

# Adaptive Message Authentication for Multi-Hop Networks

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**Abstract**—Recent benchmarks indicate that the use of public key cryptography results in non negligible verification times on platforms with limited processing power. In this paper, we focus on multi-hop Inter-Vehicle Communication and show that the increase in message processing time in vehicular nodes degrades network performance, decreasing the number of messages that reach destinations. We propose Adaptive Message Authentication (AMA), a lightweight filtering scheme that reduces the number of cryptographic operations performed by the nodes. Although based on local observations and without any additional communication channel between the nodes, our scheme achieves global improvement of network performance. We perform extensive simulations and show that our scheme resists DoS attacks and brings significant improvement even against a substantial number of adversaries in the network.

## I. INTRODUCTION

It is envisioned that inter-vehicle communications (IVC) will enable Vehicular Ad hoc Networking (VANET). Short-range wireless IVC will be based on a variant of the currently widely used IEEE 802.11 protocol. The IEEE 1609.x protocol suite, also known as the WAVE technology [1] developed for the U.S. Department of Transportation (DOT), is already at the stage of trial-use standard. Vehicles will communicate with other vehicles within range, but, equally important, they will cooperate in forwarding messages of their neighbors, other vehicles or road-side units (RSUs), across multiple hops.

Vehicular communications (VC) will support various applications, among which transportation safety and transportation efficiency play a prominent role. Congestion notification applications [2], [3], [4], envision vehicles that collect data, create useful information and then send it across multiple hops towards a “targeted” or “destination” geographic area. The receiving vehicles in the destination area will utilize these notifications, possibly to alert their drivers to avoid dangerous areas or optimize their routes.

Security is an important requirement for this manner of forwarding. In recent years the foundation for securing vehicular communications has been laid out in the literature [5], [6], [7] and a substantial effort in academia and industry has been invested in providing adequate solutions; for example, the IEEE 1609.2 trial-use standard [8], the Network On Wheels (NoW) project [9], and the Secure Vehicular Communications

(SeVeCom) project [10]. These prominent efforts are based on well-established cryptographic building blocks, such as public key cryptography, and Certification Authorities (CAs), and they mandate that all VC messages be digitally signed and carry the certificate of the signing node (vehicle or RSU). This way, without any association with the signer, the authenticity of any message can be validated by any receiving node.

Although very convenient for exploitation in vehicular networks, public key cryptography is costly and introduces significant processing overhead. Recent benchmarks, such as those obtained within the framework of the European eCrypt project [11], show that signature verification on a wide range of computing platforms takes a significant amount of time, even for the fast elliptic curve algorithms proposed for use in vehicular networks [8], [9], [10]. Due to the on-board vehicle equipment cost constraints, the currently envisioned automotive communication boxes face the same limitations: cryptographic message processing delays are typically in the order of several milliseconds [12]. More importantly, with tens of nodes (vehicles) usually in proximity, each node has to handle and validate hundreds of messages per second.

We argue that the processing overhead in intermediate nodes can result in decreased network performance, due to the limited processing capabilities of the envisioned vehicular platforms. Our goal is to decrease the number of cryptographic operations performed by the nodes and to avoid a deterioration in performance due to processing power limitations. At the same time, we verify that this reduction of message verifications does not make a vehicular network more vulnerable to outside adversaries, nor to DoS attacks.

In this paper we focus on traditional approaches to identity management and secure inter-vehicle communication in vehicular networks, such as [13]. In terms of Inter-Vehicle Communication and multi-hop forwarding, these proposals recommend two extreme strategies. The first group of proposals requires intermediate nodes to verify that messages had been sent by legitimate senders and to check the integrity of the messages before resending them. We show that this approach to secure multi-hop forwarding tends to be too pessimistic and results in many unnecessary message verifications, degrading the network performance. On the other hand, the second approach, which advocates skipping message verification in intermediate nodes, neglects nodes’ vulnerability to DoS attacks; although it performs well with few adversaries in the network, our simulations show that when no message verifications are performed, the goodput of legitimate nodes significantly drops as the number of adversarial nodes in the network increases.

The solution we propose is an adaptive scheme which inte-

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grates the best features of the two aforementioned approaches. The aim is to make nodes perform only the necessary number of cryptographic operations while skipping the redundant message verifications and improving the overall performance of the network. The scheme takes advantage of the fact that nodes in different parts of a vehicular network face different security conditions at a given point in time. For instance, nodes in less hostile areas can afford to be less cautious (check fewer messages) than others. On the other hand, given the dynamic nature of vehicular networks, the situation may change quickly and dramatically, so nodes should have the ability to adapt to changing circumstances.

