

# Vouch: A Secure Proof-of-Location Scheme for VANETs

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## ABSTRACT

In Vehicular Ad Hoc Networks (VANETs), nodes periodically share beacons in order to convey information about identity, velocity, acceleration, and position. Truthful positioning of nodes is essential for the proper behavior of applications, including the formation of vehicular platoons. Incorrect position information can cause problems such as increased fuel consumption, reduced passenger comfort, and in some cases even accidents. In this paper, we design and evaluate Vouch: a secure proof-of-location scheme tailored for VANETs. The scheme leverages the node positioning capability of fifth generation (5G) wireless network roadside units. The key idea of Vouch is to disseminate periodic proofs of location, combined with plausibility checking of movement between proofs. We show that Vouch can detect position falsification attacks in high-speed scenarios without incurring a large overhead.

## CCS CONCEPTS

• Security and privacy → Intrusion detection systems; Distributed systems security;

## KEYWORDS

VANET; intrusion detection; proof of location

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## 1 INTRODUCTION AND BACKGROUND

The main purpose of emerging VANET technologies is to enable more intelligent transportation systems, with the aim to increase safety and improve traffic efficiency. In these systems, vehicles achieve cooperative awareness through the exchange of periodic broadcast messages called *beacons*. Vehicles in the vicinity of the sender can leverage information contained in the beacons to, e.g., detect traffic jams, emergency brake, and operate platoons.

A vehicular platoon is a group of vehicles that travel closely together in a highway (or rural road). Each vehicle runs an instance

of a platoon controller that takes advantage of broadcast beacons to perform longitudinal and lateral control. A leader typically dictates the behavior of the platoon while the followers adapt to preserve stability. By reducing the inter-vehicular distance (headway time), a platoon lowers fuel consumption as a result of reduced air drag [16], and relieves the drivers in the following vehicles from controlling them.

Although platoons present clear benefits for traffic efficiency and driving comfort, using network data for vehicle control introduces a relevant threat surface that may be exploited by malicious actors. In earlier work we have shown that carefully crafted beacons can cause collisions with increased impact when multiple nodes collude in position falsification [1]. Attacks in vehicular platooning may result in injury or ultimately in loss of lives, which enforces the need for secure and dependable mechanisms.

Cooperative awareness relies on correctly perceiving the traffic environment, and the legitimate positioning of neighbor vehicles is essential. The European Telecommunications Standards Institute (ETSI) has stated that messages must be signed to provide authenticity, non-repudiation and integrity [11]. However, insider attackers may still falsify information that is contained in the signed message. While sensor fusion algorithms [18] might ameliorate position perception of neighbors, sensors themselves have limited capabilities and require inter-vehicular communication to be trustworthy.

To attest neighbor localization, position verification mechanisms have been extensively studied in mobile networks. Three main mechanisms have been employed in the literature: location estimation, plausibility verification and proof of location. Location estimation is enabled by angle of arrival or distance measurement techniques, such as radio signal strength or time of flight. Plausibility verification is employed to identify false positions by calculating feasible boundaries. Finally, proof-of-location mechanisms have been proposed in mobile and cognitive radio networks to provide truthful positioning. While the aforementioned mechanisms aim at providing location assurance, the main limitations in current works are related to handling the high mobility environment of VANETs and the real-time requirements of safety applications while preserving privacy. Our approach uses a combination of plausibility verification and proof of location while aiming at overcoming the presented limitations.

We propose and evaluate a proof-of-location scheme tailored for VANETs called Vouch. The key insights of our design are leveraging 5G-enabled roadside units and reducing overhead through mobility estimation techniques. So far, cellular radio networks have not been employed for safety-critical localization due to insufficient accuracy. However, 5G wireless technologies aim to satisfy the high-precision and low-latency requirements for vehicular positioning [12, 14, 28]. Our solution is based on such 5G-enabled roadside units

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that together with a trusted authority can provide signed messages containing the assured location of a vehicle.

The mobility estimation component in our proposed solution solves two problems. First, the high-speed mobility associated with vehicular networks (that can exhibit speeds up to 40 m/s) will make any proof of location stale in a fraction of a second. Second, the cryptographic overhead required to guarantee message integrity and authenticity would make it too costly to transmit a location proof with every beacon. Therefore, our solution uses a mobility-aware classification mechanism to determine whether a received beacon should be classified as plausible or not. This mechanism considers the recent movement of surrounding vehicles to determine if the received beacon is compatible with the last received proof. In addition to working correctly in high-speed scenarios, this allows the mechanism to operate using low proof frequencies, resulting in lower overhead by exchanging less data.

