On the Performance of Secure Vehicular Communication Systems

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***Abstract*—Vehicular communication (VC) systems are being developed primarily to enhance transportation safety and efficiency. Vehicle-to-vehicle communication, in particular frequent cooperative awareness messages or safety beacons, have been considered over the past years as a main approach. Meanwhile, the need to provide security and safeguard the users privacy is well understood, and security architectures for VC systems have been proposed. Although technical approaches to secure VC have several commonalities and a consensus has formed, there are critical questions that have remained largely unanswered: Are the proposed security and privacy schemes practical? Can the secured VC systems support the VC-enabled applications as effectively as unsecured VC would? How should security be designed so that its integration into a VC system has a limited effect on the system performance? In this paper, we provide answers to these questions, investigating the joint effect of a set of system parameters and components. We consider the state-of-the-art approach in secure VC, and we evaluate analytically and through simulations interdependencies among components and system characteristics. Overall, we identify key design choices to deploy efficient and effective secure VC systems.**

I. Introduction

Vehicular communication (VC) systems will comprise vehicles and fixed road-side equipment (RSU) with wireless transceivers, sensing and processing units. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication will enable a range of applications, with transportation safety playing a predominant role. Practically all research and development efforts converge to safety applications based on V2V communication, with vehicles frequently *beaconing* their status (e.g., position, speed, direction), along with warnings about potential dangers.

Nonetheless, VC systems can be vulnerable to attacks and jeopardize users' privacy: An adversary could, for example, inject beacons with false information, or collect vehicle messages to track their locations and infer sensitive user data. Industry, academia, and authorities have recently understood that security and privacy protection are prerequisites for the deployment of VC systems. Security architectures were developed by the IEEE 1609.2 working group [1], the SeVeCom project [2], [3], following earlier activities of the NoW project [4] and now in parallel to the Car-to-Car Communication Consortium (C2C-CC) [5] and the eSafety eSecurity working group activities [6].

Across projects and working groups, secure VC systems rely on public key cryptography and digital signatures to protect V2V and V2I messages, facilitated by *Certification Authorities* (CAs) that manage credentials for legitimate participants (vehicles and RSUs). Pseudonymous authentication, with vehicles utilizing short-lived credentials and public-private key pairs, provides protection of privacy along with security (authentication, integrity and non-repudiation as primary requirements). Security mechanisms protect all traffic sent across the 802.11p data link [7], including the safety beacons each vehicle transmits, typically every 100 to 300 ms.

Adding security for this high-rate communication will incur high overhead, both in terms of communication and processing. Consider, for example, a vehicle receiving digitally signed safety beacons from a hundred vehicles within range; it would need to validate a high percentage or practically all of those within a short delay in the order of a hundred milliseconds [7]. Even if VC is effective under such dense network conditions, the additional security overhead could cause failure in meeting the delay and reliability requirements of safety applications. This is especially so because the VC environment lacks abundant resources (bandwidth, computational power).

The following question naturally follows: Can secure VC systems be practical? Given the current system constraints and design approaches, could the addition of security and privacy mechanisms make VC systems ineffective? We address this problem in this paper, building on our previous work [8], [9]. Based on broadly accepted approach for secure and privacy-enhancing VC [1]–[4], we first outline how pseudonymous authentication is possible without repeated interactions with the CAs. Then, we present a proposal for reducing the security overhead without harming the effectiveness of the VC system, and we investigate how variants of secure VC instantiations affect the system performance. In particular, we make the following contributions: First, based on an evaluation of the communication reliability, we determine if and how VC nodes can sustain the incurred processing load, and we provide an approximate analytical evaluation and closely matching simulation results. Being able to determine if VC nodes have sufficient processing power, we consider the overall system performance with respect to transportation safety. We evaluate how effective secure VC-enabled safety applications can be,

under a broad range of system configurations. We identify interdependencies between system and protocol parameters and the safety application effectiveness. We find that appropriately designed security and privacy enhancing VC systems can essentially support a safety application as effectively as unsecured VC systems can.

In the rest of the paper, we discuss in detail the problem at hand and outline our investigation approach (Sec. II). Then, we present the set of representative secure and privacy-enhancing VC schemes that we evaluate (Sec. III). The simulation setup, our analysis and experimental results follow (Sec. IV-Sec.VIII). We discuss the cost of revocation in Sec. IX. In Sec. X we discuss related work and in Sec. XI we conclude with a summary of our findings and a discussion of future work.

II. Problem and Approach Overview

We want to determine whether the broadly accepted state of the art of secure VC is viable, especially considering how challenging VC environments are; because heavy-traffic scenarios (thus, dense network topologies) - with tens or one hundred or more vehicles (nodes) within range - can often occur. The traditional approach has been to analyze the protocol overhead and the network performance. However, in VC systems the objective is not to have a well-performing network *per se*, but rather to effectively support VC-specific applications. This is why we investigate the overall system performance, considering five dimensions: *(i) communication technology, (ii) system resources, (iii) network configuration and environmental factors, (iv) security protocols, and (v) supported applications.*

The communication technology is the IEEE 802.11p [10], which is incorporated in the Dedicated Short Range Communication (DSRC) - Wireless Access in a Vehicular Environment (WAVE) [11] and the Communication Access for Land Mobiles (CALM) [12] standards, and it is commonly accepted for V2V and V2I communication. Vehicles transmit periodic *safety beacons* on one dedicated channel, with the beaconing rate being a system variable. *Bandwidth*, one of the primary system resources, is determined by the standards, and it is considered fixed for this investigation. The second primary resource, *processing power*, can be adapted. Here, we take into consideration platforms that are currently used in VC prototypes, but any system should have sufficient processing power for its designated tasks. Thus, the system designer can always increase the processing power at the expense of increased cost.

The use of specific *cryptographic primitives* and other *protocol functionalities* determine the processing load for each node (vehicle). We consider here the basic pseudonymous authentication approach, which has gained broad acceptance: It provides message authentication, integrity, non-repudiation and it makes it hard for two or more messages from the same sender to be linked[1]. Given the large number of temporary identities (pseudonyms) in the system, pseudonymous authentication can become cumbersome to manage; therefore, we consider here a novel scheme, first presented in [8], [9], to alleviate this constraint, thanks to a more powerful but also more expensive anonymous authentication primitive. We describe these security protocols in Sec. III.

We consider *safety applications*, as they are a distinctive feature of VC systems compared to other mobile computing systems. Moreover, they are the most challenging among VC-enabled applications; their stringent time constraints and their critical nature can affect the well-being of the vehicle passengers. We focus here on one safety application, *emergency braking notification (EBN)*.

We provide a framework to analyze the effect of a given *processing load* on the node performance, so that the appropriate processing power can be determined and provisioned. Then, we consider a system for which processing is not a bottleneck (otherwise, the system would certainly fail) and we evaluate the effectiveness of the EBN application. Conversely, given such appropriate design choices (i.e., equipment with sufficient power), our investigation reveals the effect of other parameters and their interdependencies. We evaluate the performance of the EBN application for a broad range of parameter combinations along the above dimensions. Overall, we assess the practicality of secure VC systems and identify guidelines for appropriate design.

III. Secure Communication

Each node (vehicle) has a long-term, unique identity and corresponding credentials managed by a *Certification Authority (CA)*; without loss of generality, we assume there is a single CA, even though in reality a CA hierarchy would be present [13]. Instead of utilizing their long-term credentials, vehicles obtain from the CA and utilize a set of short-lived certified public keys that do not identify the vehicle; then, they digitally sign messages with the corresponding private keys. As this is the widely used approach of *pseudonymous authentication* [1]–[5], we refer to it as the *Baseline Pseudonym (BP)* scheme, and define its operation in Sec. III-A. We consider only the vehicles, as the privacy of RSUs or other infrastructure do not need to be protected.

As the BP scheme requires that numerous short-lived certificates and keys are used by the vehicles, the stronger protection of privacy the higher the number of identities would be. For large-scale systems, this and the cost of periodically preloading vehicles with temporary keys and credentials can become a significant burden. To reduce key management complexity and enhance the system usability and efficiency, we propose a method that allows nodes to self-generate, in other words to self-certify, their own pseudonyms. With this approach, first described in [8], [9], vehicles do not need to be side-lined or to compromise their user's privacy if a "fresh" pseudonym is no longer available; no "over-provisioning" in the supply of pseudonyms is necessary; and the cost of obtaining new pseudonyms over an "out-of-band" channel is avoided.