Our contribution is twofold:

- We propose AMA (Adaptive Message Authentication), a scheme that probabilistically checks messages in intermediate nodes. Our scheme is reactive in that the checking rate increases to 100% only when forged messages are detected, and only for a limited period before returning to probabilistic checks. AMA is independent of the forwarding algorithm or the wireless standard that is used for communication and it can be easily integrated in the existing frameworks for secure communications in vehicular networks.
- We show through extensive simulations that the scheme guarantees substantial performance gains over the traditional proactive approach. The adaptiveness of the scheme brings increase in performance in cases with few adversaries as well as in the cases when the adversarial nodes represent a significant percentage of the population.

The rest of the paper is organized as follows. In §II we present the example vehicular applications of interest, the motivation and the intuition behind our approach. In §III we describe the system and the adversary model that we are dealing with in this work. In §IV, we define rigorously the core of the problem we are solving. The complete description of AMA is provided in §V, and its evaluation in §VI. We discuss possible extensions of AMA in §VII. We present related work in §VIII, and we conclude in §IX.

## II. MOTIVATION AND INTUITION

In this section, we pinpoint why a group of VANET protocols and applications call for a new practical solution, such as the AMA we contribute here.

Multi-hop vehicular communication is considered in several transportation safety and efficiency applications, in particular *congestion notification* and *environmental hazard notification* applications [2], [3], [4]. These applications exploit the inter-vehicle communication and more specifically *GeoCast* or *Position-based* routing. Their messages contain the destination or target geographic area, within which all receiving vehicles should benefit from the information inside the messages.

The adversaries can try to degrade the performance of such a system by creating forged messages alleging they bear useful information (notifications, warnings, etc.). The danger is twofold: (i) the use of forged messages at destinations and (ii) reduction in goodput (expressed in the number of legitimate messages that reach their destinations) caused by flooding of

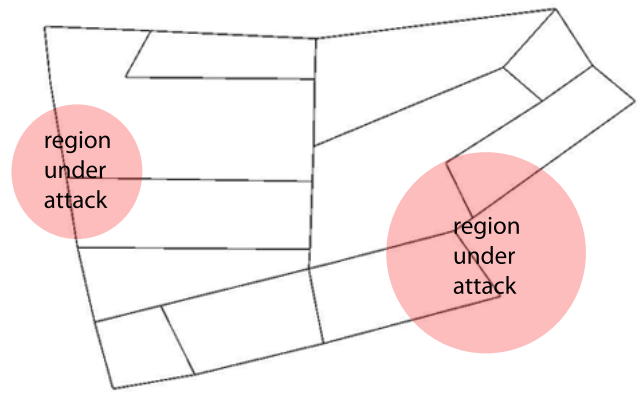


Fig. 1. A few regions in the city are under attack (shaded areas) and nodes in these regions actively defend. Nodes in the rest of the city, where the presence of the adversaries is not felt, can relax their security. We use this road map in all of our simulations.

the network with forged messages. The first risk is not really a concern, as the scheme we propose requires nodes to check each message in the destination region, prior to its use. The impact of the second threat depends critically on the ability of the security solution to prevent the spatial propagation of forged messages. We address this issue by applying an adaptive scheme, which becomes very conservative as soon as a threat is detected. If an adversary tries to inject messages with its current location as destination region (destination zone), it will be detected by all the first hop neighbors, since the scheme we propose checks all the messages received in the destination region. In case an adversary selects a region (other than its current location) as destination, the scheme fights this danger not only locally around the adversary, but all the way to the destination region, and if needed, inside the destination region itself.

When the threat is not present, our scheme relaxes security and avoids putting unnecessary processing load on resource-limited on-board equipment. We show that this does not lead to a reduction in goodput due to a possible rise in number of forged messages in the network. The goodput is actually increased, as processing bottlenecks caused by overpessimistic approach in fighting the security threats are avoided.

The basic idea we exploit is based on the observation that an adversary can in practice have only a limited physical presence [14], [7]; adversaries can select any part of a vehicular network and place it under attack, but they can only be in a limited number of locations at any given time. Fig. 1 illustrates this; it shows a part of a city with the regions in which the adversarial nodes are present (shaded areas).

