{e,3} \rangle$ . Finally, now  $v_b$  attaches the next anonymity set digital certificate:  $Sign(k_{b,1}^-, m) = \langle \text{beacon}, (cert_{AS_{1,3}}, cert_{AS_{2,4}}, cert_{AS_{3,7}}), \sigma = \dots, d = \dots, cert_{b,1} \rangle$ . Once messages with identity  $cert_{b,1}$  differ from messages with identities  $cert_{e,1}$ ,  $cert_{e,2}$  and  $cert_{e,3}$ , then  $v_b$  is a benign vehicle, while messages from  $v_e$  (multiple identities with the same set of anonymity set digital certificates) may be malicious since it is impossible to satisfy Equation 3. From  $v_a$ 's and  $v_b$ 's point of view, messages with identities  $cert_{e,1}$ ,  $cert_{e,2}$  and  $cert_{e,3}$  are suspected.

After a short time interval receiving messages with different identities,

but still containing the same anonymity set digital certificates, the vehicles in the vicinity (e.g.:  $v_a$  and  $v_b$ ) may conclude that messages with identities  $\text{cert}_{e,1}$ ,  $\text{cert}_{e,2}$  and  $\text{cert}_{e,3}$  come from a *sybil* node (e.g.:  $v_e$ ). Equation 4 defines this short time interval that vehicles  $v_a$  and  $v_b$  must wait for vehicle  $v_e$  to send the next anonymity set digital certificate after receiving the last one.  $L$  is the maximum number of anonymity set levels,  $pL$  is the number of anonymity set certificates already presented by the target vehicle, and  $N$  is the number of neighboring nodes. Therefore, after  $\delta$  ms, vehicles  $v_a$  and  $v_b$  may evaluate the vehicle  $v_e$  as a *sybil* node.

$$\delta = \text{beacon interval} + (L - pL) * N/L \quad (4)$$

Equation 4 defines a dynamic behavior in which  $\delta$  must be high as the number of vehicles in the transmission range is high, but, in order to minimize the impact of the *sybil* attack,  $\delta$  smoothly decreases as the number of presented anonymity set digital certificates per level within the beacon messages increases. A vehicle evaluates Equation 4 for each new beacon message that it receives from target (probably malicious) vehicles.

In order to detect *sybil* attacks from event-driven messages, each vehicle  $v_i$  must attach all current anonymity set digital certificates ( $\text{CERT}_{AS_i}^t$ ) in the message. Suppose the vehicle  $v_a$  reports an emergency braking alert (EBBL). Hence, the messages would be as follows:  $\text{Sign}(k_{a,1}^-, m) = \langle \text{EBBL}, (\text{cert}_{AS_{1,2}}, \text{cert}_{AS_{2,4}}, \text{cert}_{AS_{3,2}}, \text{cert}_{AS_{4,4}}, \text{cert}_{AS_{5,1}}), \sigma = \text{Sign}(gpk, gsk_a, d), d = \dots, \text{cert}_{a,1} \rangle$ . According to property 4 of the multilevel anonymity sets architecture, it is impossible for two different vehicles to announce the same event with the same *anonymity set digital certificates*. This approach definitely avoids a *sybil* attack from event-driven messages without compromising the privacy of the vehicles.

## 2.6. Sybil Attack Prosecution Phase (Phase 4)

Once a misbehaved vehicle  $v_e$  is detected, all other vehicles  $v_i$  in  $l$  store  $v_e$ 's messages as a set of sample  $n$  suspected messages  $M_{e,n}$ . Thus, a prosecution protocol is executed as illustrated in Figure 7. In Step 1, each vehicle  $v_i$  generates a digitally signed prosecution message and sends it to the nearby RSU. Each vehicle  $v_i$  that detected the *sybil* vehicle (e.g.:  $v_a$  and  $v_b$ ) uses its group signing key (e.g.:  $gsk_a$  and  $gsk_b$ ) to digitally sign the prosecution message, and also attach the sample of suspected messages evaluated as *sybil* messages (e.g.:  $m_{e,1}, m_{e,2}, m_{e,3}, \dots, m_{e,n} \in M_{v_e,n}$ ). In Step 2, the RSU

forwards the received prosecution messages to the CA. In Step 3, the CA extracts the suspected messages from the prosecution message and traces their owners using its  $gmsk$  key. If all  $n$  messages describe the same event  $evt$  and are originated from the same vehicle  $v_e$  (it digitally signed all messages), then the CA resolves each message to the same unique vehicle identity (i.e.: a *sybil* vehicle). Equation 5 formally describes the verification process. Finally, the CA inserts the malicious vehicle's group revocation token (e.g.:  $grt_e$ ) into the revocation token list (RL), and sends the RL to all RSUs in Step 4.

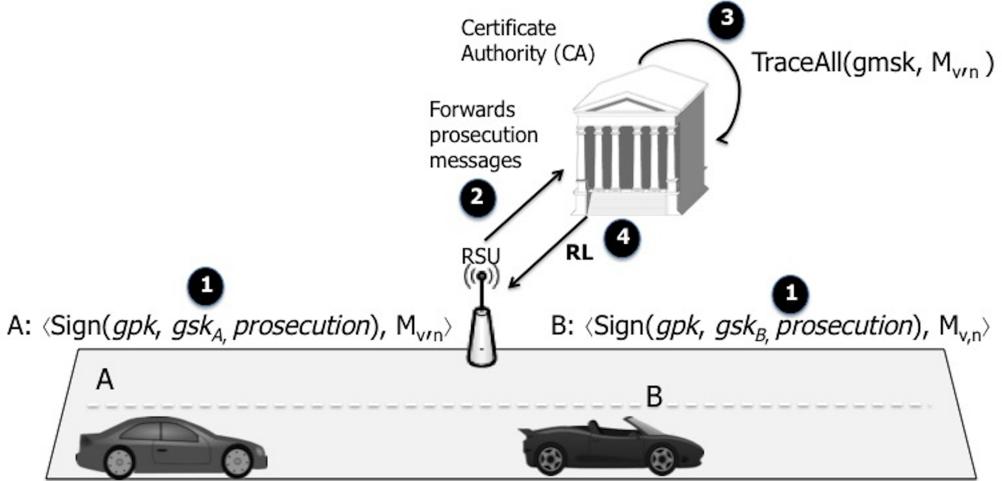


Figure 7: The prosecution of misbehaved vehicles.

$$\begin{aligned} TraceAll(gmsk, M_{v_e,n}) = & \forall m_i, m_j \in M_{v_e,n}, (evt_i \in m_i = evt_j \in m_j) \wedge \\ & (Signed_{v_e}^{\sigma_i} \wedge Signed_{v_e}^{\sigma_j}) \leftrightarrow sybil_{v_e}\{i, j, n \in \mathbb{N} : 1 \leq i \leq n, 1 \leq j \leq n, i \neq j\} \end{aligned} \quad (5)$$

### 3. Protocol Analysis and Experimental Results

This section presents the experimental results of the proposed solution. First, we analyze the management, storage, computation, and communication overheads; mainly w.r.t. the cryptography key management and its processing. Afterwards, we show the correctness verification of the pseudonym renewal protocol. Finally, we present the simulation results of the proposed *sybil* detection approach.