This can be achieved with the use of *anonymous authentication* primitives, notably *Group Signatures (GS)* we

[1]More precisely, it allows that messages produced by a node over a protocol-selectable period of time, τ, be linked. But messages m_1, m_2 generated at times t_1, t_2 respectively, such that $t_2 > t_1 + \tau$, should not be linkable. The shorter τ is the fewer the linkable messages are and the harder tracking a node becomes.

describe in Sec. III-B. As the practicality of GS in the VC context is limited by their overhead, in terms of computation and communication, we propose in Sec. III-C our *Hybrid (HP)* scheme that allows vehicles to generate on-the-fly their pseudonyms, by combining the BP and GS approaches. This alleviates the management overhead of the BP; but in principle it is more costly than BP. To reduce the cost of the HP scheme to be roughly the same as that of BP and to increase the robustness of any pseudonymous approach, we propose a set of optimizations in Sec. III-D.

Concerning revocation, all the approaches make use of *Revocation Lists* (RL), generated by the CA and distributed to vehicles primarily via the infrastructure [2], [13]. When a node validates a certificate, it checks whether the sender is revoked; if successful (i.e. the sender is not revoked), it proceeds with validating the other digital signatures. We discuss further revocation-related functionality in Sec. XI.

A. Baseline Pseudonym (BP) Scheme

Each node V is equipped with a set of *pseudonyms*, which are certified *public keys* without any information identifying V. More specifically, for the i-th pseudonym K_V^i for node V, the CA provides a certificate $Cert_{CA}(K_V^i)$, simply a CA signature on the public key K_V^i (unlike the common notion of certificate, for example the X.509 certificate). The node uses the private key k_V^i for the pseudonym K_V^i to digitally sign messages. To enable message validation, the pseudonym and the certificate of the signer are attached in each message. With $\sigma_{k_V^i}()$ denoting V's signature under its i-th pseudonym and m the signed message payload, the message format is:

$$M1 : m, \sigma_{k_V^i}(m), K_V^i, Cert_{CA}(K_V^i)$$

Upon receipt of *M*1, a node, with the public key of the CA assumed available, validates $Cert_{CA}(K_V^i)$, and then verifies the signature using K_V^i.

Each pseudonym is used at most for a period τ (referenced in the rest of the paper as the *pseudonym lifetime*) and then discarded. We abstract away a number of possible implementation aspects, such as (i) the dynamic adaptation of the period of pseudonym usage, (ii) the number of pseudonyms (K_V^i and the corresponding k_V^i, $Cert_{CA}(K_V^i)$) that are pre-loaded to V, (iii) the the frequency of pseudonym refills, and (iv) policies for pseudonym change, such as factors rendering a pseudonym change unnecessary (e.g., a TCP connection to an access point), and interactions of pseudonym changes with the network stack [14]. All these are important yet largely orthogonal to this investigation. The CA maintains a map from the long-term identity of V to the $\{K_V^i\}$ set of pseudonyms provided to a node. If presented with a message *M*1, the CA can perform the inverse mapping and identify the signer.

B. Group Signature (GS) Scheme

Each node V is equipped with a secret *group signing key* gsk_V, with the *group* members comprising all vehicles registered with the CA. A *group public key* GPK_{CA} allows for the validation (by any node) of any *group signature* $\Sigma_{CA,V}$ generated by a group member. Intuitively, a group signature scheme allows any node V to sign a message on behalf of the group, *without* V's identity being revealed to the signature verifier. Moreover, it is impossible to link any two signatures of a legitimate group member. Note that no public key or other credentials need to be attached to an anonymously authenticated message; the format is:

$$M2 : m, \Sigma_{CA,V}(m)$$

The concept of group signatures, introduced by Chaum [15], is revisited in numerous works, e.g., [16]–[19], with formal definitions in [20], [21]. For the rest of the discussion, we assume and utilize the group signature scheme proposed in [22]. If the identification of a signer is necessary, the CA can perform an *Open* operation [20], [21] and reveal the signer's identity.

C. Hybrid Pseudonym (HP) Scheme

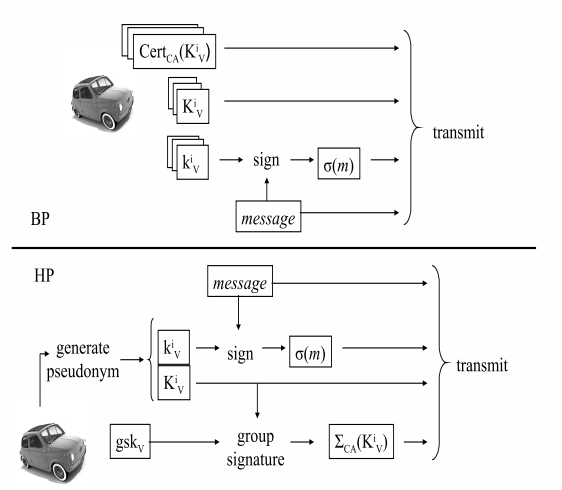
The combination of the BP and GS schemes is the basic element of our proposal [8], [9]. Each node V is equipped with a group signing key gsk_V and the group public key GPK_{CA} (recall that the group is the total of vehicles registered with the CA). Rather than generating group signatures to protect messages, a node generates its own set of pseudonyms $\{K_V^i\}$ (according to the BP public key cryptosystem). As for the BP scheme (Sec. III-A), a pseudonym is a public key without identification information, and $\{k_V^i\}$ is the set of corresponding private keys. For HP, the CA does not provide a certificate on K_V^i; instead, V uses gsk_V to generate a group signature $\Sigma_{CA,V}()$ on each pseudonym K_V^i instead. In other words, it generates and "self-certifies" K_V^i on-the-fly, by producing $\Sigma_{CA,V}(K_V^i)$. Similarly to *M*1, V attaches $\Sigma_{CA,V}(K_V^i)$ to each message, and signs with the corresponding k_V^i:

$$M3 : m, \sigma_{k_V^i}(m), K_V^i, \Sigma_{CA,V}(K_V^i)$$

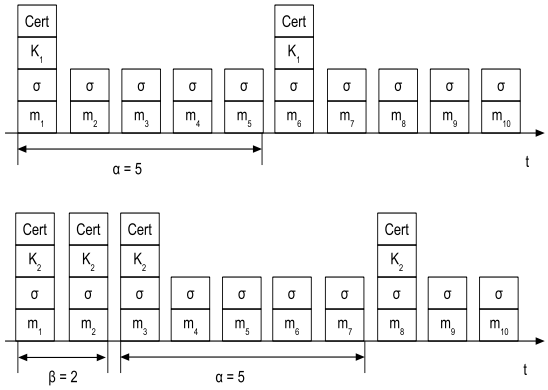
When a node receives a message *M*3, the group signature $\Sigma_{CA,V}(K_V^i)$ is verified, using GPK_{CA}. If successful, the receiver infers that a legitimate system (group) member generated pseudonym K_V^i. We emphasize that, as per the properties of group signatures, the receiver/verifier of the certificate *cannot* identify V and *cannot* link this certificate and pseudonym to any prior pseudonym used by V. Once the legitimacy of the pseudonym is established, the validation of $\sigma_{k_V^i}(m)$ is identical to that for *M*1. To identify the message signer, an *Open* on the $\Sigma_{CA,V}(K_V^i)$ group signature is necessary; message m is bound to K_V^i via $\sigma_{k_V^i}(m)$, and K_V^i is bound to V via $\Sigma_{CA,V}(K_V^i)$. Fig. 1(a) compares the BP and HP approaches.

D. Optimizations for the BP and HP Schemes

We describe optimizations to reduce overhead (Optimizations 1 and 2) and enhance robustness (Optimization 3). We employ the notation of the HP scheme, but the same considerations hold for BP too. Figure 1(b) summarizes Optimizations 2 and 3.



(a) Illustration of the BP and HP schemes.



(b) Illustration of Optimizations 2 and 3, with $\alpha = 5$ and $\beta = 2$. One *LONG* message is sent every 5, and repeated 2 times after a pseudonym renewal.

Fig. 1: Illustration of the BP and HP security schemes and related optimizations.

Optimization 1: At the sender side, $\Sigma_{CA,V}(K_V^i)$ is computed only once per K_V^i, because $\Sigma_{CA,V}(K_V^i)$ remains unchanged throughout the pseudonym lifetime τ. For the same reason, on the verifier's side the $\Sigma_{CA,V}(K_V^i)$ is validated upon the first reception and stored, even though the sender appends it to multiple (all) messages. For all subsequent receptions, if $\Sigma_{CA,V}(K_V^i)$ has already been seen, the verifier skips its validation. This optimization is useful because in practice $\tau \gg \gamma^{-1}$, where γ is defined as the *beacon frequency*.

Optimization 2: The sender appends its signature $\sigma_{k_V^i}(m)$ to all messages, but it appends the corresponding $K_V^i, \Sigma_{CA,V}(K_V^i)$ only once every α messages. We term such messages (*M*1 and *M*3) as *LONG*. *M*4 is defined as follows:

$$M4 : m, \sigma_{k_V^i}(m)$$

We denote *M*4 as *SHORT*, and α as the *Certificate Period*. $\alpha \in [1, \tau\gamma]$, where $\tau\gamma$ is the total number of transmissions during the pseudonym lifetime τ. To allow the user to choose the right K_V^i to verify an incoming *SHORT* message, all messages will carry a randomly generated 4-byte *keyID* field. This does not affect privacy as all *SHORT* messages signed under the same K_V^i can be trivially linked.