So, if the security conditions in different parts of the network are completely different, why would the nodes in these areas behave in the same manner? In other words, a node should respond to a threat only when it is affected by an attack and should reduce its defensive activities when the threat is not present, assuming that these activities consume resources and cause the node to underperform. With this approach, as we show with our solution, the performance of a network as a whole increases, as nodes perform only the necessary cryptographic operations but skip the redundant ones.

### III. SYSTEM AND ADVERSARY MODEL

**Vehicular Communications (VCs):** We consider a system with vehicles equipped with a variant of IEEE 802.11, on-board sensors, and a computing platform. The vehicle on-board equipment, which we term a node, allows the exchange of information among vehicles and roadside infrastructure and enables a range of applications, notably including *safety* (e.g., accident alerts) and *traffic efficiency* (e.g., distributed congestion notification) [15], [16]. VC-enabled applications entail two basic types of communication: (i) one-hop high-rate safety messaging (beaconing), with messages bearing information on the location, speed, acceleration and heading of the sender, transmitted at a rate of 3 to 10 beacons per second, and (ii) multi-hop communication between any sender disseminating information to one or more receivers, identified primarily by their location.

Safety beaconing rates are specified by standards and processing of those beacons is obligatory: a node must maintain a fine-grained knowledge of the motion dynamics of other vehicles in its vicinity, for example, to be able to detect a danger from a slowly moving vehicle ahead or one that attempts a left turn. On the other hand, multi-hop communication serves, in general, less time-critical applications, and the amount of traffic depends on the supported application(s), and in principle any node could initiate such a transmission.

We define  $L$  to be the set of legitimate users running applications enabled by multihop communication and  $N_i$  as the number of legitimate messages received by destination  $i$  over the time period of interest. We consider here multihop transmissions originating at each node at a constant rate of  $r_L$  messages per second. Then, in the presence of any communication impairments and networking faults and delays, we define the *goodput*  $\gamma_L$  as:

$$\gamma_L = \frac{1}{|L|} \sum_{i \in L} \frac{N_i}{\text{total time}} \quad (1)$$

Position-based communication protocols appear as a natural choice for multi-hop communication, as nodes are expected to be aware of their own location (through GPS, or other localization techniques with respect to terrestrial infrastructure), and the highly volatile topology would make other mobile ad hoc networking protocols inefficient in this setting. Such algorithms, largely termed geocast protocols, are currently under consideration towards standardization [4]. As the exact implementation of the communication is largely orthogonal to our paper, we consider here two representative position-based algorithms. The first algorithm, Cached Greedy GeoCast (CGGC) [17] belongs to the group of beacon-based unicast routing algorithms. CGGC relies on beacons to discover the position of neighboring nodes (within the nominal communication range), and then forwards messages in the geographic direction of the destination, picking the node whose coordinates are the closest to the destination. If the local optimum is reached, the message is added to the local cache, where it is kept until a suitable next hop is found. The second algorithm we consider is Contention-Based Forwarding (CBF) with the basic suppression scheme based on timers [18]. Unlike CGGC,

CBF is based on broadcast and performs greedy forwarding without the help of beacons and neighbors' tables. We believe that this selection of routing algorithms covers two major groups of geocast routing algorithms proposed for vehicular networks. The first group is composed of routing algorithms that heavily rely on beacons and neighbors' tables in the process of suitable next hop selection. The second group contains CBF algorithms with different suppression schemes that leave the next hop selection process and the forwarding decision to the neighbors in the transmission range.

**Security Assumptions:** As proposed in [9], [8], [10] the node identities are managed by a Certification Authority (CA). Each node in the network is assigned a set of private/public key pairs, with the latter certified by a CA. Each legitimate node registered with the CA can participate in the VC system operation. Basically, nodes use their private keys to digitally sign messages they generate and the public keys of the senders of messages they receive to validate the senders' signatures.

In accordance with the state of the art in secure VC [8], [10], we assume that all messages are signed with an Elliptic Curve Digital Signature Algorithm (EC-DSA), and that for each message the certificate of the sender is attached to enable validation of the message. The validation includes first the validation of the certificate (by validating the CA's signature), and then the validation of the sender's signature.