We evaluate Vouch through a simulation based study using the vehicular networking simulator tool Veins as well as the Plexe extension that enables realistic simulation of vehicular platoons. In our experiments we consider an attack scenario where a malicious vehicle is able to manipulate beacons making them appear as coming from multiple vehicles and change their position at will. We show that Vouch is able to correctly classify all beacons where the position falsification exceeds a few meters as implausible.

The contributions of this paper are outlined below:

- We design Vouch: a proof-of-location scheme tailored for VANETs that couples distinct positioning verification systems as components.
- Vouch is evaluated according to accuracy and overhead metrics. We show that our proposal incurs in low overhead while maintaining anomaly detection and overcomes limitations of previous works.

The paper is organized as follows: Section 2 presents the literature review on proof-of-location systems. Section 3 provides the design proposal while Section 4 shows the evaluation results. Section 5 concludes the paper and outlines future work.

## 2 RELATED WORK

Proof-of-location mechanisms have been employed in diverse mobile environments. In this section, we describe the state-of-the-art mechanisms that have been proposed in the fields of mobile ad hoc network and database-driven cognitive radio networks.

Waters and Felten [27] discuss the generation of location proofs that have integrity capabilities and preserve the privacy of the user. They design a scheme that measures the round-trip signal propagation latency and location managers provide the proof to users.

STAMP [26] uses Spatial-Temporal Provenance (STP) proofs. It was designed to provide a provenance proof that users can use to attest a certain location history. In order to respect privacy, the authors propose the usage of commitment schemes [3, 7, 8]. The authors define two types of collusion attacks: Prover-Witness (P-W) and Prover-Prover (P-P). In P-W collusion, a witness is able to generate an STP proof even though the prover, the witness or even both are not at that location. In P-P, provers A and B collude

in order to generate a proof for a location that B is not. In order to protect against P-P collusion attacks, the Bussard-Bagga [2] distance bounding protocol was employed. STAMP also uses an entropy-based trust model to protect against P-W collusion.

APPLAUS [29] was designed similarly to STAMP. APPLAUS is also based on co-located users that act as alibis for generating location proofs. Differently from STAMP, APPLAUS use periodically changing pseudonyms in its scheme to preserve user's privacy. This incurs an operational overhead due to the necessity of careful management and scheduling of the identities, in addition to having dummy pseudonyms that require additional storage and data transfer.

Witness ORiented Asserted Location provenance (WORAL) [10] is a witness-based scheme framework. The authors consider a service provider that manages the accounts of the other three entities: the mobile devices (users/witnesses), the location authority and the auditor. The authors use design principles for secure location provenance presented on the OTIT model [15]. WORAL considers that collusion attacks may be conducted by malicious users, location authorities and/or witnesses.

VeriPlace [17] is a location-proof system with privacy and cheating detection capabilities. By observing proofs continuously, the system architecture can detect anomalies if proofs are geographically distant but chronologically close. In order to perform such detection, however, the system requires users to provide frequent proofs. VeriPlace depends upon three trusted third parties in order to defend against collusion attacks, one that manages user information, one that manages location information and one that performs anomaly detection.

Hasan and Burns [9] have proposed a scheme that uses both APs and witnesses to generate a proof. In this mechanism, a user first discovers a location authority and sends a proof request that includes the chronological information from the latest entry of the user's provenance chain. The mechanism uses a distance bounding and time stamping to generate chronologically-ordered proofs. Hash chains and Bloom filters schemes are proposed as privacy-preserving mechanisms to protect the integrity of the location proofs chronological entries.

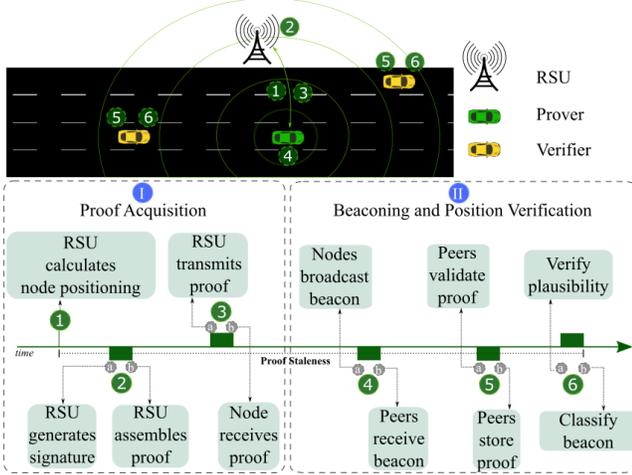
Existing works on proof of location, presented above, are not suitable for VANETs due to real-time, high-mobility and privacy constraints combined. In order to cope with the requirements of the vehicular environment, we design and evaluate a VANET-tailored proof-of-location scheme. Our proposal can handle high mobility and is lightweight so that the channel load is minimally impacted. In this paper, the combination of these characteristics in the proposed method are proven to effectively detect position falsification attacks.