### 3.1. Management, Storage, Computation and Communication Overheads

In spite of the number of security properties involved, the following overhead analysis shows that *ASAP-V* is a lightweight protocol within the context of VANETs.

- *Management overhead*: the CA is only responsible for managing the anonymity set digital certificates and the group signing keys, which do not change frequently. In addition, vehicles must only manage the pseudonyms renewal which requires minimal changes;
- *Storage overhead*: the CA stores the anonymity set digital certificates, which takes  $n * m * 56$  bytes long using a 224bits Elliptic Curve Digital Signature Algorithm (ECDSA) [45], and the public (800 bytes) and private group signing keys, which take  $|V| * 64$  bytes long using a representative Efficient Group Signature Algorithm (EGSA) [46]. It is important to note that the CA does not need to store vehicle pseudonyms, which reduces the storage overhead found in other works, such as [33] and [34]. Moreover, the RSUs store the Revocation List (contains each vehicle's group revocation tokens), which is also small when compared to traditional revocation lists of the public key infrastructure (which stores all non-valid public keys). Finally, vehicles store only the set of  $w$  pseudonyms (public/private key pairs and digital certificates), which are  $w * 56$  bytes long, as well as the anonymity set digital certificates, which are  $k * m * 56$  bytes long, and the public (800 bytes) and private group signing keys (64 bytes);
- *Computation Overhead*: the computation costs were evaluated on a 2.9 GHz Intel Core i7 processor for V2V and V2I communications:
  - On V2V communication: to sign a message in a V2V communication (message detailed in Figure 4), a vehicle  $v_c$  first signs the payload  $d$  ( $\sigma$ ) with its group signing key  $gsk_c$  using EGSA, which takes 11 ms; and after that, the whole message with its  $i^{th}$  temporary private key  $k_{c,i}^-$ , which takes 0,1 ms using ECDSA. Thus,  $v_c$  takes 11,1 ms to sign the whole message. On the other hand, when another vehicle  $v_e$  receives the message, it verifies the message's authentication in two steps: first it verifies the sender's ( $v_c$ ) public key  $k_{c,i}^+$  authenticity, which is available in the digital certificate  $cert_{c,i}$ ; and second, the whole message authentication

itself. Thus, a vehicle must first check the  $cert_{c,i}$  authentication using the RSU's public key  $k_{RSU}^+$ , which takes  $0,4\text{ ms}$ , and then the whole message's authentication, which also takes  $0,4\text{ ms}$ . The total message verification process takes  $0,8\text{ ms}$ . It is important to point out that a vehicle does not need to check  $cert_{c,i}$  of the subsequent messages. Moreover,  $v_e$  does not need to check the group digital signature  $\sigma$  since it is used only for non-repudiation purposes. In short, a vehicle may sign 90 messages per second, while it may verify 1250 messages per second;

- On V2I communication: on Phase 2 of the proposed protocol, a vehicle signs the request message  $m$  with its group signing key, which takes  $11\text{ ms}$  (Step 1); when a RSU receives the message  $m$  (Step 2), it checks the group signature authentication, which takes  $132\text{ ms}$ , generates each  $w$  key pair, which takes  $w*83\text{ ms}$  and signs  $w$  key pairs, which takes  $w*0,1\text{ ms}$ . Hence, the total computation cost is  $11\text{ ms} + w*83\text{ ms} + w*0,1\text{ ms}$ . In order to avoid high overhead during key generation, the RSU may generate the set of key pairs previously without waiting for vehicles' pseudonym renewal requests, which would reduce  $w*83\text{ ms}$  in the computation cost.

- *Communication Overhead:*

- On V2V communication: the beacon message size basically requires one anonymity set digital certificate  $cert_{AS_{1,j}}$ , which takes 56 bytes in a  $224bit$  ECDSA; the group signature  $\sigma$  of the payload  $d$ , which takes 225 bytes (128 bits security level); the  $i^{th}$  temporary digital certificate  $cert_{v,i}$ , which takes 56 bytes; and finally, the whole message authentication, which also takes 56 bytes. Therefore, the minimum message size to be transmitted is 393 bytes. On the other hand, as the number of anonymity set digital certificates increases due to the *sybil* detection phase, the message size is 56 bytes longer. On the next subsection, we evaluate the *sybil* detection process for Levels 4, 5 and 6;
- On V2I communication: during Phase 2, a vehicle  $v_c$  signs a request message including a group signature, which takes 225 bytes (128 bits security level); and attaches the  $i^{th}$  temporary digital certificate, which takes 56 bytes, and also the tamper-proof device's

digital certificate  $cert_{c,TPD}$ , which also takes 56 bytes. Hence, the total message size is 337 bytes. The RSU response includes the new set of temporary key pairs  $TK_v$ , which is  $w * 56$  bytes longer, as well as the tamper-proof device's digital certificate and the message authentication, which also take 56 bytes. Thus, the total response size is  $w * 56 + 2 * 56$  bytes.

In a VANET, energy and computational power constraints are not relevant issues when compared to other types of wireless sensor networks. Therefore, our combination of cryptography schemes, such as group signature and asymmetric key pairs, are feasible candidates to provide privacy-preserving authentication and non-repudiation in VANETs.

### 3.2. Correctness Verification of the Pseudonym Renovation Protocol

In this section, we formally verify the correctness of the pseudonym renewal protocol (Phase 2) based on the BAN logic, which is a formal logic used to reason about beliefs, encryption, and protocols. The following four postulates of the BAN logic were used in order to prove the correctness of the proposed protocol. Let  $P$  and  $Q$  be two abstract entities, while  $X$  and  $Y$  are formulas:

- A. 
$$\frac{P \models Q \stackrel{Y}{\Rightarrow} P, P \triangleleft \langle X \rangle Y}{P \models Q \mid \sim X};$$
- B. 
$$\frac{P \models \#(X), P \models Q \mid \sim X}{P \models Q \models X};$$
- C. 
$$\frac{P \models Q \Rightarrow X, P \models Q \models X}{P \models X};$$
- D. 
$$\frac{P \models \#(X)}{P \models \#(Y, X)}.$$

Table 2 summarizes the idealized protocol in BAN Logic syntax, with the following nomenclatures:  $Y$  is the  $i^{th}$   $v_c$ 's temporary digital certificate  $cert_{c,i} \in Tk_{c,w}$ ;  $Z$  is the  $i^{th}$   $v_c$ 's public key  $k_{c,i}^+ \in cert_{c,i}$ ;  $X$  denotes the request on Step 1 of the proposed pseudonym renewal protocol; and, finally,  $P$  represents the new set of temporary public/private key pairs  $Tk'_{c,w}$  to vehicle  $v_c$ .