In the rest of the paper, we refer to a message validation as "message checking." We denote the *processing delay* needed for a message to be checked by  $t_C$ . The value of this delay depends on the processing power of the on-board platform. For platforms similar to those currently considered for the proof-of-concept implementations of VC systems, characteristic delays are provided in [12], [19], while for other efforts PowerPC based platforms are used (e.g., DENSO platform [20]), with representative processing delays available in the eCrypt project benchmarks [11].<sup>1</sup> Lastly, the IEEE 1609.2 efforts currently consider for proof-of-concept purposes hardware accelerated signature verification at several milliseconds. In all existing and upcoming systems, the cryptographic processing delays constitute a bottleneck. For example, even for the most powerful of those platforms [12],  $t_C$  would be 7.2ms; if we consider this value in a rather favorable environment, with 20 neighbors beaconing at the lowest possible rate of 3 beacons/second, by multiplying the three numbers, we obtain as a result that 43.2% of the CPU time would be devoted to message checking. In denser network settings, e.g. four-lane highways, and with the wireless medium impairments taken into consideration, as well as specific optimizations, still the average processing load is at the limit of the processor for safety traffic only.

**Adversary Model:** In this paper our focus is on the *external* adversaries, that is, adversarial nodes that do not have in their possession system credentials (certificates issued by the CA). Each such adversarial node is a computing platform that can fabricate and inject messages, but cannot sign on behalf of a legitimate node. The direct goal of adversaries is to reduce the goodput  $\gamma_L$  of legitimate nodes by injecting the forged

<sup>1</sup>On 533MHz CPU Power PC platform, signature verification for EC-DSA with 192-bit curve (nist-p-192), requires 9 ms on average.

messages and making legitimate nodes waste their processing time on forged messages verification. All adversarial nodes inject forged messages at a rate  $r_A$  messages per second.

**We assume that the adversaries are aware of their number in relation to the number of legitimate nodes in the network and we define  $a$  as the percentage of adversaries in the network. Knowing  $a$ , the adversaries choose their sending rate  $r_A$  in order to minimize  $\gamma_L$ .**

We emphasize that none of the forged messages injected by an adversarial node can be perceived as valid if it is checked by a legitimate node. Nonetheless, the stress imposed by the need to validate those messages is exactly what can lead to DoS. For such an attack, any PDA or laptop can be used, while no tampering with hardware that stores vehicle’s cryptographic keys [10], [7] or no cryptanalytic attack are necessary. By preventing even a small fraction of legitimate traffic from reaching its destination, the adversary can prevent reception of messages in an area within the necessary deadlines: for example, consider road condition information that cannot be validated in the targeted geographical area, resulting in traffic jams. Or, consider increased loads from fabricated traffic that prevent a node from performing safety related operations.

#### IV. PROBLEM DEFINITION

The usage of geocast routing algorithms implies that messages can traverse several intermediate hops before reaching the destination region. A logical question that arises is what strategy an intermediate node should adopt with regard to checking a large group of messages that are only relayed by that node. It is not clear whether a message that requires relaying should be checked by an intermediate node or just resent without any prior verification.

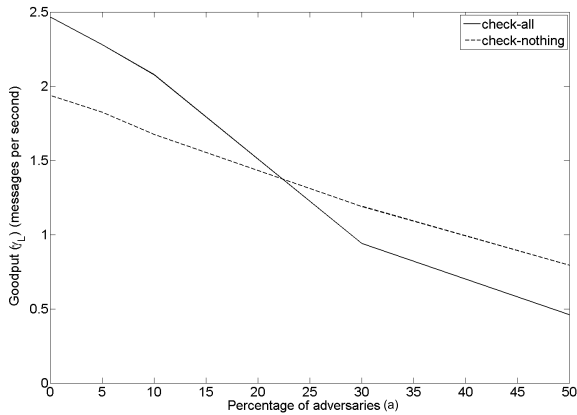


Fig. 2. The performance of “check-all” vs. “check-nothing” algorithm obtained for CBF geocast routing algorithm.

We define “check-all” and “check-nothing” as two extreme approaches that can be applied to relayed messages. “Check-all,” as mentioned in Section I, is the default strategy in the existing proposals and it assumes checking of each relayed message, whereas “check-nothing” assumes that none of the relayed messages are checked. Both approaches perform well under certain circumstances, but underperform in other

cases. Our goal is to propose a scheme that provides good performance for a wide range of values of  $a$  (percentage of adversaries in the network) and  $r_A$  (their sending rate) and to test it with the state of the art in vehicular routing algorithms.

The “check-all” strategy guarantees the fewest forged messages in the network, as it contains them locally and prevents their propagation. Given unlimited processing power in each node (implying a negligible checking time  $t_C$ ), checking each relayed message would be the best strategy. In this case, less time would be spent forwarding the forged messages and the limited wireless capacity would be used only for forwarding the valid messages.