When a pseudonym change occurs, the new triplet $\sigma_{k_V^{i+1}}(m), K_V^{i+1}, \Sigma_{CA,V}(K_V^{i+1})$ must be computed and transmitted. V will sign messages with the new k_V^{i+1} corresponding to K_V^{i+1} from then on.

Optimization 2 can affect the protocol robustness, if the message that carries $K_V^{i+1}, \Sigma_{CA,V}(K_V^{i+1})$ is not received. Then, nodes in range of V must wait for α messages for the next pseudonym transmission, while being unable to validate *any* message from V. This can be dangerous if vehicles are close to each other and/or move at high relative speeds. Thus, we propose the following scheme to mitigate this problem.

Optimization 3: V repeats the transmission of $K_V^{i+1}, \Sigma_{CA,V}(K_V^{i+1})$ for β consecutive messages when K_V^{i+1} is issued, with β denoted as the *Push Counter*. After the β repetitions, with $\beta \in [0, \alpha - 1]$, the normal sequence 1 *LONG*, $\alpha - 1$ *SHORT* starts again.

Parameter	Symbol	Range	Unit
Certificate Period	α	1,5,10,15,30,50	*messages*
Push Period	β	0 to 10	*messages*
Beacon Frequency	γ	3.33 and 10	beacons/*s*
Pseudonym Lifetime	τ	60	*s*
Number of Neighbors	*N*	160, 240, 320	vehicles
Packet Payload	*m*	200	bytes
Initial Vehicle Spacing	*s*	20±1.5, 150, 200	*m*
Average Vehicle Speed	*v*	65 and 80	*Km/h*
Road Setup	-	4,6,8	lanes
Security Schemes	-	BP and HP	-
Nominal Communication Range	*r*	200	*m*

TABLE I: System parameters and values assigned for the evaluation.

IV. Evaluation Overview

We analyze the system performance of secure VC along the dimensions presented in Sec. II. Given the complexity of the problem, we employ simulation as a primary tool of analysis and we provide analytical approximations. We want to see the effectiveness of the EBN application in a variety of setups, each defined in the sections that follow, with the analysis results in the relevant section. We analyze the system operation to gain insight into the role of each of the system parameters; indicative values for these are summarized in Table I. We study challenging or extreme transportation conditions, because the system has to remain operational, even under these conditions.

We assume that only vehicles transmit because RSUs will always be less numerous (each serving an area with tens or hundreds of vehicles), and often completely absent; thus, almost all of the safety-related data will be generated by vehicles. Finally, we also assume that all beacons carry

Algorithm	Security level (bits)	Sign (ms)	Verify (ms)	Signature (bytes)	Public key (bytes)	Private key (bytes)
ECDSA-192	96	0.5	3	48	25	24
ECDSA-256	128	0.8	4.2	64	33	32
GS	128	53.7	49.3	225	800	64

TABLE II: Computation costs on a 1.5GHz Centrino processor and communication overhead for different signing algorithms: Elliptic Curve Digital Signature Algorithm (ECDSA) utilizing different standardized elliptic curves, and a representative efficient Group Signature (GS) algorithm [22].

	Sign (ms)	Verify (ms)	Overhead (bytes)
BP *LONG*	1.3	7.2	141
HP *LONG*	54.2	52.3	302
SHORT	0.5	3	52

TABLE III: Processing delay (in ms) and communication overhead (in bytes) for different packet types.

	Packets per beacon period γ^{-1}
BP *LONG*	13.9
HP *LONG*	1.9
SHORT	33.3

TABLE IV: Maximum number of verifiable packets per γ^{-1} s, for $\gamma = 10$.

relevant information for safety applications. We couple the *ns-2* simulator, which simulates V2V communication, with a custom module written in C, which simulates (i) the EBN application and its effect on vehicles movement and (ii) the security processing of messages. We choose such a combination because we could not find another publicly available simulation environment with security functionality integrated and with nodes adjusting their behavior according to the messages they receive.

First, in Sec. V, we evaluate the cryptographic overhead, in terms of communication and processing, and we choose a representative choice of primitives, security level, and reference platform. Then, we analyze the communication reliability in Sec. VI. Based on those two elements, we study the effect of processing overhead on individual nodes in Sec. VII. Finally, in Sec. VIII, assuming that nodes are provisioned with sufficient processing power, we perform a system-wide analysis for the considered EBN safety application and its performance.

V. Cryptographic Overhead

We choose to use EC-DSA as the basic signature algorithm [23], the group signature algorithm proposed by [22], and security level of $t = 96$ bits for message signatures and $t = 128$ bits for CA certificates in BP and for group signatures used in GS and HP. High security might not be necessary for the short-lived K_V^i, but it is required for the long-term keys and CA certificates. Table II shows the costs for signature generation and verification along with the overhead for the chosen algorithms.

Overhead: The $K_V^i, Cert_{CA}(K_V^i)$ is 89 bytes for BP, and with $\sigma_{k_V^i}(m)$ and *KeyID* the overhead is 141 bytes per message. For GS, the overhead is $\Sigma_{CA,V}(m)$, thus 225 bytes per message. For HP, the overhead is $\sigma_{k_V^i}(m), K_V^i, \Sigma_{CA,V}(K_V^i)$, *KeyID*, in total 302 bytes per message. For the $\alpha - 1$ *SHORT* messages, the overhead is $\sigma_{k_V^i}(m)$, *KeyID*, thus 52 bytes. The effective overhead reduction depends on the value of α, as explained in Sec. VI.

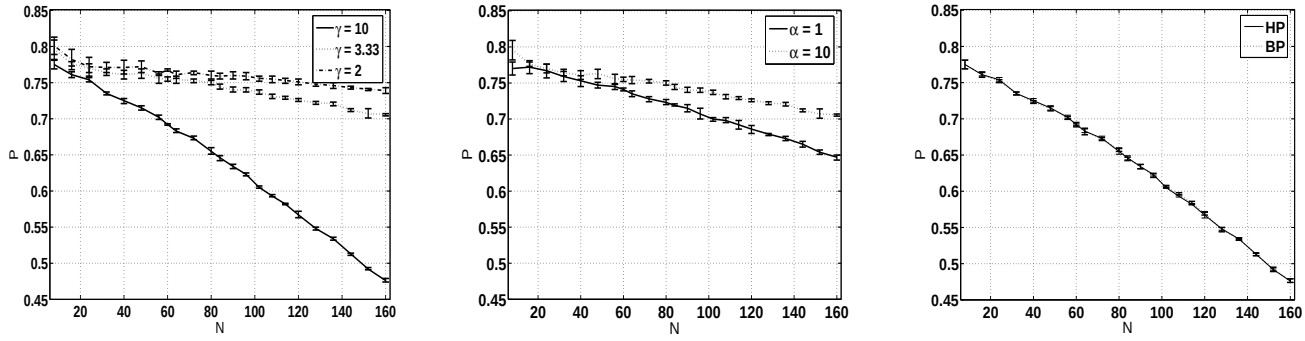
Computation: We make use of a Centrino machine with the clock speed set at 1.5 GHz, which is close to the CVIS (Cooperative Vehicle-Infrastructure System) vehicle PC, a rather powerful platform (compared to generally available embedded processors) adopted for the development of future VANET applications [24]. We obtain an EC-DSA benchmark on the platform through the OpenSSL standard test suite [25]. As for group signatures, a well-established implementation of the chosen algorithm [22] is not yet available. Thus, to estimate the processing delay, we calculate the number of 32-bit word scalar multiplications required for GS signing and verifying, extracting the relevant data from [26] and [27]; then, we benchmark the scalar multiplication operation.

Table II shows the costs for signature, verification and overhead for the chosen algorithms. To obtain individual processing delays for a given type of message, it suffices to take the sum of the corresponding cryptographic primitive delays (M1, M3 and M4). As mentioned earlier, security levels are $t = 96$ for $\sigma_{k_V^i}(m)$, and $t = 128$ for $Cert_{CA}(K_V^i)$, $\Sigma_{CA,V}(m)$ and thus $\Sigma_{CA,V}(K_V^i)$. We summarize the results per message in Table III.

VI. Communication Reliability

The communication reliability is of central importance and depends on the channel properties and load; the more loaded the channel is, the more likely it is for a packet collision to occur at the wireless medium, which depends on the number of transmitters, *N*, the beacon frequency, γ, and the packet size (including the security overhead). We implement beacons with information on vehicle position, and on speed and direction, with a timestamp, and safety warnings in a payload, m, of 200 bytes. The physical layer transmissions are across a realistic radio propagation model [28], [29], with a nominal communication range of *r* = 200 *m* and a bandwidth of 6 *Mb/s* [7], [30], [31].