Table 2: Idealized Protocol.

Steps	BAN Description
Step 1	$v_c \rightarrow RSU_n : < X > Y$
Step 3	$RSU_n \rightarrow v_c : \{P\}_Z$

The Steps 1 through 8 bellow describe the assumptions considered to the verification process, while Table 3 summarizes the goals of correctness verification. The goal is to check if the vehicle and RSU trust the received messages. In other words, if the request is fresh and, hence, it is not originated from replay attacks, as well as if the message's data are authentic.

1.  $RSU_n \models v_c \xrightarrow{Y} RSU_n;$
2.  $RSU_n \models \#(X);$
3.  $RSU_n \models v_c \Rightarrow X;$
4.  $RSU_n \triangleleft < X > Y;$
5.  $v_c \triangleleft < P > Z;$
6.  $v_c \models RSU_n \xrightarrow{Z} v_c;$
7.  $v_c \models RSU_n \Rightarrow P;$
8.  $v_c \models \#(P).$

Table 3: Goals of the Correctness Verification.

Goal	BAN Syntax	Description
1	$RSU_n \models X$	RSU believes the request $m$ .
2	$RSU_n \models \#(Y, X)$	RSU believes that the request $m$ and the $v_c$ 's digital certificate are fresh.
3	$v_c \models P$	$v_c$ believes the new set of pseudonym.
4	$v_c \models \#(P, Z)$	$v_c$ believes that the RSU response is fresh.

The verification process is as follows:

- I. Postulate A applied to assumptions 1 and 4:

$$\frac{RSU_n \models v_c \xrightarrow{Y} RSU_n, RSU_n \triangleleft < X > Y}{RSU_n \models v_c | \sim X} : \text{if RSU believes that it shares the secret } Y \text{ with vehicle } v_c, \text{ and it receives the request } X \text{ combined with } Y, \text{ then it believes that } v_c \text{ once sent } X;$$

II. Postulate B applied to assumption 2 and to result I:

$$\frac{RSU_n \models \#(X), RSU_n \models v_c | \sim X}{RSU_n \models v_c \models X} : \text{if RSU believes that the request } X \text{ could have been uttered only recently (through the message timestamp), and the RSU believes that the vehicle } v_c \text{ once sent } X \text{ (due to the } i^{\text{th}} \text{ digital certificate } cert_{k,i}), \text{ then the RSU believes that } v_c \text{ believes } X;$$

III. Postulate C applied to assumption 3 and result II:

$$\frac{RSU_n \models v_c \Rightarrow X, RSU_n \models v_c \models X}{RSU_n \models X} : \text{if the RSU believes that the vehicle } v_c \text{ has jurisdiction over } X \text{ (due to the } i^{\text{th}} \text{ digital certificate } cert_{k,i}), \text{ then the RSU trusts } v_c \text{ on the truth of } X. \text{ Hence, goal 1 is achieved;}$$

IV. Postulate D applied to assumption 2:

$$\frac{RSU \models \#(X)}{RSU \models \#(Y, X)} : \text{if the RSU believes that the request } X \text{ is fresh, then the entire message is also fresh. Hence, goal 2 is achieved;}$$

V. Postulate A applied to assumptions 5 and 6:

$$\frac{v_c \models RSU_n \xrightarrow{Z} v_c, v_c \triangleleft \langle P \rangle Z}{v_c \models RSU_n | \sim P} : \text{if the vehicle } v_c \text{ believes that it shares its public key } Z \text{ with the RSU, and it receives the set of new public/private key pairs } P \text{ from RSU combined with } Z, \text{ then the vehicle } v_c \text{ believes that RSU once sent } P;$$

VI. Postulate B applied to assumption 8 and to result V:

$$\frac{v_c \models \#(P), v_c \models RSU_n | \sim P}{v_c \models RSU_n \models P} : \text{if the vehicle } v_c \text{ believes that the new set of public/private key pairs } P \text{ could have been uttered only recently, and the } v_c \text{ believes that the RSU once sent } P, \text{ then } v_c \text{ believes that the RSU believes } P;$$

VII. Postulate C applied to assumption 7 and to result VI:

$$\frac{v_c \models RSU_n \Rightarrow P, v_c \models RSU_n \models P}{v_c \models P} : \text{if vehicle } v_c \text{ believes that the RSU has jurisdiction over the new set of public/private key pairs } P \text{ (once the RSU digitally signs each key pair), and the vehicle } v_c \text{ trusts RSU on the truth of } P, \text{ then } v_c \text{ trusts } P. \text{ Hence, goal 3 is achieved;}$$

VIII. Postulate D applied to assumption 8:

$$\frac{v_c \models \#(P)}{v_c \models \#(P, Z)} : \text{if the vehicle } v_c \text{ believes the set of new public/private key pairs } P \text{ is fresh (once each key pair digital certificate also carries}$$

a timestamp), then the whole formula is also fresh. That is, the RSU response message is also fresh. Hence, goal 4 is achieved.

Finally, according to the Equations III, IV, VII and VIII, they together accomplish the verification correctness.

### 3.3. Sybil Attack Detection Evaluation Results

The *sybil* detection evaluation aimed to answer three questions, summarized as follows:

1. if two different vehicles  $v_i$  and  $v_j$  are in the transmission range of each other ( $v_i, v_j \in V_l$ ), and both belong to the same anonymity sets (considering property 4 of the multilevel anonymity set architecture), what is the average time that another vehicle  $v_k \in V_l$  takes to decide that the messages are, in fact, from two different vehicles, and not from a (potential) *sybil* node?
2. what is the average time one vehicle takes to detect a *sybil* attack from *beacon* messages?
3. what are the false-positive (a non-*sybil* node is evaluated as *sybil*) and false-negative (a *sybil* node was not evaluated as one) detection rates?