## 3 DESIGN OF VOUCH

This section describes the design of Vouch. The scheme includes a **protocol** used for *proof acquisition and dissemination* and a **classifier mechanism** that applies the *plausibility model* to detect inconsistencies. In this section, these components are presented. For presentation purposes, the workflow is presented under a static scenario and the mobility-aware component of the classification is presented in Section 3.4.

### 3.1 Vouch Overview

To simplify the presentation of the scheme, consider a scenario in which the nodes are static. Figure 1 shows the main steps of Vouch including the beacon classification. It presents the corresponding timeline of events containing the *Proof Acquisition* and *Beaconing and Position Verification*. The RSU is represented by the antenna in the highway's border, the node willing to prove its location is represented by the green car (prover) while peers that will verify the proof are the yellow ones (verifiers). For this present work, we assume that a trusted authority provides certificates and cryptographic keys to the entities and that the neighbor vehicles already possess the RSUs' public keys, in order to verify the *proof* digital signatures. Such trusted authority is expected to exist according to many privacy-preserving authentication schemes for VANETs[5, 19].



**Figure 1: Timeline with proof acquisition and beaconing/position verification using static nodes**

After registration, a prover will continuously receive a stream of proofs. The proof acquisition comprehends the position estimation of the vehicle by the RSU (step 1), *proof* generation (step 2) and transmission (step 3). The overhead associated with estimating the position is not inherent to the proposed mechanism since 5G communication base stations have to continuously track user equipments (in our case, vehicles) in order to utilize beamforming [13]. Once the prover acquires the proof, it will be transmitted in the next broadcast beacon (step 4). Proof acquisition and beaconing are asynchronous procedures as they can work in distinct frequencies. ETSI standards define that beaconing is performed up to 10 Hz frequency. A proof will be included in every beacon transmission if the acquisition is also performed at the same frequency. Otherwise, nodes can share proofs less frequently and verifiers will use stale proofs to perform the plausibility check in subsequent beacons. Once neighbors receive a beacon, they verify if a proof is included and, if so, verify its signature. If the proof is authentic, then it is stored (step 5). For every beacon that is received, a plausibility check is executed and the beacon is classified as plausible or implausible (step 6).

Note that the detection of an implausible beacon should result in some action at the application layer. However, we have not evaluated such mitigation mechanisms in this work. One straightforward strategy that could be utilized is to simply discard those beacons that are classified as implausible.

Three parameters are used to define the operation of Vouch, *Proof Size*, *Proof Frequency* and *Plausibility Check Threshold*. Proof size is the amount of data that needs to be transferred for each proof and is measured in *bytes*. Proof frequency is the amount of proofs per second that will be provided by the RSU to the vehicles, measured in Hz. The plausibility check threshold is a tolerance of the position accuracy error by the positioning mechanism in the RSU.

### 3.2 Protocol

The protocol is divided into three phases: *registration*, *proof acquisition and dissemination*, and *unregistration*. The signed trusted positioning, hereby referenced as *proof*, is provided by RSUs once the vehicles register by using a *proofReq* request. Figure 2 details the protocol, representing a certificate of entity  $x$  as  $cert_x$ , timestamp of entity  $x$  as  $timestamp_x$ , signature of data  $y$  by entity  $x$  as  $S_x(y)$ , position of entity  $x$  as  $pos_x$ , confidence of positioning as  $C_{pos}$ , and public key of pseudonym  $n$  for the entity  $x$  as  $k_{x,n}^+$ . The vehicle entity is represented by  $a$  and the roadside unit as  $RSU$ . The protocol uses Elliptic Curve Digital Signature Algorithm (ECDSA) to ensure integrity, authenticity and non-repudiation, which is in line with the objectives of current vehicular communication standards. The usage of pseudonyms in the protocol ensures that our scheme is compatible with privacy-preserving protocols proposed for VANETs.

Once a *proofReq* is received, the RSU validates the certificate, extracts the public key from the certificate and verifies the signature of the request. The timestamp is compared with the current clock reading at the RSU to avoid replay attacks. A *reqAck* is sent to the vehicle to confirm its registration and includes the certificate of the RSU, a timestamp and a digital signature. The vehicle is then able to verify the authenticity of the RSU and extract the public key from the certificate in order to validate the signature of *reqAck* and the succeeding *proof* messages. After sending a *reqAck*, the RSU begins to provide periodic *proof* messages to the vehicle. A *proof* consists of the position coordinates, a timestamp, its confidence on the position accuracy and the digital signature. This *proof*, as will be further detailed, is relayed by the vehicle to its neighbors as an assurance of its legitimate location. To unregister, a vehicle may send a *finReq* request at any time.