We estimate, with the help of detailed simulations, the average probability of successful reception at a receiving node at the center of a 200-meter radius disc that covers the entire width of a multi-lane highway and it is filled with N uniformly spaced neighbors. We consider various settings, increasing the number of lanes and decreasing the vehicle density, varying the size of N from 8 to 160; a subset of these settings (four-, six-



(a) Ratio of messages received for the HP scheme; $\alpha = 10$.

(b) Ratio of messages received for the HP scheme; $\gamma = 3.33$ beacons/s.

(c) Ratio of messages received for the BP and HP schemes; $\gamma = 10$ beacons/s and $\alpha = 10$.

Fig. 2: Reliability of message reception for secure VC (beaconing), as a function of the neighborhood size, N.

and eight- lanes with average spacing of 20 meters) is used in Sec. VIII. This metric is independent of the distance between the transmitter and the receiver. The reception probability as a function of the sender-receiver distance is presented in our previous work [9], and it is omitted here for simplicity and due to lack of space. The results are shown in Fig. 2 with 95% confidence intervals, and are repeated 5 times, with each repetition lasting 60 *s* of simulated time.

We note that the 802.11p broadcast communication, a CSMA/CA protocol without acknowledgements, could be modeled and evaluated analytically, for example, in terms of the probability of successful reception and throughput, following numerous works for similar CSMA/CA protocols under various assumptions (on traffic conditions, presence or absence or channel errors, packet sizes, impact of hidden terminals, etc). An effort to craft a precise analytical model for VC is orthogonal to our investigation. What we need here is an accurate evaluation of the communication reliability, as a stepping stone for our security-related investigation; this can be obtained via detailed simulations.

With the fixed available bandwidth, specific for the communication technology, the communication reliability depends on the offered load; Table V summarizes the load for each of the scenarios in this paper. Fig. 2 shows the estimate of the probability of reception, P (i.e. the ratio of received messages over transmitted beacons), as a function of the number of transmitters, N, the beacon frequency, γ, and the protocol parameter α. We observe that the communication performance degrades fast with N when γ is high (Fig. 2(a) for HP), while the degradation is much slower as N increases for lower γ values. The effect of increasing α, thus reducing overhead is significant even when γ is not very high (e.g., $\gamma = 3.33$ beacons/s, Fig. 2(b) again for HP). Finally, as shown by Fig. 2(c) for γ=10 and α=10, the BP and HP schemes perform almost identically.

These results show that γ turns out to be the most significant channel load factor. Choosing a smaller value for γ decreases the channel saturation and thus the processing overhead (fewer messages are sent); but it also affects the transportation safety, as we show in Sec. VIII. At the same time, the appropriate choice of BP and HP parameters can reduce security overhead

γ **(bcn./s.)**	**HP** $\alpha = 1$	**HP** $\alpha = 10$	**BP** $\alpha = 1$	**BP** $\alpha = 10$
10	5020	2770	3410	2609
3.33	1671.66	922.41	1135.53	868.70
2	1004	554	682	521.8

TABLE V: Offered load per transmitter, in bytes/s, for different security schemes and settings.

(notably α, as it will become clear in Sec. VIII the needed β values incur very limited overhead). The almost identical P for BP and HP also show the benefit from the proposed optimizations, as both schemes have comparable overhead (with the advantages of HP).

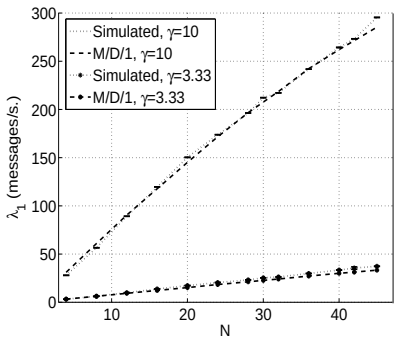
VII. Processing Overhead

We want to answer the following questions: (i) How many packets does a given node $V_{\mathcal{R}}$ have to verify per time unit, in various VC settings? (ii) What is the additional message verification delay introduced by security? We consider one *beacon period*, i.e. γ^{-1} seconds, as the time unit, as specified by transportation safety requirements.

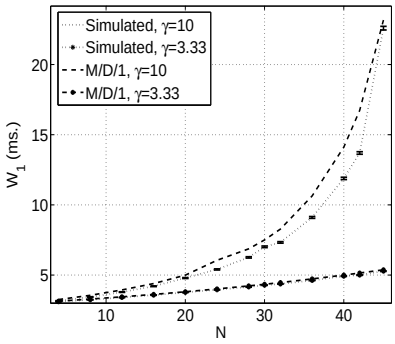
The BP and HP schemes use two general message types, according to the induced security communication overhead: *SHORT* messages carrying a node signature, and *LONG* messages carrying a node signature and certificate. Each node transmits one *LONG* message every α *SHORT* messages, with β additional consecutive *LONG* messages sent upon a pseudonym change.

The processing load at some node $V_{\mathcal{R}}$ depends on the number of packets it needs to verify. This consists primarily of signature verifications for essentially all received beacons, as they carry safety-related information. In a given slot, if $V_{\mathcal{R}}$ has N neighbors in range, it should validate $O(N)$ messages per time unit. Due to Optimization 1, $V_{\mathcal{R}}$ needs to validate the certificate signature only the first time it receives it from each neighbor. In contrast, $V_{\mathcal{R}}$ generates only one signature per time unit, and for HP specifically it generates one group signature per pseudonym lifetime.

N nodes V_i, $i = 1, ..., N$, produce messages at an aggregate rate λ, and $V_{\mathcal{R}}$ processes them at a rate μ. λ depends on the number of neighbors, N, the message generation rate,



(a) Analytical and simulated λ_1; $\alpha = 10$, $\beta = 0$, $\tau = 60$.



(b) Message verification delay at $V_{\mathcal{R}}$; $\alpha = 10$, $\beta = 0$, $\tau = 60$.

Fig. 3: HP scheme: Comparison between analytical approximation (labeled as *M/D/1*) and simulations: Arrival rate λ_1, and processing delay W_1, for *SHORT* messages, as a function of the neighborhood size *N*.

γ, the type of generated messages, and the reliability of communication across the wireless channel. μ depends on the choice of security primitives (and their security level) and the available on-board processing power. Thus, μ is constant for a given system configuration.

We view the system operation as a queue: We are interested in the system stability, which depends on λ, μ, and the queuing model. To identify an appropriate model, we characterize the arrival process and demonstrate that it can be closely approximated by a Poisson process. Then, we provide an analytical estimate for the average arrival rate, λ, and validate it through simulations. Finally, we apply queuing theory results, in order to answer the questions outlined above.

A. Characterization of the Arrival Process

We simulate the system and collect the message inter-arrival times at some $V_{\mathcal{R}}$, for different setups of traffic conditions and tuning of the security parameters α and β. Then, we fit known distributions to the empirically obtained data and perform a χ^2 test to assess the quality of the fitting (p-value=0.05). We find that the exponential distribution fits well the empirical data; its memoryless property and the orderliness of packet reception (any node receives one packet at a time and no two or more arrivals occur simultaneously) suffice to approximate arrivals as a Poisson process. Note that this is valid for the type of traffic under consideration, i.e. safety beaconing, which is going to be the majority of the traffic exchanged between vehicles. If the type of traffic changes, then the arrival process would in principle change.

We assume one processor at $V_{\mathcal{R}}$ with deterministic service times. We consider both *LONG* and *SHORT* packets in the same single queue, with no priority policy and no preemption[2]. The queue is then a multi-class M/D/1, in this case with two classes. The *average waiting time*, W_i, is given by [32]:

$$W_i = t_i + \frac{\sum_{j=1}^{r} \lambda_j t_j^2}{2(1-\rho)} \quad (1)$$

[2]We adopt this as a baseline approach, as we are interested mainly in validating the general queuing theory approach. Obviously, several other policies and system models can be employed.

where W_i, λ_i and t_i are the total time in queue, the arrival rate and the service time of the *i*-th (out of *r*=2) classes respectively, $\rho = \sum_{i=1}^{r} \rho_i$ and $\rho_i = \lambda_i t_i$. The *queue length*, L_i, can be derived from Eq. 1 and Little's law [33].

B. Estimation of λ

An estimate for λ_1, the arrival rate for *SHORT* messages (derived in the Appendix) is:

$$\lambda_1 = NP(1-(1-P)^K) \quad (2)$$

with N the number of neighbors, P the average reception probability for messages (beacons), and $K = \frac{\lfloor \tau\gamma/\alpha \rfloor}{2}$. We focus on *SHORT* packets because they are the majority of the processing load as explained above and in [9]. From the description of the BP and HP schemes (with Optimizations), the simulations, and the derivation, it appears that *LONG* messages have a limited impact.