The simulation was performed by using the Veins simulation environment, which is based on OMNeT++ framework for event-based network simulation, and SUMO for road traffic microsimulation. Furthermore, it considered different vehicle densities, beacon frequencies (Packet Transmission Rate), and different anonymity set levels. Table 4 summarizes the simulation parameters.

Table 4: Simulation Parameters.

Parameter	Value
Total number of executions	900
Simulation Duration	between 10s to 120s
MAC and PHY protocols	802.11p
Transmission Power	20mW
Bit rate	18Mbps
Beacon rates	3, 5, and 10 beacon/s
<i>continued on next page</i>	

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Parameter	Value
Number of Vehicles	3, 5, 7, 12, 17, 22, 25, 50, 70, 90
Average vehicle speed	between 15 m/s and 22 m/s
Anonymity set levels ( $m$ )	4, 5 and 6

Figures 8 and 9 illustrate the experimental results (average time on 95% confidence intervals) for the first and the second questions, considering 100 ms, 200 ms and 300 ms beacon message transmission intervals. This experimental approach is based on the assumption that it is possible to send beacons as frequently as possible but without overloading the communication channel [47]. The solution adaptively updates the beacon frequency based on the importance of messages and based on the available capacity of the wireless channel.

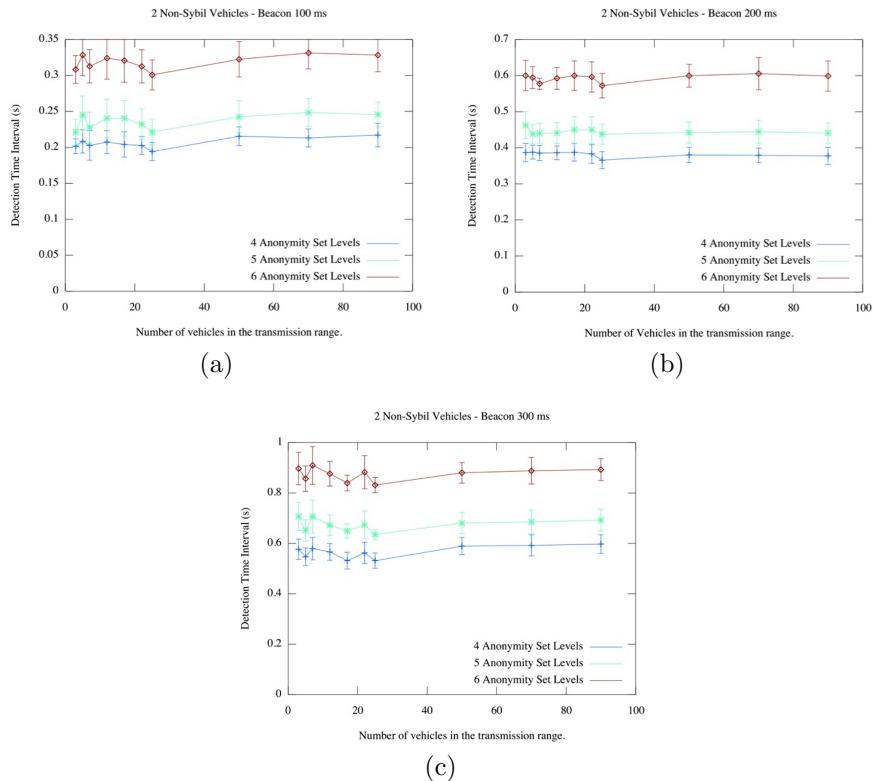


Figure 8: The average time to detect two benign vehicles in the transmission range. The vehicles belong to the same  $m - 1$  anonymity sets. (a) 10 packets per second (100 ms beacon interval); (b) 5 packets per second (200 ms beacon interval); (c) 3 packets per second (300 ms beacon interval).

The experiments considered the worst scenarios for a given level  $m$  of the proposed multilevel anonymity set architecture. Thus, the anonymity sets digital certificates from two vehicles were different only at the anonymity set of the last level. In this context, the Equation 3 was satisfied only at Levels 4, 5 or 6.

Figures 8a, 8b and 8c depict the average time to detect two benign vehicles that belong to the same anonymity set at Levels 3, 4, or 5 for 100, 200, and 300 beacon intervals, respectively. In short, the time to detect was lower than 0.4, 0.7, and 1 second, respectively. Since the contention is expected to be higher as the number of vehicles increases, the impact on the results was quite minimal. Therefore, the proposed approach provides a stable average of detection time as the number of nodes increases.

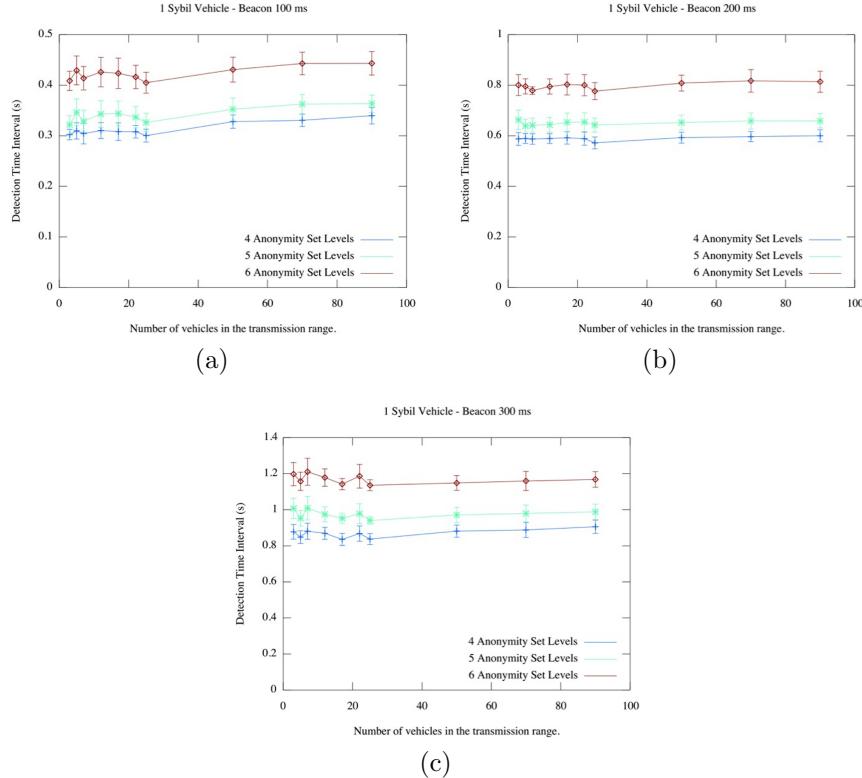


Figure 9: The average time to detect a *sybil* vehicle when another benign vehicle in the transmission range belongs to the same  $m - 1$  anonymity sets. (a) 10 packets per second (100 ms beacon interval); (b) 5 packets per second (200 ms beacon interval); (c) 3 packets per second (300 ms beacon interval).