The “check-nothing” strategy promises good results with few adversaries in the network, or with few injected forged messages in the network (Figure 2). In this case, not checking any relayed traffic guarantees that no time is wasted on signature verifications in intermediate nodes and the goodput  $\gamma_L$  of legitimate users is improved. However, an increase in the number of adversaries in the network quickly makes this strategy inferior to “check-all”.

So, “check-all” is not the best approach for networks with few adversaries and “check-nothing” gets worse as the number of adversaries increases. We want a scheme that performs well in both cases. It should contain the forged messages locally (like “check-all”) in the presence of adversaries and behave similarly to “check-nothing” with no adversaries around.

#### V. AMA - ADAPTIVE MESSAGE AUTHENTICATION

The reasoning behind our scheme is driven by the observation that the adversaries are limited in scope and that they cannot keep the whole network under attack at all times. Consequently, we designed a scheme that is shown in Figure 3. We call it AMA (Adaptive Message Authentication).

AMA has two modes of operation. We call them “check-all” and “relaxed”. The “relaxed” mode allows nodes to pay less attention to defensive measures. All the legitimate nodes are initially in the “relaxed” mode. It is this mode that is expected to bring performance gain to the scheme, as only a fraction of received messages are checked by a node in the “relaxed mode”. Nodes distinguish between the messages that have the current location of the node as the destination zone and those that only have to be relayed to others. Each message in the first group is checked with probability 1 and each message in the second group with probability  $p$ . If they happen to check a forged message, the forgery is always detected and it forces the node to switch its mode of operation to “check-all”.

“Check-all” mode is conservative and it mandates checking each received message. A legitimate node is expected to be in this mode when there are adversarial nodes nearby. A node stays in “check-all” mode until it receives  $c$  consecutive legitimate messages. Then, it switches back to “relaxed” mode.

The rationale is that if a node senses that the current “temperature” of the neighborhood is low (no adversaries in the neighborhood), a node can relay most of the messages without prior authentication and integrity check and keep checking only a small fraction of these messages in order to ensure a timely detection of security threats. While the selected

messages are being checked, the other messages that need to be relayed do not have to wait before being forwarded.

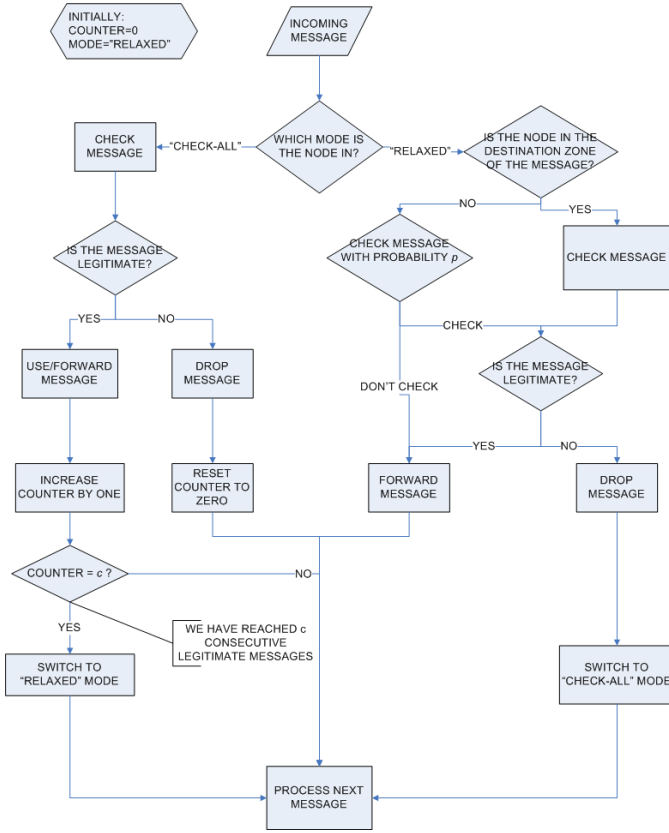


Fig. 3. AMA - the scheme for adaptive authentication and integrity check of messages exchanged between vehicles. Briefly, an AMA node can be in one of two modes: “check-all” and “relaxed.” A node starts in “relaxed” mode. In this mode, a node checks with probability 1 the messages destined for itself, but only with probability  $p$  the messages destined for other nodes. If it detects a forgery, the node switches to the “check-all” mode. In the “check-all” mode, a node checks all messages with probability 1, and switches to “relaxed” mode only if  $c$  consecutive legitimate messages are received.