In Fig. 3, we plot the analytical and simulation results, for N ranging from 4 to 48 vehicles and $\gamma = 10$ or $\gamma = 3.33$ beacons/s; we average over 1000 randomly seeded simulations. Fig. 3(a) shows how many packets $V_{\mathcal{R}}$ must process as a function of *N*, and that this relation is almost linear. As Table IV shows, 333 signature verifications (*SHORT* packets) per second is the maximum the node we consider here can handle. This means that for $\lambda_1 \geq 333$ msg/s, considering that incoming packets as *SHORT*, the node would be unable to keep up and its queue of messages would grow fast. We observe that for $\gamma = 10$, the value considered most often in the literature, the arrival rate increases towards this threshold while the message processing delay, W_1 in Fig. 3(b), increases fast with N.

Consider an example to illustrate this: with 80 transmitting vehicles in range of $V_{\mathcal{R}}$, $\alpha = 10$, $\beta = 0$, $\gamma = 10$, and $\tau = 60$, and the resultant $P = 0.655$ (Fig. 2(a)). We assume a highway scenario and a simple content-based optimization: $V_{\mathcal{R}}$ processes a beacon if it comes from a neighbor moving in the same direction (stream of traffic). For simplicity, if the two parts of the road are equally balanced, we consider $N = 40$ vehicles out of the 80 neighbors in range. From Eq. 2 we

obtain $\lambda_1 = 264.3$ msg/*s* and from the simulation of the same scenario, the arrival rate would be 259.7 msg/s.

VIII. Transportation Safety

We investigate how security affects transportation safety in *two settings*. First, we consider *pairs of vehicles*, one in a dangerous condition transmitting an EBN message and another approaching vehicle that is previously unaware of the transmitter and must receive the EBN message. We analyze a fundamental metric, *the ability to be early notified*: We capture this as the distance at which the receiver is first able to validate the safety messages. The second setting we consider is more involved: We study the occurrence of collisions among vehicles in a *platoon of one hundred vehicles*, with and without the use of security; the latter serves clearly as a benchmark. We also investigate the impact of penetration rate of vehicular communication rate, to gain insight on how security affects the ability of the vehicular communication system to achieve one of its fundamental goals.

We integrate here the results obtained in the previous sections; we assume that vehicles have sufficient processing power and are able to verify the signatures on all incoming packets. We average over 1000 randomly seeded simulations and present results with 95% confidence intervals. Recall that Table I summarizes parameter values.

A. Simulation Setup

We consider four-, six- and eight-lane scenarios, with vehicles placed in two opposing two-, three- and four-lane flows of traffic, respectively. This corresponds to a neighborhood N of 80, 120 and 160 vehicles respectively. Vehicles are 4-meter long and they are initially uniformly randomly placed along each lane, with an average vehicle-to-vehicle distance of s meters. We focus on one lane of traffic within such a neighborhood of N vehicles, which changes mildly because of mobility. In the two-vehicle setting, there is a small initial "gap" in one lane, depending on the initial spacing of the pair of vehicles; e.g., when they are at 200 meters, there are initially 10 vehicles less present, or in other words 70 (110 or 150) vehicles instead of 80 (120 or 160). The vehicle velocities are initially random with an average v, unless stated otherwise; velocities are adapted according the VC system functionality and, in the platoon setting, upon visual contact with the preceding vehicle's braking lights. Vehicles do not change lanes during the simulation, and they process messages originating from vehicles in the same traffic flow (i.e., with the same heading).

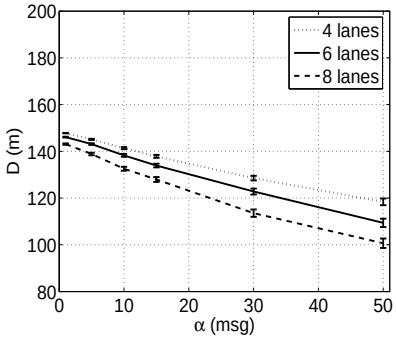
We consider an emergency braking (EBN) application, with one vehicle in an emergency situation that brakes and starts the transmission of EBN messages. Braking has two effects: (i) it turns on the vehicle rear red lights that visually warn drivers within range of sight (which depends on the simulated weather conditions), and (ii) it triggers the transmission of EBN warning messages. Besides warning other vehicles, an EBN-warned vehicle warns its driver to start braking shortly afterwards. We model driver reaction times as a result of VC-enabled and visual warnings, with a random variable uniformly distributed between 0.75 and 1.5 *s*. We model weather conditions by setting vehicle braking capabilities and visibility conditions; for example, on a wet road, braking is possible at a rate of 4 m/s^2 and a driver can see up to 30 *m*. Our simulation conditions are in agreement with related work in the transportation engineering area, e.g., [34], [35].

Two-Vehicle Setup: We consider one transmitter, V_t, and one receiver, $V_{\mathcal{R}}$, at an initial distance of d meters, with $V_{\mathcal{R}}$ always behind V_t in the same lane and with a velocity for $V_{\mathcal{R}}$ higher than that of V_t. $V_{\mathcal{R}}$ moves at a constant relative speed Δv with respect to V_t, without any other vehicle in between. For simplicity, we elect s to be such that it is less than or equal to the nominal communication range at the beginning of each simulation. We choose two setups, one with $\Delta v = 20$ *Km/h* and $s = 150$ *m*, and the other with $\Delta v = 35$ *Km/h* and $s = 200$ *m*. We evaluate how the optimization parameters, α and β, affect the distance, D, at which $V_{\mathcal{R}}$ receives the first $K^i_{V_t}, \Sigma_{CA,V}(K^i_V)$ from V_t. In this setting, we wish to test the ability of the secure VC system to deliver safety information, especially under challenging conditions; e.g., $V_{\mathcal{R}}$ is very close to V_t when the latter changes to a new pseudonym (and private key). Therefore, in order to evaluate the VC performance alone, we do not consider the rear red lights of V_t; which, of course, would naturally warn the driver of a $V_{\mathcal{R}}$ in line of sight.

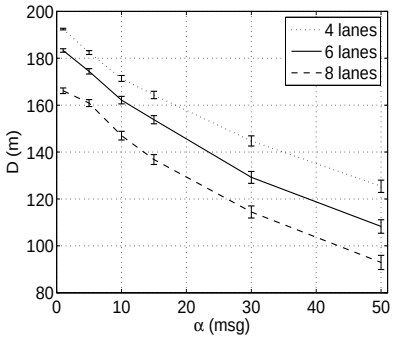
Vehicle Platoon Setup: We focus on a platoon of one hundred cars along a single lane moving with similar velocities, denoted as V_1 to V_{100}, with V_1 for the vehicle at the front and V_{100} at the rear of the platoon. We utilize values of $s = 20$ *m*, velocities on the average $v = 80$ *Km/h*. We analyze how many collisions occur when the leading vehicle V_1 makes an emergency brake and starts sending EBN messages. Once some V_i, with $i > 1$ receives the warning, it starts sending EBN messages itself. As proposed in [36]–[38], when V_i receives a warning from a V_j with $j > i$, it stops transmitting warnings, assuming that at least one vehicle behind V_i has already been warned. In this setting, we consider rear red-light warnings.

We choose pseudonym lifetime $\tau = 60$ *s*. We consider the first 60 *s* of the simulation time as a warm up period, during which no emergency conditions arise. This approximates a realistic situation: When an emergency arises, vehicles have already validated (identified) some of their neighbors and can thus immediately accept their warnings. The simulation concludes when all vehicles in the platoon are immobile, with V_1 not resuming any motion after its emergency braking action.

First, we consider scenarios where all vehicles are equipped with VC systems. Intuitively, these full deployment settings can lead to better safety thanks to the VC technology. But they also correspond to more strenuous conditions, in terms of processing and communication overhead. Nonetheless, VC will be deployed gradually, over a period of several years. Thus, we define the *penetration rate*, pr, as the fraction of VC-enabled vehicles, and we analyze the system behavior as a function of pr. Equipped vehicles behave as described above, while non equipped vehicles rely only on visual means (the red lights of the preceding vehicle) to detect emergencies. We

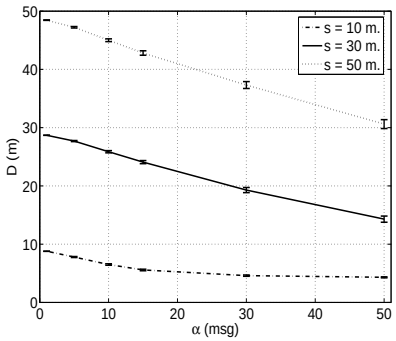


(a) Reception distance for $s = 150$ *m*, $\Delta v = 20$ *Km/h*.