Figures 9a, 9b and 9c depict the average time to detect a *sybil* vehicle with three different identities. Similarly, the wireless contention had minimum impact as the number of vehicle increases. On the other hand, the results exceeded 1 second for 300 ms beacon interval at Levels 5 and 6. This happens since the neighbor vehicles must evaluate Equation 4 in order to wait the next anonymity set digital certificates before deducing a *sybil* attack.

Finally, the main parameters that may affect the *sybil* detection are the beacon time intervals and the number of anonymity sets (per level) in which two or more vehicles together belong to. The results are considered acceptable since the messages from a *sybil* vehicle are dropped (and kept for future purposes) by neighboring vehicles during the attack, and the average detection time is faster than other approaches (as discussed on next section). Moreover, most of the safety-based applications for VANETs require fast drivers' reactions (e.g., *blind spot* scenarios) and therefore, they demand fast decision protocols.

The other two evaluated metrics were the *false-positive* and *false-negative* *sybil* detection rates. Figure 10 depicts a scenario in which the former metric was evaluated in 0,28% of the experimental cases. It is a classical hidden terminal scenario where vehicles *C* and *A* belong to the same first level anonymity set (e.g.:  $AS_{1,2}$ ). The vehicle *B* receives beacon messages from the vehicles *C* and *A*. However, due to the *A*'s and *C*'s transmission ranges, neither *A* nor *C* receives the messages from each other. Therefore, they keep sending messages with their first level anonymity set digital certificate  $cert_{AS_{1,2}}$ . From the *B*'s perspective, since the vehicles *A* and *C* keep sending messages without presenting the next anonymity set digital certificates, after  $\delta$  ms (Equation 4), *B* evaluates *A*'s and *C*'s messages as originated from a *sybil* vehicle. However, both *A* and *C* are two benign vehicles.

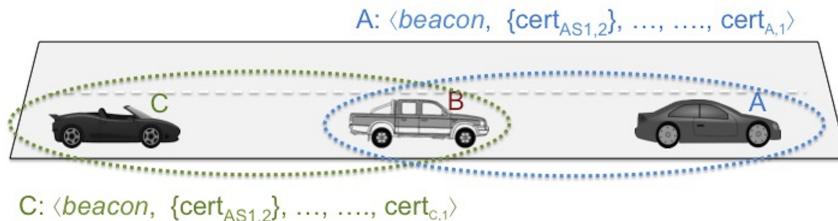


Figure 10: Hidden terminals scenarios may lead to false-positive *sybil* detections.

The proposed approach is totally resilient to *false-negative* results because any given vehicle may not send messages that describe the same event with different anonymity set digital certificates (property 4 of the proposed anonymity set multilevel architecture). Moreover, a set of messages that describe the same event and contain the same set of anonymity set digital certificate are kept as suspected by the neighboring vehicles. For instance, suppose that a malicious vehicle keeps sending beacon messages with different identities, but they contain only one anonymity set digital certificate. These messages are kept as suspected until Equation 4 is satisfied, or when Equation 3 is satisfied, which leads to the prosecution phase.

#### 4. Related Work

Malicious users may launch and explore *sybil* attacks in different types of networks, such as *peer-to-peer* (P2P) [21], sensor [48], and mobile ad hoc networks [38]. Moreover, the attack may compromise many types of applications, such as voting [49], reputation systems [50], as well as distributed storage and resource sharing systems [51], to name a few. Thus, there have been many approaches to avoid and detect *sybil* attacks.

Initially, Douceur [21] proposed the resource testing method. In short, Douceur's assumption requires that each physical entity is limited in resources such as computation, storage and communication. Hence, a *sybil* entity would not perform a set of tasks in a given time interval as expected if these identities would belong to different entities. However, in ad hoc networks, one node may have more computational resources than other nodes. Similarly, in sensor networks, the radio resource testing, proposed by Newsome [48], assumes that each physical entity has only one radio resource and is able to send and receive only on one channel simultaneously. This cannot be a realistic assumption on VANET.

Zhou et al. [33, 34] propose a privacy-preserving *sybil* attack detection protocol called *P<sup>2</sup>DAP*. First, a CA provides to every vehicle a pool of pseudonyms that are used for preserving the vehicle's privacy. To prevent *sybil* attacks, the pseudonyms assigned to a particular vehicle are hashed to a common value called *coarse-grained hash value*. Afterwards, the same pseudonyms are hashed to another hash value called *fine-grained hash value*. Vehicles with the same coarse-grained values are grouped together, while the pseudonyms with fine-grained values are unique to each vehicle. To detect a *sybil* attack, an RSU captures the messages sent from the vehicles along a

road and verifies the *course-grained hash values*. If two or more messages have the same *coarse-grained hash values*, the RSU forwards the messages to the CA. The CA then verifies the *fine-grained hash values* and checks if these values are also the same. If it evaluates to true, this vehicle is malicious (a *sybil* vehicle). The drawback of such approach is that a *sybil* attacker will not be detected if the CA is unavailable or there are no RSUs around. Hence, the approach is highly dependent on the RSU deployment methods and its availability (e.g.: DoS attack may compromise V2V communications). Moreover, experimental results show that a *sybil* detection may achieve 20 seconds due to high overhead imposed on RSUs, which is a high average time for real world on-road services. On the other hand, our approach does not need a fixed infrastructure to avoid or detect *sybil* attacks and, as well as for the same number of vehicles and *sybil* attacker (e.g.: 90 vehicles, and one *sybil* vehicle), our approach detects the *sybil* attack faster than  $P^2DAP$ .

Another strategy for detecting *sybil* attacks is based on a timestamp series approach [35, 36, 37]. The approach explores the relationship between time and space, where two or more vehicles will not pass nearby the same RSU and send requests to it at the same time. Thus, an RSU issues digitally signed timestamps to each vehicle. Then, each vehicle must attach to beacon messages at least the last two timestamps. If two different messages with different identities contain the same last two timestamps, then they belong to a *sybil* vehicle. This approach may compromise users' privacy since it requires vehicle authentication at each RSU, which allows third-party entities to assemble a vehicle routing profile. In addition, the scheme cannot be applied directly to an urban environment with a very complex roadway infrastructure, many signals and intersections, as deeply discussed in [37]. Our approach does not depend on the roadway infrastructure.