It is worth noting that only the timestamp is used as data for generating the digital signature of *proofReq*, *reqAck* and *finReq* since the certificate already contains a signature by the Certificate Authority (CA) that can be used to assert its integrity and authenticity.

### 3.3 Beacon Classification

In the classification mechanism, the nodes validate if the position is plausible or not. In a static scenario, a threshold for the positioning accuracy is the only source of uncertainty as the nodes are not moving. The threshold is derived from the RSU's confidence in the positioning accuracy, transmitted as  $C_{pos}$  in the proof. Figure 3

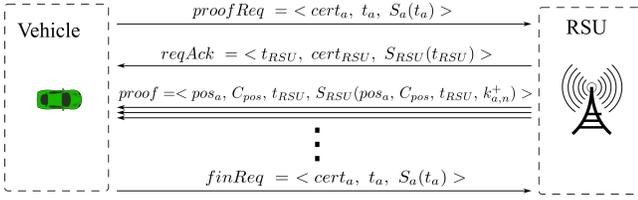


Figure 2: Proof-of-location protocol

depicts the classification in a static scenario. The position contained in the beacon along with the position and threshold contained in the last received proof are used as input to the classifier. The output is a classification of the position as plausible or not. Algorithm 1 shows an example of a basic bounds verification algorithm that compare the beacon position and proof position along two dimensions (X and Y) separately.

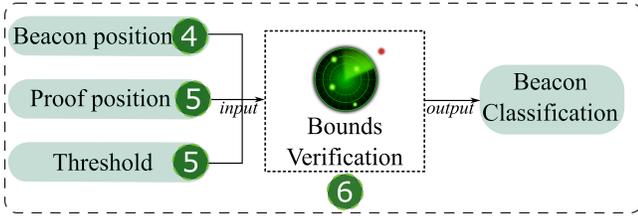


Figure 3: Beacon classification procedure in a static scenario

**Algorithm 1** Bounds Verification

- 1: **procedure** BOUNDSVERIFICATION
- 2:  $(X_b, Y_b) \leftarrow$  beacon position
- 3:  $(X_p, Y_p) \leftarrow$  proof position
- 4:  $(T_x, T_y) \leftarrow$  positioning accuracy threshold
- 5: **if**  $|X_p - X_b| \geq T_x$  OR  $|Y_p - Y_b| \geq T_y$  **then**
- 6:     **return** implausible
- 7: **else**
- 8:     **return** plausible

Figure 4 includes an example of a timeline comprising the *Proof Acquisition* and *Beaconing and Position Verification*. In this example, a proof is acquired at 2 Hz frequency while beaconing is performed at 10 Hz frequency. According to the aforementioned design of the mechanism, the plausibility check will be performed at the reception of every beacon.

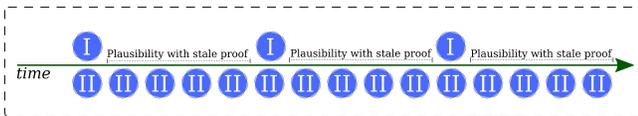


Figure 4: Example of proof acquisition with 2 Hz and beacon transmission/plausibility check events

### 3.4 Mobility-aware Classification

In mobile scenarios, such as when vehicles are traveling in a highway, the position accuracy noise is not the only source of the uncertainty. As vehicles change their speed and possibly turn, the position error may differ in lateral and longitudinal coordinates according to their movement. This scenario requires the classification to take into account the mobility of the nodes.

An important aspect of the proof then becomes its *staleness*, i.e., its age. As shown in Figure 1, there is a gap between the vehicle's position estimation in step 1 and the usage of the proof by neighbor vehicles in step 6. As the vehicles are moving, the position contained in the proof will always be outdated, meaning that at the time of verification it will have already changed. This is illustrated in Figure 5 as the prover moves between proof generation by the RSU and verification by its peers.

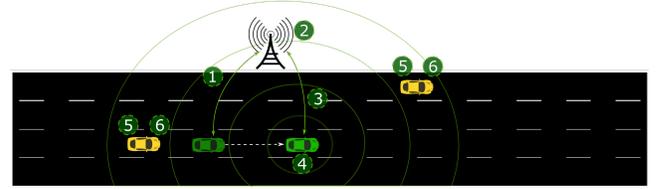


Figure 5: Illustration of events for proof dissemination

The plausibility check is an independent component of our mechanism. Its purpose is to classify a position reported by a vehicle based on the last proof received given a time difference between the proof and beacon. The proof staleness is directly tied to the plausibility check; the older the proof, the broader will be the position acceptance. In the present work, the mobility models are derived from the Constant Velocity (CV) for the X dimension while Y takes Constant Turn Rate and Velocity (CTRV) [22] to account for turning.