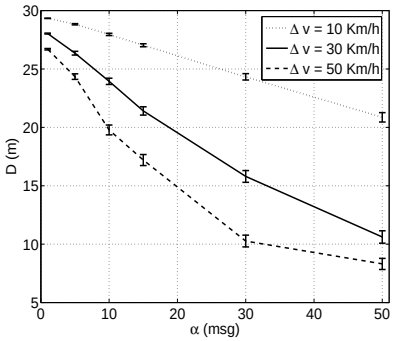


(b) Reception distance for $s = 200$ *m*, $\Delta v = 35$ *Km/h*.

Fig. 4: Distance D, at the time of reception of the first certificate at the trailing vehicle, $V_{\mathcal{R}}$, as a function the Certificate Period α; without Optimization 3, varying the network size; HP scheme, γ=10 beacons/s.



(a) Reception distance, D, for 8 lanes, $\Delta v = 20$ *Km/h*.



(b) Reception distance, D, for 8 lanes, $s = 30$ *m*.

Fig. 5: Distance D, at the time of reception of the first certificate at the trailing vehicle, $V_{\mathcal{R}}$, as a function of the Certificate Period, α; without Optimization 3, varying s and Δv; HP scheme, γ = 10 beacons/s.

analyze this scenario with 4 lanes of traffic, α equal to 1 or 10, β to 0, γ to 10 or 3.33 beacons/s, and pr ranging from 0.05 to 1.

B. Two-Vehicle Simulation

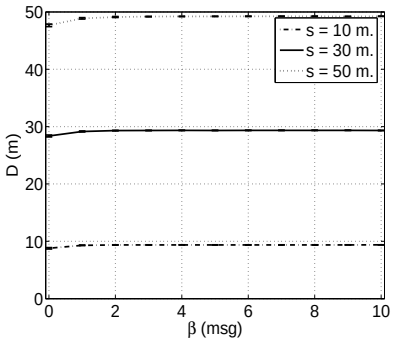
In Fig. 4, the distance D at which $V_{\mathcal{R}}$ receives the first certificate $\Sigma_{CA,V}(K_V^i)$ decreases as the Certificate Period α increases: If a *LONG* message from V_t is missed, $V_{\mathcal{R}}$ has a chance to receive the next one only after α additional beacons from V_t. Nonetheless, we observe that messages from V_t can be validated in all cases before the distance becomes dangerously small.

Impact of pseudonym change on safety: Missing a new pseudonym could be dangerous if $V_{\mathcal{R}}$ (and in general for any vehicle) is close to V_t at the time of pseudonym change and has high positive relative speeds (i.e., approaching fast V_t). To capture such situations, we vary s between V_t and $V_{\mathcal{R}}$, with results in Fig. 5(a): the curve generated by $s = 10$ *m* indicates that $V_{\mathcal{R}}$ is not able to validate V_t before reaching it (and thus crashing in our simulation[3]). In another set of scenarios, we fix $s = 30$ *m*, and we vary Δv = 10, 20 and 50 *Km/h* (Fig. 5(b)): The effect of α remains, but we also observe that with a higher Δv, the drop in the reception distance with α is faster. Overall, pseudonym switching can be risky if it happens when vehicles are close to each other.

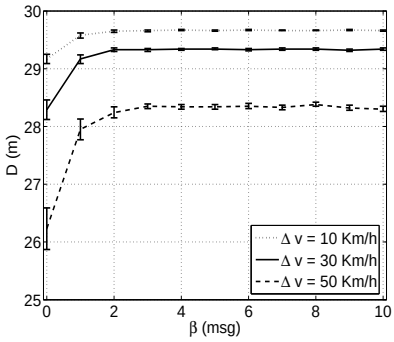
Optimization 3, not used so far, can address this problem. Fig. 6(a) and Fig. 6(b), for $\alpha = 10$ and with β varying from 0 to 10, show that Optimization 3 is effective. Even a single "pushed" message ($\beta = 1$) enables reception roughly within 2 meters after the pseudonym change, regardless of speed and initial distance (clearly, the actual reception distance depends on those parameters). Increasing redundancy, that is setting β beyond 3, does not improve robustness any further. We observe in Figs.6(a), 6(b) that an "optimal" is reached in most cases for $\beta = 1$.

Intuitively, this is because the probability of receiving a *LONG* message when $V_{\mathcal{R}}$ and V_t are very close to each other is relatively very high. If these two nodes are far, the

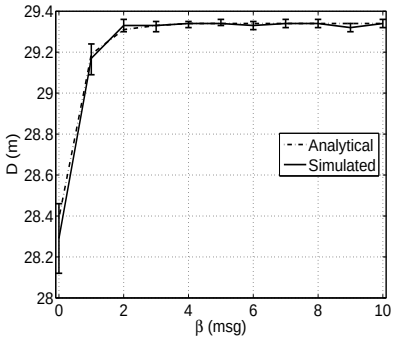
[3]In Fig. 5(a), the curve for $s = 10$ *m* converges eventually at $s = 4$ *m*: distances are computed from the front of the approaching vehicle to the back of the preceding one. In this extreme scenario, the VC functionality for an optimistic protocol configuration (e.g., α=30 or 50) results to collision; which, of course, would have been averted by the visual contact and the driver reaction that we purposefully omit from this setting.



(a) Reception of first certificate for 8 lanes, $\Delta v = 20$ *Km/h*, $\alpha = 10$.

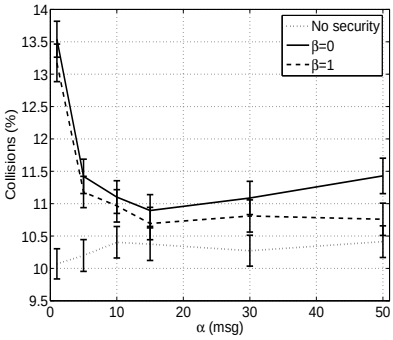


(b) Reception of first certificate for 8 lanes, $s = 30$ *m*, $\alpha = 10$.

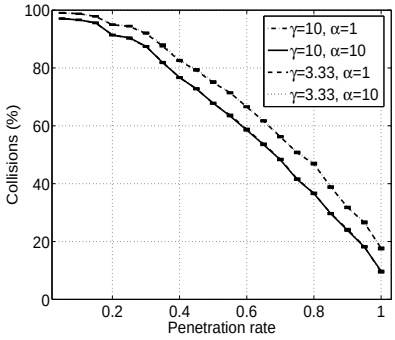


(c) Analytical and simulated reception distance for $\alpha = 10$, $s = 30$ *m*, $\Delta v = 20$ *Km/h*, 8 lanes of traffic.

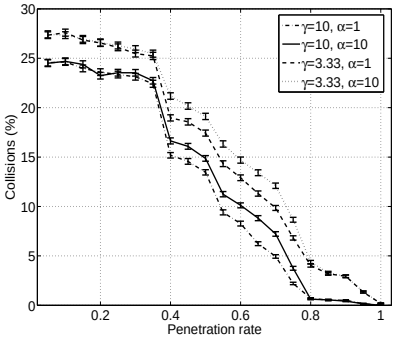
Fig. 6: Distance D, at the time of reception of the first certificate at the trailing vehicle, $V_{\mathcal{R}}$, as a function of β; HP scheme, γ = 10 beacons/s.



(a) Collisions in a Platoon of 100 cars, as a function of α, β; 8-lane highway; comparison with unsecured VC.



(b) Collisions in a Platoon of 100 cars, as a function of the penetration rate, pr; 4-lane highway, wet road conditions.



(c) Collisions in a Platoon of 100 cars, as a function of the penetration rate, pr; 4-lane highway, dry road conditions.

Fig. 7: Transportation safety with secure VC: Collisions, as a percentage of vehicles, in an emergency situation; varying road conditions, message rates, protocol parameters, and VC technology penetration rate; HP scheme, γ = 10 beacons/s.

probability of successful reception is relatively low but there will be several opportunities (subsequent transmissions) for $V_{\mathcal{R}}$ to receive a *LONG* message from V_t. To express this more precisely, let *Z* be a discrete random variable for the slot in which a *LONG* message is first received (during the lifetime of the pseudonym). If *E(Z)* is the mean value, the average distance from V_t that the first *LONG* is received by $V_{\mathcal{R}}$ is $D = E(Z)\gamma^{-1}\Delta v$.