Finally, a *sybil* detection approach may use data from neighboring vehicles to filter malicious vehicles [38, 39]. In Grover's et al. approach [52], every vehicle builds a neighboring table (which contains vehicles' identities) with different time interval. After this process, each vehicle shares its neighboring table with other vehicles. If every vehicle has the same neighbors' identities for different time intervals, then these identities may belong to the same (*sybil*) vehicle. Nonetheless, a *sybil* vehicle may never be detected (*false-negative* results) if it changes its identities between consecutive time intervals. As previously discussed, our approach is resilient to *false-negative* results. To sum up, if different vehicles stay together for a long period of time, then it results in *false-positive* *sybil* detections.

We compare our proposed privacy-preserving *sybil* detection protocol to other similar approaches on Table 5. The main advantage of our scheme is it's resilience to *false-negative* detection results without a centralized infrastructure during detection time, which imposes less overhead on RSUs and, therefore, significantly decreases the average time to detect *sybil* attacks. The dependency on a centralized infrastructure may also compromise VANET services if a more sophisticated network attack also makes such infrastructure unavailable.

Table 5: Comparison to other approaches.

	False-Positive False-Negative Resilient	Non- Repudiation	Beacon or Event	Infrastructure- Dependent	Roadway Infrastructure- Dependent
Our	<b>Negative</b>	Yes	Both	<b>No</b>	No
[33]	Negative	Yes	Both	Yes	No
[35]	None	*	Both	Yes	Yes
[36]	None	*	Both	Yes	Yes
[37]	None	No	Both	Yes	Yes
[52]	None	*	Beacon	No	No
[39]	None	*	Beacon	No	No

\*It depends on the authentication model.

## 5. Conclusion and Future Work

In this paper we have presented a privacy-preserving authentication and *sybil* detection protocol for vehicular ad hoc networks called *ASAP-V*. In order to provide users' privacy, the protocol provides a multilevel anonymity set architecture, with group signature and pseudonyms. The experimental results show that the proposed authentication approach is secure, and the *sybil* detection protocol is acceptable with respect to detection time, once VANET requires low latency. Moreover, *ASAP-V* is also resilient to *false-negative* detections without the support of centralized infrastructures during *sybil* attack detection time.

The challenge in detecting *sybil* attacks in VANETs resides in the potential threats to users' privacy, since during *sybil* detection time, multiple

identities must be linked to a one single, yet non-malicious, entity. According to Douceur [21], without a logically, yet trusted centralized authority (CA), which will vouch for a one-to-one correspondence between entity and identity, *sybil* attacks are always possible except under extreme and unrealistic assumptions of resource parity and coordination among entities. On the other hand, when a central authority may not be always available in VANETs, a potential solution for detecting *sybil* attacks must consider only the vehicles in the region of attack, in which each vehicle must share control data in order to detect the attack.

For future work, a kind of *sybil attack signaling message* has been studied and aims at allowing one vehicle to announce to neighboring vehicles that there are two or more vehicles in the vicinity that belong to the same first level anonymity set. This signaling message aims to avoid *false-positive* detections in hidden terminals scenarios (Figure 10). For instance, vehicle B broadcasts signaling messages with identities A and C. Once all vehicles may listen to the *signaling* messages, the vehicles A and C may detect that they are suspected and may attach the next anonymity set digital certificates in their next beacon messages.

The V2I communication type is the most important communication type that still must be evaluated. Vehicles and RSUs communicate to negotiate new sets of pseudonyms, as well as during the prosecution phase. The communication overhead, w.r.t. the network traffic, of both depends on the number of vehicles that send the renewal or prosecution messages to a given RSU. The former is a kind of *three-way-handshake* protocol, which, at a first glance, does not impose high overhead on RSUs due to the low probability that a high number of vehicles need to change the set of pseudonyms at the same time. The last one tends to impose a high overhead on RSUs if there is a high number of vehicles that made part of a *sybil* detection process at the same region and they send prosecution messages to the same RSU. In order to avoid the RSU from forwarding each single prosecution message to the CA, the RSU must first evaluate if the messages belong to the same *sybil* detection process. This will avoid a CA from measuring redundant prosecution messages. Both V2I communications are still being evaluated.

As another future work, we are evaluating the achieved degree of anonymity of a given anonymity set  $AS_{i,j}$ . In other words, we would like to measure the probability of a malicious entity, which controls several sensors that are scattered across an entire city, to build a vehicle's route profile of a specific distance (e.g.: 3 km) while the vehicle exposes the anonymity sets that it be-

longs to. Therefore, we are measuring a number of anonymity sets  $k$  (for each level) that a vehicle must belong to in order to minimize the probability of the user's privacy violations. Based on the concept of Shannon's entropy [53], as well as on the model to quantify the degree of anonymity of a set of users grouped in several subsets [54], the anonymity of a given anonymity set  $AS_{i,j}$  may be evaluated. Therefore, it is also possible to define how vehicles may be allocated into the anonymity sets in order to maximize users' privacy with a low impact on message processing and data management overheads.

The security aspects are one of the biggest forthcoming challenges for actually deploying the concepts of VANET. The reliability of the whole system may not be compromised due to the high impact it has on people's lives. In this context, among other security-related concepts, authentication, non-repudiation, user's privacy control, and *sybil* attack detections play a key role in vehicular environments and, therefore, they have gained a special attention from the research community.

## References

- [1] S. Al-Sultan, M. M. Al-Doori, A. H. Al-Bayatti, H. Zedan, A comprehensive survey on vehicular ad hoc network, *Journal of Network and Computer Applications* 37 (2014) 380–392.  
URL <http://dx.doi.org/10.1016/j.jnca.2013.02.036>
- [2] V. D. Khairnar, K. Kotecha, Performance of vehicle-to-vehicle communication using ieee 802.11p in vehicular ad-hoc network environment., *International Journal of Network Security & Its Applications* 5 (2).
- [3] S. Gillani, F. Shahzad, A. Qayyum, R. Mehmood, A survey on security in vehicular ad hoc networks, in: *Communication Technologies for Vehicles*, Springer, 2013, pp. 59–74.
- [4] M.-W. Li, T.-H. Wu, W.-Y. Lin, K.-C. Lan, C.-M. Chou, C.-H. Hsu, On the feasibility of using 802.11 p for communication of electronic toll collection systems, *ISRN Communications and Networking* (2011) 31doi:10.5402/2011/723814.  
URL <http://dx.doi.org/10.5402/2011/723814>
- [5] M. Riley, K. Akkaya, K. Fong, A survey of authentication schemes for vehicular ad hoc networks, *Security and Communication Networks* 4 (10) (2011) 1137–1152. doi:10.1002/sec.239.