Figure 6 depicts the mobility-aware classification. The last stored proof and required information from the beacon are used in the presented plausibility model to calculate the position bounds. Then, the resulting bounds are combined with the proof  $C_{pos}$  accuracy confidence as threshold and compared with the claimed position in the beacon. The output is a classification as plausible or not.

$$x_{k+1} = x_k + \dot{x}_k \cdot \Delta t + \ddot{x}_k \cdot \frac{1}{2} \Delta t^2 \quad (1)$$

$$y_{k+1} = y_k + \frac{\dot{x} + \Delta t \ddot{x}}{\dot{\psi}} (-\cos(\psi + \dot{\psi} \Delta t) + \cos(\psi)) \quad (2)$$

Equations 1 and 2 take the following variables for position estimation in time  $k + 1$  given information from time  $k$ :  $x$  and  $y$  are absolute positions ( $m$ ),  $\dot{x}$  represents velocity ( $m/s$ ),  $\ddot{x}$  represents acceleration ( $m/s^2$ ),  $\dot{\psi}$  represents the yaw rate (rad),  $\psi$  determines heading (rad) and  $\Delta t$  is the timestamp difference between proof and beacon (s). The bounds are determined using minimum and maximum values for acceleration and yaw rate while the remaining information is obtained via beacons.

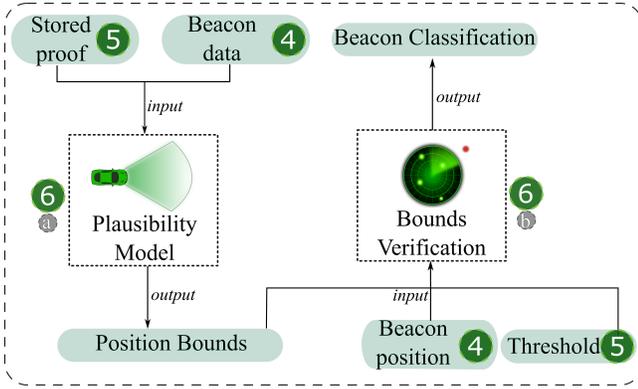


Figure 6: Mobility-aware beacon classification procedure

## 4 EVALUATION OF VOUCH

In this section, Vouch is evaluated in terms of detection performance and overhead costs in a platooning context. The effectiveness of the scheme is verified through simulations that use both benign and colluding attacker nodes. The attacker model presented in our previous work [1] is employed in the evaluation, and an overview is included in this section.

### 4.1 Attack Scenario Overview

Consider a vehicular platoon composed of eight vehicles that travel along a highway. Vehicles in the vicinity of the platoon may request to join the formation to leverage platooning benefits. Our threat model is composed of an attacker that forges false vehicles by tampering with the position in the beacons, which are then signed with valid cryptographic keys. The attacker impersonates multiple false vehicles (joining them into the platoon) by conducting a Sybil attack [1, 6] or possibly by having stolen credentials to support the attack. Figure 7 illustrates the attack scenario and the coordinates falsification (represented by  $X$  and  $Y$ ) that the attacker must perform in order to situate the false vehicles. To make the attack harder to detect, the attacker travels closely beside the position of the false node, which minimizes the amount of position error. In this attack, one false vehicle is inserted between the first pair of legitimate members and another false vehicle between the second pair. After introducing the false vehicles into the platoon (which occurs at 30 s in our simulation), the attacker manipulates the beacons by increasing the position error to cause unwanted effects in the controllers of following vehicles (which occurs at 100 s in our simulation). The first false node subtracts its position in 250 m while the second increases by the same amount, resulting in a collision.

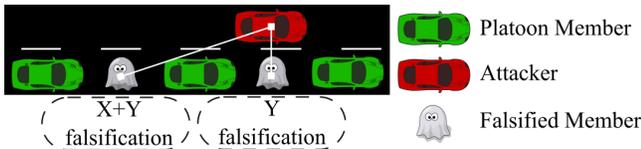


Figure 7: Attack scenario overview

### 4.2 Simulation Environment

The evaluation of Vouch was performed using Plexe [23]. Plexe is an extension to Veins [24], a VANET simulator that combines network simulation through the Omnet++ framework and mobility simulation through SUMO. The cryptographic operations of the scheme were implemented using the OpenSSL APIs. As illustrated in Figure 8, the attacker model is used to evaluate the detection performance of the scheme when an attack is being conducted. A model of the RSU that provides the proofs is implemented in Plexe and connected to the external module that provides the cryptographic operations. The plausibility model introduced in Section 3 is included as a platooning application of the simulator. The simulation parameters are included in Table 1. Each simulation setup was executed 33 times with distinct seeds.