V_t transmits a *LONG* packets for β consecutive slots, and every $k\alpha$ slots. The probability *LONG* is first received at some j slot is simply the probability it is not received at any of the $i < j$ slots and it is received at the j-th, where i, j take values from $I = 1, 2, ..., \beta, \beta + 1, ..., \beta + 1 + \alpha, ...$:

$$P_j = P(j) \prod_{k \in I} (1 - P(k)) \tag{3}$$

The probabilities at each slot, $P(k)$, differ, as they depend on the distance of the two nodes (and their neighborhood more generally). Using values for different distances obtained experimentally (Sec. VI and [9]), we compare Eq. 3 to the simulation results, for $s = 30$ *m*, $\Delta v = 20$ *Km/h*, $\alpha = 10$, 8 lanes of traffic and $\gamma^{-1} = 100$ *ms*. Fig. 6(c) shows D calculated with the help of Eq. 3 and the experimental data, to clarify why low β values suffice.

C. Platoon Analysis

1) Fully deployed VC: Fig. 7(a) shows the percentage of vehicles within a platoon of one hundred that crash as a function of α. As a reference, we simulate the VC system and EBN application without security. In the absence of V2V communications, 80%-100% of vehicles crash; for the same scenarios, safety messaging reduces the number of crashes to approximately 10% of all vehicles. Then, overall, as expected, security increases crashes compared to not secured VCs: the increased network overhead and protocol restrictions on which alert message can be validated delay the reception of valid EBN messages[4].

However, we observe that the tuning of the secure VC protocols affects the safety application. We observe first a decrease in the average fraction of crashes, as α increases, and then a slow increase as α increases further. This is due to two

[4]For non-secured VC, the x-axis, the α, is not a parameter that affects its operation. This is why the corresponding curve is essentially flat, with minor variability due to the randomly seeded simulation scenarios.

competing factors: the increase of α reduces the channel load and thus increases the per-packet reception probability, but the authentication delay for a receiver missing a *LONG* packet also increases; e.g., for $\alpha = 50$, the authentication delay is (at least) 5 *s*. We note also that the use of Optimization 3 reduces the number of crashes with respect to the non optimized protocol, with the same value for α, as it adds negligible overhead but manages to reduce the authentication delay, as explained above.

2) Effect of VC penetration rate on safety: First, we observe in Fig. 7(b) that the crash average decreases when *pr* increases, as expected. Then, we observe that γ is dominant; the curves for $\alpha = 1$ and $\alpha = 10$ almost overlap for a given value of γ. We also observe that the group of curves with different values of γ are well separated, with a higher number of crashes for $\gamma = 3.33$. This beacon frequency is not sufficient, in our scenario to warn the drivers, although the channel reliability is higher (as shown in Fig. 2(a)). Vehicles send many (one third) messages less compared with the case $\gamma = 10$.

Fig. 7(c) shows what happens in a less challenging scenario, with average inter-vehicle spacing of 40 *m*, vehicle speed of 65 Km/h, braking capability of 6 m/s^2 and visual range of 70 *m* (modeling dry road conditions and good weather). First, we observe a much lower percentage of crashes, now ranging between 25-30% and no crashes; the separation between the curves for different γ values is also smaller, even though a higher percentage of crashes is observed for the low γ = 3.33 beacons/s. Tuning α affects the number of crashes when *pr* is in the range of 40-80 %; for $\alpha = 10$ we observe an increase variable from 15 to 40 % compared to the case with $\alpha = 1$. Conversely, if VC has relatively low (*pr* < 0.4) or high (*pr* $>$ 0.8) penetration, security optimizations have a limited impact.

IX. Revocation

We discuss here the revocation costs, based on the use of Revocation Lists (RLs). We note that this is a largely orthogonal problem to this investigation and out of the scope of this paper; moreover, there are several unknown parameters and factors in terms of the instantiation of a revocation solution. Nonetheless, in order to provide a complete picture, we consider the revocation overhead for each of the security schemes considered. We did not consider revocation in Sec. VII, but it is straightforward to do so. It suffices to add the revocation processing delay to that for validating *LONG* messages (in fact, the first-received *LONG* per node and pseudonym lifetime for BP and HP).

The basic difference between BP and HP (and GS) schemes is that the former deals with short term keys while the latter with long-term ones. The number of vehicles that would be revoked is not currently known and it is hard to estimate, because it would depend on policy decisions, the size of the system in each region, among other currently unknown aspects. Here we denote the number of revoked vehicles as R. Then, for the HP (and GS) scheme, the size of the revocation list would be $|RL_{HP}| = R$. While, for BP, $|RL_{BP}| = c \times R$, where c is essentially the number of temporary keys each vehicle holds at the time of its revocation.

c can be a large number, in the order of 10^4 to 10^6; but, again, its actual value depends on factors out of the scope of this paper. For example, the ability of vehicles to have frequent access to a trusted third party to obtain their short-term certificates, or the autonomy of vehicle policies mandate. Approximately, we can consider that c corresponds to the number of pseudonyms a vehicle obtains at a "*pseudonym refill*", and we can assume that pseudonyms are valid only between two consecutive refills. Then, a revoked node running BP would be unable to obtain a new set of pseudonyms [14], and RL_{BP} would include only the pseudonyms granted at the last refill. Consider an example for c: with τ=60 s, in one day a vehicle V would "consume" 1440 pseudonyms. Assuming that pseudonym refills take place once per month, then $c = 43200$; if the refill were made once per year, then $c = 518400$. In the rest of the discussion, to provide illustrative examples, we assume that on the average $c \approx 10^4$.

The cost to verify whether a pseudonym is revoked is the cost of a lookup into the *RL*. This can be achieved in constant time, e.g. by using a hash table. In this case, the construction of the data structure is proportional to $|RL_{BP}|$, and it must be performed every time a new RL_{BP} is received. The required memory is also $\approx |RL_{BP}| \times E_{BP}$ bytes, where E_{BP} is the size of one entry in the hash table. E_{BP} is composed by a serial number and a revocation date and it sums to E_{BP}= 14 bytes [1]. Thus, for each revoked vehicle (i.e. long-term identity) holding c pseudonyms, at least 140 KB would be needed.

For GS and HP schemes, we extract relevant data from [22], [27]. Each entry in RL_{HP} is a *revocation token* of 32 bytes (Note: for simplicity, we use interchangeably the subscript GS for HP in terms of revocation.). Then, we consider two related revocation methods proposed in [22]: the first one, we term *GS-I*, incurs a processing cost that is proportional to the size of the RL; the second one, *GS-II*, has a fixed cost independent of the RL size, but it might allow the linking of some Group Signatures [22].

GS-I: The revocation tokens, each E_{GS}=32 bytes, are used directly for the revocation check process. The cost to verify one entry is $C_p \times |RL_{GS}|$, where C_p is the cost of computing one bilinear map. Group signatures of not-revoked nodes cannot be linked under any circumstances, but checking if a singer is revoked requires a traversal of the entire RL_{HP} (in other words, it is linear in the number of revoked vehicles).

GS-II: The basic difference from *GS-I* is the calculation of the Group Signatures, which include some intended recipient, S, a random positive integer r, now chosen by the signer to have a value less than a security parameter k. As it will be explained in further detail below, this construction allows S to pre-compute k revocation values and check revocation status of the signer through a simple look-up; if, however, k were low, the signer might be forced to re-use r values, in which case these group signatures from the same signer could be linked.

Since the safety beacons are broadcasted, we need to adapt the scheme to the VC context: We redefine S to be $S =< G, T >$, where G indicates a geographical area and T a time interval. Essentially, in a given area and time, every recipient

	BP	GS-I	GS-II
RL size	$144R$ KB	$32R$ B	$32R$ B
Revocation check cost	1 μs.	$15R$ ms.	30 ms.
Hash table construction	$0.1R$ s.	-	$1.5R$ s.
Memory requirements	$140R$ KB	-	$38.4R$ KB

TABLE VI: Indicative values for revocation check costs as a function of R, for $C_p = 15$ ms, k=100, τ=60 s.

can perform the fast revocation status check. For practical reasons, G and T can be coarsely defined, so that receiving nodes can easily determine the appropriate values (e.g., with the help of their on-board clock, GPS receiver, or other localization means with the help of terrestrial infrastructure).

Upon reception of a new RL_{GS}, a verifier $V_{\mathcal{R}}$ in S pre-computes and stores the k revocation values for each entry in the RL_{GS}, at a cost of $2C_p$ per entry. The cost to build this data structure is then $2C_p \times R \times k$. Upon receipt of a $\Sigma_{CA,V}(K_V^i)$, the verifier $V_{\mathcal{R}}$ performs a lookup into the table and if no match is not found (i.e. the signer is not revoked) it validates the signature. The cost to verify if the sender is revoked is $2C_p$, plus the lookup cost which is negligible compared to C_p. The memory needed is approximately $|RL_{GS}| \times k \times E_{GS}$ bytes. E_{GS} in this case is the result of one pairing computed from the revocation token, and its size is 384 bytes.