- [6] M. Raya, J.-P. Hubaux, Securing vehicular ad hoc networks, *Journal of Computer Security* 15 (1) (2007) 39–68.  
URL <http://dl.acm.org/citation.cfm?id=1370616.1370618>
- [7] A. Wasef, R. Lu, X. Lin, X. Shen, Complementing public key infrastructure to secure vehicular ad hoc networks, *Wireless Communications* 17 (5) (2010) 22–28. doi:10.1109/MWC.2010.5601954.
- [8] A. Bradai, H. Afifi, A framework using ibc achieving non-repudiation and privacy in vehicular network, in: Conference on Network and Information Systems Security, IEEE, 2011, pp. 1–6. doi:10.1109/SARSSI.2011.5931386.
- [9] Y. Hao, Y. Chengcheng, C. Zhou, W. Song, A distributed key management framework with cooperative message authentication in vanets, *Selected Areas in Communications, IEEE Journal on* 29 (3) (2011) 616–629. doi:10.1109/JSAC.2011.110311.  
URL <http://dx.doi.org/10.1109/JSAC.2011.110311>
- [10] J. Sun, C. Zhang, Y. Zhang, Y. Fang, An identity-based security system for user privacy in vehicular ad hoc networks, *Parallel and Distributed Systems, IEEE Transactions on* 21 (9) (2010) 1227–1239.  
URL <http://doi.ieee.org/10.1109/TPDS.2010.14>
- [11] J. Freudiger, M. Raya, M. Félegyházi, P. Papadimitratos, et al., Mix-zones for location privacy in vehicular networks, in: Proceedings of the first international workshop on wireless networking for intelligent transportation systems, 2007.
- [12] J. J. Haas, Y.-C. Hu, K. P. Laberteaux, The impact of key assignment on vanet privacy, *Security and Communication Networks* 3 (2-3) (2010) 233–249.  
URL <http://dx.doi.org/10.1002/sec.143>
- [13] G. Calandriello, P. Papadimitratos, J.-P. Hubaux, A. Lioy, Efficient and robust pseudonymous authentication in vanet, in: Proceedings of the fourth ACM international workshop on Vehicular ad hoc networks, ACM, 2007, pp. 19–28.  
URL <http://dx.doi.org/10.1145/1287748.1287752>

- [14] Y. Sun, R. Lu, X. Lin, X. Shen, J. Su, An efficient pseudonymous authentication scheme with strong privacy preservation for vehicular communications, *Vehicular Technology, IEEE Transactions on* 59 (7) (2010) 3589–3603.
- [15] A. R. Beresford, F. Stajano, Location privacy in pervasive computing, *Pervasive Computing, IEEE* 2 (1) (2003) 46–55. doi:10.1109/MPRV.2003.1186725.  
URL <http://dx.doi.org/10.1109/MPRV.2003.1186725>
- [16] R. Lu, X. Li, T. H. Luan, X. Liang, X. Shen, Pseudonym changing at social spots: An effective strategy for location privacy in vanets, *Vehicular Technology, IEEE Transactions on* 61 (1) (2012) 86–96. doi:10.1109/TVT.2011.2162864.
- [17] L. Buttyán, T. Holczer, I. Vajda, On the effectiveness of changing pseudonyms to provide location privacy in vanets, in: *Security and Privacy in Ad-hoc and Sensor Networks*, Springer, 2007, pp. 129–141. doi:10.1007/978-3-540-73275-4\_10.
- [18] K. Sampigethaya, L. Huang, M. Li, R. Poovendran, K. Matsuura, K. Sezaki, Caravan: Providing location privacy for vanet, in: in *Embedded Security in Cars*, 2005.
- [19] L. Buttyán, T. Holczer, A. Weimerskirch, W. Whyte, Slow: A practical pseudonym changing scheme for location privacy in vanets, in: *Vehicular Networking Conference, IEEE*, 2009, pp. 1–8.
- [20] S. Du, H. Zhu, X. Li, K. Ota, M. Dong, Mixzone in motion: Achieving dynamically cooperative location privacy protection in delay-tolerant networks, *Vehicular Technology, IEEE Transactions on* 62 (9) (2013) 4565–4575. doi:10.1109/TVT.2013.2266347.
- [21] J. R. Douceur, The sybil attack, in: *Revised Papers from the First International Workshop on Peer-to-Peer Systems*, Springer-Verlag, London, UK, UK, 2002, pp. 251–260.
- [22] T. Leinmüller, E. Schoch, Greedy routing in highway scenarios: The impact of position faking nodes, in: *Proceedings of Workshop On Intelligent Transportation*, 2006.

- [23] J. Grover, D. Kumar, M. Sargurunathan, M. Gaur, V. Laxmi, Performance evaluation and detection of sybil attacks in vehicular ad-hoc networks, *Recent Trends in Network Security and Applications* (2010) 473–482.  
URL [http://dx.doi.org/10.1007/978-3-642-14478-3\\_47](http://dx.doi.org/10.1007/978-3-642-14478-3_47)
- [24] S. Ramachandran, V. Shanmugan, Impact of sybil and wormhole attacks in location based geographic multicast routing protocol for wireless sensor networks, *Journal of Computer Science* 7 (7) (2011) 973–979.
- [25] Y. Hao, Y. Chengcheng, C. Zhou, W. Song, A distributed key management framework with cooperative message authentication in vanets, *IEEE J.Sel. A. Commun.* 29 (3) (2011) 616–629. doi:10.1109/JSAC.2011.110311.
- [26] C. Zhang, X. Lin, R. Lu, P.-H. Ho, Raise: An efficient rsu-aided message authentication scheme in vehicular communication networks, in: *IEEE International Conference on Communications*, 2008, pp. 1451–1457. doi:10.1109/ICC.2008.281.
- [27] C. Zhang, X. Lin, R. Lu, P. Ho, X. Shen, An efficient message authentication scheme for vehicular communications, *IEEE Transactions on Vehicular Technology* 57 (6) (2008) 3357–3368. doi:10.1109/TVT.2008.928581.
- [28] M. Verma, D. Huang, Segcom: secure group communication in vanets, in: *6th IEEE Consumer Communications and Networking Conference*, IEEE, 2009, pp. 1–5. doi:10.1109/CCNC.2009.4784943.
- [29] R. Hussain, S. Kim, H. Oh, Towards privacy aware pseudonymless strategy for avoiding profile generation in vanet, *Information Security Applications* (2009) 268–280doi:10.1007/978-3-642-10838-9\_20.
- [30] T. Wu, W. Liao, C. Chang, A cost-effective strategy for road-side unit placement in vehicular networks, *IEEE Transactions on Communications* 60 (8) (2012) 2295–2303.  
URL <http://dx.doi.org/10.1109/TCOMM.2012.062512.100550>
- [31] O. Trullols, M. Fiore, C. Casetti, C. Chiasseroni, J. Barcelo Ordinas, Planning roadside infrastructure for information dissemination in intelligent transportation systems, *Computer Communications* 33 (4) (2010)

432–442. doi:10.1016/j.comcom.2009.11.021.