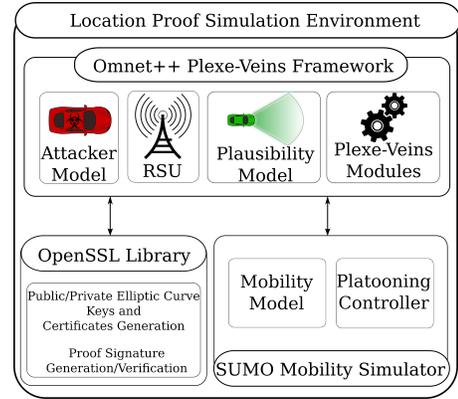


Figure 8: Simulation architecture

Table 1: Traffic simulation parameters

Freeway length	10 km
Number of lanes	4
Car speeds	20/40/60/80/100 km/h
Platoon size	8 cars
Platooning car max acceleration	2.5 m/s <sup>2</sup>
Platooning car mass	1460 kg
Platooning car length	4 m
Headway time	0.8 s
Longitudinal control algorithm	Consensus [20]
Simulation time	200 s
Beaconing frequency	10 Hz
Communication interface	802.11p
Radio frequency	5.89 GHz
Transmission power	20 mW
Position noise mean/ $\sigma$	0/0.5 m
Path loss model	Free space ( $\alpha = 2.0$ )
Proof size	100 bytes
Proof frequency	10 Hz, 5 Hz, 2 Hz, 1 Hz
Plausibility check threshold	1 $\sigma$ , 2 $\sigma$ , 3 $\sigma$ , 4 $\sigma$

### 4.3 Evaluation Metrics

In this section, the detection and overhead metrics are presented.

**Detection Metrics.** The evaluation of detection performance is performed using a set of metrics which are derived from the variables defined below. The following nomenclature is used: a *falsified beacon* is a beacon that contains a position that was manipulated by the attacker. A *correct beacon* contains a legitimate position that was not modified by an attacker. Beacons with positions in the acceptable boundaries are *plausible* while out-of-boundary beacons are *implausible*.

- True Positive (TP): Falsified beacon is classified as implausible
- True Negative (TN): Correct beacon is classified as plausible
- False Positive (FP): Correct beacon is classified as implausible
- False Negative (FN): Falsified beacon is classified as plausible

Based on these variables, we evaluate four metrics: Accuracy (ACC), True Positive Rate (TPR), False Negative Rate (FNR) and False Positive Rate (FPR). Accuracy is the description of systematic errors in the detection mechanism. Equation 3 details the definition of the accuracy metric. The TPR, given by Equation 4, provides the rate of correct detection of attacks. Equation 5 provides the calculation of the FNR that details the rate of attack beacons that were not detected by the mechanism. In Equation 6, FPR is defined and represents the rate of correct beacons that were detected.

$$ACC = \frac{TP + TN}{TP + FP + FN + TN} \quad (3) \quad TPR = \frac{TP}{TP + FN} \quad (4)$$

$$FNR = \frac{FN}{TP + FN} \quad (5) \quad FPR = \frac{FP}{FP + TN} \quad (6)$$

**Overhead Metrics.** As presented in the design details of Vouch in Section 3, the scheme can operate in varying frequencies. The usage of higher dissemination frequencies means that a larger amount of data must be exchanged and consequently results in a higher channel load, which could cause information loss [21]. Vehicular networks aim at supporting the execution of safety-critical applications that require low-latency and transmission reliability. These applications may be negatively impacted as network collisions and instabilities occur, thus it is desirable to minimize such conditions. As stated by Sommer et al. [25], the computation of collision rates in 802.11 networks is complex and simulators currently lack simple models to study these effects. While the increase in network utilization does not necessarily result in degradation of safety performance, it is a good indicator of the network load. To determine the additional channel utilization introduced by our mechanism's overhead, we analyze the channel busy time ratio to measure the potential additional load by means of transmitting proof data in beacons. The evaluation scenario consists of a platoon composed of eight members and fifty additional interfering vehicles traveling close to the platoon that also broadcast proofs. The busy time is computed in all vehicles of the scenario and a mean is calculated for each simulation run. In addition to the four proof frequencies, we also evaluate the busy time ratio under the absence of proofs, which is represented by the 0 Hz frequency. In addition to network load, our scheme also depends on the execution of cryptographic operations. While CPU overhead is not measured in this work, we

capture the effects of crypto-generated delays during the scheme operation. The ECDSA signature generation and verification overheads are accounted according to benchmarks in [4] for ECDSA *nistp256*.

### 4.4 Simulation Results

This section describes the simulation results. We consider three main performance aspects in the evaluation. First, since the motivation of this work is to enable position verification for high-speed vehicular scenarios, we investigate the impact of vehicles speed on the detection capability of Vouch. Second, we analyze the detection performance of Vouch under varying parameter settings and the trade-off between the true and false positive rates as detection the detection threshold varies. Finally, we measure the busy-time ratio of the network as an indicator of the overhead of the proof dissemination protocol, and how this depends on the proof frequency.