For a given $S =< G, T >$, the value of k should be chosen such that a single sender is not forced to use the same r twice or more. Basically, it should be $k \geq \lceil |T|/\tau \rceil$. However, high k would increase the pre-computation costs, which also depends on how the RL_{GS} changes over time. Investigating trade-offs due to chosen values, e.g., τ, $|T|$, is left as future work. In order to provide a numeric example, we fix k=100, which corresponds to $|T|$=1h 40min, and we summarize the results in Table VI, assuming $C_p = 15$ms, k=100, τ=60s, and the basic operations on the hash table, such as memory copy and data lookup, to be 1 μs.

Clearly, the BP scheme incurs the minimum computational overhead but it has by far the longest RL. Moreover, the GS-I method could be cumbersome to apply, especially for the platform we considered here and for sizeable RLs. Then, the cost of GS-II is independent of R but it remains higher than that of BP. Nonetheless, the advantage of GS-I and GS-II is the much smaller size of RLs, and the lower memory and bandwidth their storage and transmission require.

Finally, recall that for the GS scheme, the revocation status check must be performed for each message; while for the HP scheme, the check is needed only once per previously unseen pseudonym. It is also important to note that the revocation of a node implies its anonymity is lost; then, any entity that has a transcript of its past transmissions in a given area, can use the corresponding revocation token and identify which messages in the transcript were sent by the revoked node.

X. Related work

The use of pseudonyms was first envisioned in [39] and more recent works considered their use in the context of VCs, e.g., [14], [40], [41]. More generally, several recent works are concerned with different aspects of security and privacy of vehicular networks, either outlining challenges [42], [43], describing particular attacks [44], [45] or more general attack overviews [46], [47], proposing mechanisms [48], [41], [49], [1], [50] that combines public and symmetric key cryptography to authenticate messages and is complementary to our work, and schemes for revocation [2], [13], [51].

The idea of pseudonym self-generation for ubiquitous computing is proposed, independently of our work, in [52]. More recently, [53] applied that crypto-system to VANET. These works do not consider all the system-level issues we consider in this work, such as certificate distribution and application robustness. Our findings and mechanisms also apply to their work, complementing and extending it.

An alternate approach to reduce packet overhead and computation efforts is presented in [54], which proposes that a signer attaches its certificate to messages only when it detects a change in its neighborhood, with such changes detected from beacons. In dense topology settings, the results of [54], although obtained in less realistic conditions, are comparable to ours.

A couple of recent works propose to use bilinear pairings to provide privacy in VANET. The approach of [55] is similar to our GS scheme, thus it would be cumbersome if not impossible to apply for safety beaconing. [56] employs a mix of traditional public-key cryptography and bilinear pairings; this bears some resemblance to our HP scheme, but it is mainly limited by its strong reliance on the presence of RSUs; they are not envisioned to be densely present in most, if not all, deployment scenarios.

A few other papers [30], [36]–[38] proposed algorithms to provide transportation safety based on VC and analyzed their effectiveness. Transportation engineers also studied the problem of reducing collision chains in a platoon of cars [34], [35]. But the combined study of transportation safety applications enabled by VC and the effect of security overhead has not been considered.

XI. Conclusion and Future Work

We analyzed the effect of security, in particular pseudonymous authentication that has been broadly accepted, on the VC system effectiveness and notably a safety application with stringent reliability and delay requirements. We considered several dimensions of the system operation; we provided a framework to analyze the performance of secure VC systems, along with schemes that reduce the complexity and the overhead of security; and we identified the interdependencies of various factors and system limitations.

We found that indeed the communication reliability is significantly affected by the security overhead in challenging yet likely to occur in reality situations (e.g. densely packed vehicles in multi-lane highways). Then, we characterized the arrival process for the incoming traffic for the security and networking protocols in questions, and we determined the processing load at each node. We derived an analytical approximation and a rule-of-thumb method to determine if nodes and thus the system can be stable in its operation for

a given security functionality. As a result, the appropriate on-board processing power (and memory resources, even though this is a lesser challenge) can be easily determined and thus provisioned.

Assuming that sufficient on-board processing power and resources are indeed available, we analyzed the effectiveness of the secure VC system in challenging communication environments. Given the unreliable communication, especially among remote but nominally in-range nodes, we found that our schemes reduce security overhead and increase the system effectiveness. In fact, reduction of overhead, which is welcome in all cases, is more effective in highly loaded scenarios, while only limited targeted redundancy (when pseudonyms change) can remedy the communication unreliability. Overall, the tuning of the security and privacy enhancing protocols is very simple yet effective. We considered numerous parameters, including road conditions, drivers' reactions, as well as a simple two-vehicle setting but also a one-hundred-car platoon in a multi-lane high-way, and also the VC equipment penetration rate. This comprehensive evaluation is the first of its kind, and shows that secure VC systems, as currently envisioned in the research community, can be practical, that is, support demanding and critical applications as effectively as unsecured ones.

We strongly believe that systematic evaluation of the overall performance is critical, especially for pervasive computing systems that are tightly coupled to their users. Exactly because security and privacy are paramount for those systems, yet they incur significant overhead, designs should be validated, to show that the secured systems can be effective as envisioned and needed. This is what we do for a system as complex as vehicular communications; this being the first work taking this approach, we aspire to produce and see further results for a technology that can be very widely deployed in the near future.

Additional characteristics of the transportation environment, and completely different scenarios are to be considered as part of future work. For example, urban settings, with traffic lights, change of routes in case of congestion or emergency, as well as alternative safety applications, such as an emergency vehicle propagating a right-of-way message or corner-collision avoidance, are interesting features for our future investigations. The role and the presence of infrastructure could be debatable; or, more complex VC-enabled applications which are currently still under development could be analyzed. Moreover, alternative communication technologies can be part of future work, posing differing constraints and limitations in terms of communication performance (e.g., reliability as a function of the networking environment).

Alternative security and privacy enhancing mechanisms is another future work direction. For example, alternative cryptographic primitives or additional cryptographic protocol functionality are to be investigated. In this paper, we chose to work on the widely accepted solutions, including those that are currently moving on towards standardization. As alternative solutions can emerge, each of them must be evaluated in terms of its practicality, notably to achieve the supported system's (application) objectives. The framework we present here offers a straightforward approach to investigate in detail such new schemes. Then, for any scenario we can identify the processing power needed to enable a given design for revocation, and proceed with the overall system (application) performance evaluation.

APPENDIX

We derive here the approximation for λ_1, the average arrival rate for $SHORT$ messages, i.e. Eq. 2 in Sec. VII. We consider a set of *N* transmitters V_i and one receiver $V_{\mathcal{R}}$, all running the protocol with the same configuration (i.e. all V_i use the same beacon interval γ, the same pseudonym lifetime τ, and the same Certificate Period α, and $\beta = 0$ as a minor simplification due to the low effect of β on overhead for the values recommended by the findings in Sec. VIII). As discussed in Sec. VIII and Sec. VI, each message is received with a different probability depending not only on the overall setup but also the (fast changing) distance between sender and receiver; obtaining these values is far from trivial.

Here, we make a few simplifying assumptions: We consider some slot, t, and assume that all N transmitters send a beacon, $SHORT$ or $LONG$ during that slot. Recall that each $LONG$ entails a calculation equivalent to a $SHORT$ (due to the verification of the ECDSA signature), plus an additional overhead when $V_{\mathcal{R}}$ receives a $LONG$ with a new pseudonym (due to the GS verification). We assume that each beacon is received with probability P, independently from all other $N-1$ beacons. (The probability of reception is for example the average of the probabilities of reception at different distances for the given neighborhood, obtained from Sec. VI).

For some sending node V_i, its message will be verified by $V_{\mathcal{R}}$ with probability $p \times Prob\{V_i$*'s LONG was already received*$\}$. This is determined by how many times the given V_i transmitted a *LONG* message (as we assume that the reception of $LONG$ packets is also with probability P). By the definition of the scheme (HP or BP), during τ seconds, a pseudonym lifetime, V_i transmits $\lfloor \tau\gamma/\alpha \rfloor$ *LONG* packets.

The number of these *LONG* packets from V_i that $V_{\mathcal{R}}$ observed (i.e. could potentially receive, e.g., being in range) depends on various factors beyond this model (e.g., mobility, individual vehicle trajectories, road shape, communication obstructions). Here we make one more final simplifying assumption: Each V_i is on the average "half way through" its current τ, thus, it has on the average transmitted $K = \frac{\lfloor \tau\gamma/\alpha \rfloor}{2}$ *LONG* packets.

Then, the $Prob\{V_i$*'s LONG was already received*$\}$ is essentially the $Prob\{V_i$*'s LONG was received at least in one of K tries*$\}$; this is equal to $1 - Prob\{V_i$*'s LONG was received in none of K tries*$\} = 1 - (1-P)^K$. As all of the N nodes sent out a packet, in each slot, on average $V_{\mathcal{R}}$ will receive

$$\lambda_1 = NP(1-(1-P)^K) \tag{4}$$

to process. This completes the derivation of the approximation of Eq. 2.

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