URL <http://dx.doi.org/10.1016/j.comcom.2009.11.021>

- [32] E. S. Cavalcante, A. L. Aquino, G. L. Pappa, A. A. Loureiro, Roadside unit deployment for information dissemination in a vanet: an evolutionary approach, in: Proceedings of the fourteenth international conference on Genetic and evolutionary computation conference companion, GECCO Companion '12, ACM, New York, NY, USA, 2012, pp. 27–34. doi:10.1145/2330784.2330789.
- [33] T. Zhou, R. Choudhury, P. Ning, K. Chakrabarty, P2dap-sybil attacks detection in vehicular ad hoc networks, Selected Areas in Communications, IEEE Journal on 29 (3) (2011) 582–594. doi:10.1109/JSAC.2011.110308.
- [34] T. Zhou, R. R. Choudhury, P. Ning, K. Chakrabarty, Privacy-preserving detection of sybil attacks in vehicular ad hoc networks, in: Mobile and Ubiquitous Systems: Networking & Services, 2007. MobiQuitous 2007. Fourth Annual International Conference on, IEEE, 2007, pp. 1–8. doi:10.1109/MOBIQ.2007.4451013.  
URL <http://dx.doi.org/10.1109/MOBIQ.2007.4451013>
- [35] S. Chang, Y. Qi, H. Zhu, J. Zhao, X. Shen, Footprint: Detecting sybil attacks in urban vehicular networks, Parallel and Distributed Systems, IEEE Transactions on 23 (6) (2012) 1103–1114.  
URL <http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.263>
- [36] C. Chen, X. Wang, W. Han, B. Zang, A robust detection of the sybil attack in urban vanets, in: Distributed Computing Systems Workshops, 2009. ICDCSW Workshops' 09. 29th IEEE International Conference on, IEEE, 2009, pp. 270–276. doi:10.1109/ICDCSW.2009.48.  
URL <http://dx.doi.org/10.1109/ICDCSW.2009.48>
- [37] S. Park, B. Aslam, D. Turgut, C. Zou, Defense against sybil attack in vehicular ad hoc network based on roadside unit support, in: Military Communications Conference, 2009. MILCOM 2009. IEEE, IEEE, 2009, pp. 1–7.  
URL <http://dl.acm.org/citation.cfm?id=1856821.1856828>

- [38] C. Piro, C. Shields, B. Levine, Detecting the sybil attack in mobile ad hoc networks, in: Securecomm and Workshops, 2006, IEEE, 2006, pp. 1–11.
- [39] Y. Hao, J. Tang, Y. Cheng, Cooperative sybil attack detection for position based applications in privacy preserved vanets, in: Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE, IEEE, 2011, pp. 1–5. doi:10.1109/GLOCOM.2011.6134242.
- [40] D. Chaum, E. Van Heyst, Group signatures, in: Advances in Cryptology-EUROCRYPT'91, Springer, 1991, pp. 257–265. doi:10.1007/3-540-46416-6\_22.
- [41] L. Sweeney, k-anonymity: a model for protecting privacy, *Int. J. Uncertain. Fuzziness Knowl.-Based Syst.* 10 (5) (2002) 557–570. doi:10.1142/S0218488502001648.
- [42] G. Theodorakopoulos, J. S. Baras, On trust models and trust evaluation metrics for ad hoc networks, *Selected Areas in Communications, IEEE Journal on* 24 (2) (2006) 318–328. doi:10.1109/JSAC.2005.861390.
- [43] M. Burrows, M. Abadi, R. M. Needham, A logic of authentication, *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences* 426 (1871) (1989) 233–271. doi:10.1145/77648.77649.  
URL <http://doi.acm.org/10.1145/77648.77649>
- [44] P. Syverson, A taxonomy of replay attacks [cryptographic protocols], in: Computer Security Foundations Workshop VII, 1994. CSFW 7. Proceedings, IEEE, 1994, pp. 187–191. doi:10.1109/CSFW.1994.315935.
- [45] N. Koblitz, Elliptic curve cryptography, *Mathematics of Computation* 48 (177).
- [46] D. Boneh, H. Shacham, Group signatures with verifier-local revocation, in: Proceedings of the 11th ACM conference on Computer and communications security, ACM, 2004, pp. 168–177.  
URL <http://dx.doi.org/10.1145/1030083.1030106>
- [47] C. Sommer, O. K. Tonguz, F. Dressler, Traffic information systems: efficient message dissemination via adaptive beaconing, *Communications Magazine, IEEE* 49 (5) (2011) 173–179. doi:10.1109/MCOM.2011.5762815.

- [48] J. Newsome, E. Shi, D. Song, A. Perrig, The sybil attack in sensor networks: analysis & defenses, in: Proceedings of the 3rd international symposium on Information processing in sensor networks, ACM, 2004, pp. 259–268.
- [49] N. Tran, Combating sybil attacks in cooperative systems, Ph.D. thesis, New York University (2012).
- [50] K. Hoffman, D. Zage, C. Nita-Rotaru, A survey of attack and defense techniques for reputation systems, ACM Computing Surveys (CSUR) 42 (1) (2009) 1. doi:10.1145/1592451.1592452.  
URL <http://doi.acm.org/10.1145/1592451.1592452>
- [51] Y. Xiao, Security in Distributed, Grid, Mobile, and Pervasive Computing, Taylor & Francis, 2007.
- [52] J. Grover, M. Gaur, V. Laxmi, N. Prajapati, A sybil attack detection approach using neighboring vehicles in vanet, in: Proceedings of the 4th international conference on Security of information and networks, ACM, 2011, pp. 151–158. doi:10.1145/2070425.2070450.  
URL <http://doi.acm.org/10.1145/2070425.2070450>
- [53] C. E. Shannon, A mathematical theory of communication, ACM SIGMOBILE Mobile Computing and Communications Review 5 (1) (2001) 3–55. doi:10.1002/j.1538-7305.1948.tb00917.x.
- [54] C. Diaz, J. Claessens, S. Seys, B. Preneel, Information theory and anonymity, in: Proceedings of the 23rd Symposium on Information Theory in the Benelux, 2002, pp. 179–186.