**Impact of vehicle speed.** High mobility is the key characteristic of VANETs that renders existent proof-of-location schemes unsuitable for this environment. Figure 10 shows the accuracy (orange colors) and FPR (purple colors) for distinct platoon speeds using 5 Hz proof frequency and  $3\sigma$  threshold. We compare the static classifier (presented in Section 3.3) with the mobility-aware classifier used in Vouch. It is noticeable that as vehicles move at higher speeds, detection metrics degrade when using static classifiers, the accuracy goes from almost 90% at 20km/h to under 40% at 100km/h, and the FPR increases to over 70% in the high-mobility case. However, our mobility-aware classifier maintains the same performance regardless of vehicle speed.

**Detection performance.** Figure 9a includes Receiver Operating Characteristic (ROC) curves that present FPR and TPR relations for distinct parameters. For each curve, the threshold parameter is varied (from  $1\sigma$  to  $4\sigma$ ). It is clear that the 5 and 10 Hz proof frequencies result in very similar detection performance, whereas the lower frequencies (1 Hz and 2 Hz) result in significantly worse performance.

Figure 9b shows another view of the results for 5Hz proof frequency. It is clear that for low thresholds (below  $3\sigma$ ), the false positive rate is completely unacceptable. Even for higher thresholds ( $3\sigma$  and  $4\sigma$ ), the FPR is higher than what would be acceptable for an intrusion detection system for corporate networks. However, as noted in Section 3 the classifier should be complemented with a mechanism for reacting to the outcome of the classification, for which false positives might not be a major issue. For example, if all implausible beacons are dropped (filtered), having a false positive is no worse than regular packet loss.

Finally, it is interesting to investigate which beacons are incorrectly classified. In Figure 11, beacon detection results are included for 5 Hz frequency and  $3\sigma$  threshold. In this plot, the X axis represents the simulation time and the Y axis measures the position error between the beacon position and the plausible boundary. The higher the Y value, the farther the beacon position is from the plausible range. Blue marks are beacons that are out of the bounds and were correctly detected by the model, hence classified as true positives. False positives are represented by purple marks and can be caused by noise in the positioning accuracy.

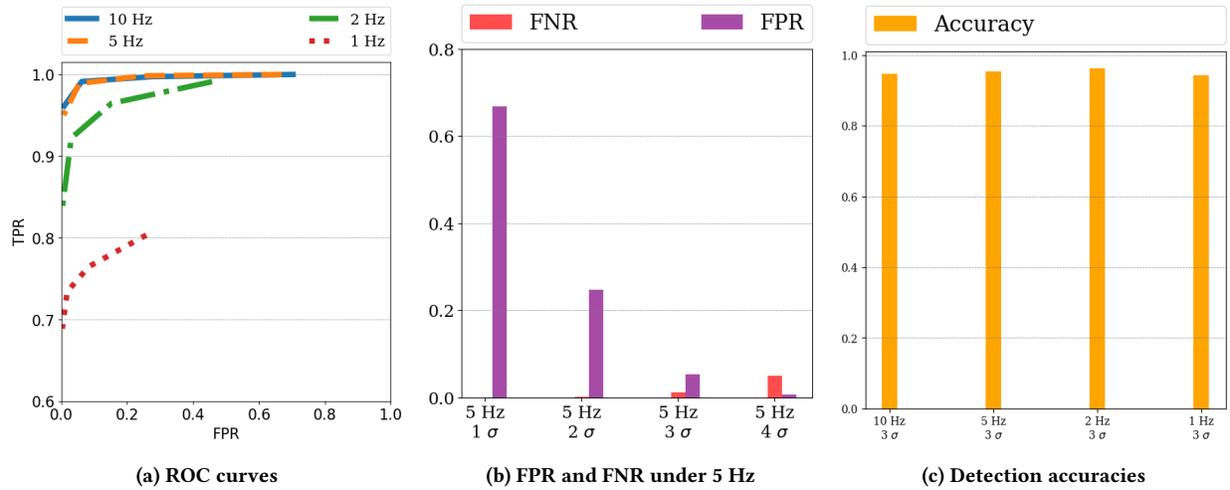


Figure 9: Detection results

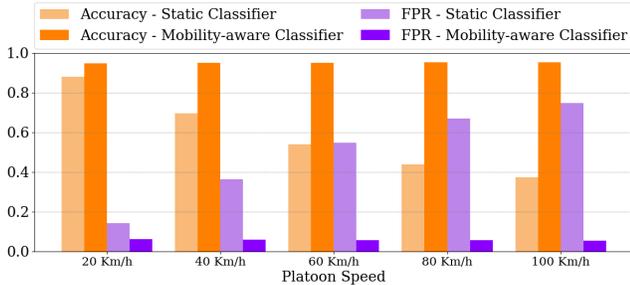


Figure 10: Detection results using the static and mobility-aware classifiers under distinct speeds

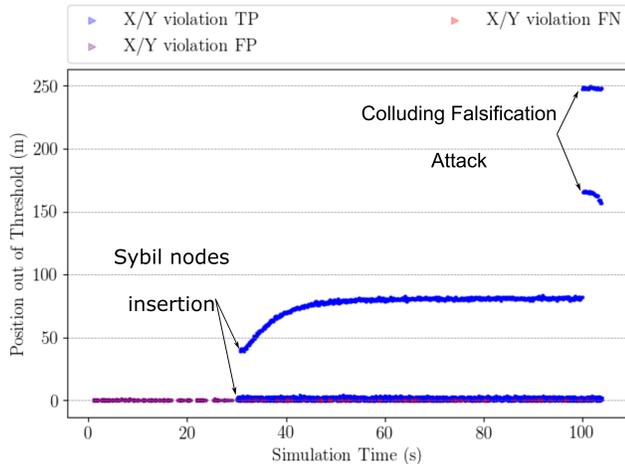


Figure 11: Detection results using 5 Hz proof frequency and  $3\sigma$

At simulation time 30 s, the Sybil nodes are introduced in the platoon formation. Even though the attacker operates the controller

without any modification until 100 s, it is possible to detect incorrect positions with the use of the proofs. Purple marks represent false positives, which means that the position noises of the beacon and the proof combined were sufficient to be classified out of the bounds. Vouch allows the detection of falsified nodes during the first phase of attack, even before they conduct the position falsification that will cause unwanted behavior in the controllers.

It is fair to highlight that this evaluation considers the best scenario for the attacker, the malicious vehicle travels right beside the false node's position and remains driving stable during the course of the attack. While in a real world attack it would be harder to achieve such scenario, a well-motivated attacker could still be able to accomplish this action. Also, the dangerous beacons (the ones far away from the real locations) are correctly classified as implausible.

**Overhead.** Figure 12 depicts the busy time ratio for distinct frequencies. The box is limited by the first and third quartiles and the median is represented by the orange line in the box. Outliers are represented by black circles. As can be observed, the mechanism has a low impact in the channel load especially under low frequencies operation. Given that accuracies for lower proof frequencies show similar detection performance (illustrated by Figures 9c and 9a), it is possible to achieve lower channel utilization overhead.

To summarize, results show that the mechanism provides the location-assurance requirement for safety-critical applications. The proof dissemination may be enforced by nodes before they accept beacons from neighbors (e.g. in a platoon join or merge request) or to continuously ensure proper behavior (e.g. in a platoon operation). Provided that implausible beacons are filtered out, our proposed scheme would discard no more than 5% of all correct beacons (considering 5 Hz and  $3\sigma$ ), while still correctly classifying all beacons with falsification error larger than a few meters as implausible.

## 5 CONCLUSION AND FUTURE WORK

The challenges to create secure and dependable connected vehicular applications are substantial, and position assurance is a fundamental requirement to support trust between vehicles. In this paper,

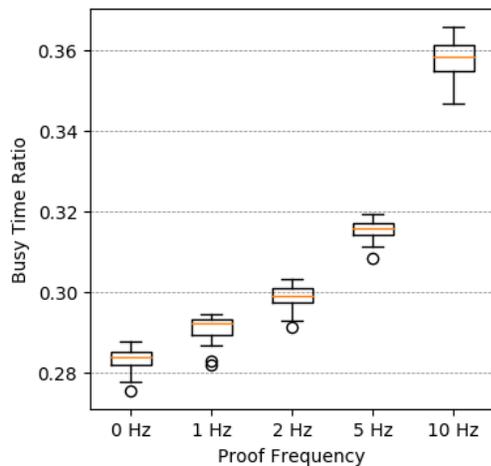


Figure 12: Busy time ratio under distinct proof frequencies

we design and evaluate Vouch: a secure proof-of-location scheme tailored for VANETs. We demonstrate that the use of location proofs combined with a plausibility model can detect position-based attacks. Results show that it is possible to achieve acceptable false positive and false negative rates in the detection metrics. Finally, the use of the proposed proof-of-location mechanism is motivated as a security control for position-dependent critical applications as platooning. While the specific studied use case is platooning, this scheme can be applied in any position-dependent application. The proposed proof-of-location mechanism has shown to perform well in the detection metrics under the studied constraints, however, future work opportunities exist. Particularly, reaction strategies have to be designed and evaluated so that applications can effectively take advantage of the scheme. In addition, advancements in the mobility model is prone to result in better detection metrics, which can consequently enable further reduction in the proof frequency dissemination and network channel utilization.

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