It is possible, of course, to use a different function for the checking rate increase, not just a step function. We show that even this simple scheme guarantees significant performance gains, for an appropriate choice of the parameters  $p$  and  $c$ , under very realistic assumptions (the scheme and both parameters  $p$  and  $c$  are known to the adversary).

## VI. EVALUATION

### A. Simulation Setup

The goal of the experimental validation is to compare the goodput  $\gamma_L$  (defined in Section III) achieved when AMA, “check-all,” and “check-nothing” are used. The three strategies are tested on top of two state of the art routing algorithms for vehicular networks. These are Cached Greedy GeoCast (CGGC) [17] and Contention Based Forwarding (CBF) with the basic suppression scheme based on timers [18].

For generating mobility traces, based on network topologies obtained from real maps, we use the SUMO traffic simulator (v 0.9.8) [21] with the TraNS extension [22], [23]. Vehicular mobility traces, generated for a specific road topology, are then passed to the SWANS network simulator [24].

The area that we use for our simulations is about 6 sq. km in size and it is shown in Fig. 1. It is populated with 600 vehicles that follow routes obtained from the SUMO traffic simulator with speeds that are within the legal speed limits for the observed road group. The full TCP/IP stack is implemented in each node with the exception of the transport layer. At the physical layer we use the two-ray pathloss model, which incorporates ground reflection. At the link layer, 802.11b is used and the range is limited to 200m. The SWANS implementation of 802.11b includes the complete DCF function, with retransmission, NAV and backoff functionality.

For the “check-all” and “check-nothing” approaches we run 20 simulations for every combination of percentage of adversaries  $a \in \{0, 5, 10, 30, 50\}$  and adversaries’ sending rates  $r_A \in \{0, 1, 2, 5, 10\}$  messages per second. For AMA we run 20 simulations for every combination of percentage of adversaries  $a\%$ , adversaries’ sending rates  $r_A$ , and AMA parameters  $p \in \{0.05, 0.1, 0.2, 0.3, 0.5\}$  and  $c \in \{20, 40, 60, 80, 100\}$ . For each run, we randomly pick  $a\%$  adversaries out of the total set of nodes in the network. For each generated message, a destination region is selected at random. The legitimate node sending rate  $r_L$  is 1 message per second. The size of each geocast message is 300 bytes. The checking time  $t_c$  is 10ms. Each simulation lasts for 500 seconds of simulation time.

Verification of beacons is extremely important from the security point of view, so as explained in Section III we assume that nodes check all received beacons in the simulated beaconing based routing algorithm (CGGC). Beacons make a large percentage of total traffic in all the beaconing-based routing algorithms and for this reason we wanted to be as realistic as possible when simulating the load that beaconing traffic puts on the processor. The beaconing rate in the CGGC routing protocol that we use in our simulations is 1 beacon/300ms, i.e., the value that is likely to become part of the standard.

### B. AMA parameter selection

Having calculated, through the simulations, the goodput  $\gamma_L$  achieved under AMA for all combinations of the parameters  $(p, c, a, r_A)$ , we now show how to select the parameters  $p$  and  $c$  to maximize it. This selection would be done by the network administrator before deploying the scheme in the network. When doing this selection, we have to keep in mind two things:

- The percentage  $a$  of adversaries is fixed, but may or may not be known to the administrator. Below, we distinguish two cases according to whether it is known or not.
- The adversaries will learn the selected values of  $p$  and  $c$ , and choose their sending rate  $r_A$  to minimize the goodput.

In the first case, which we call the *pessimistic* case, we do not know  $a$ . So, we will select the  $p$  and  $c$  that maximize the resulting  $\gamma_L$  against a worst case combination of  $a$  and  $r_A$ .

$$(p^*, c^*) = \operatorname{argmax}_{(p,c)} \min_{(a,r_A)} \gamma_L(p, c, a, r_A) \quad (2)$$

To visualize this selection, consider the following table, where each entry is equal to the goodput achieved with the corresponding row-column combination of parameters:

	$(a^1, r_A^1)$	...	$(a^1, r_A^k)$	$(a^2, r_A^1)$	...
$(p^1, c^1)$	$\gamma_L^{1111}$	...	$\gamma_L^{111k}$	$\gamma_L^{1121}$	...
$(p^1, c^2)$	$\gamma_L^{1211}$	...	$\gamma_L^{121k}$	$\gamma_L^{1221}$	...
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$
$(p^1, c^m)$	$\gamma_L^{1m11}$	...	$\gamma_L^{1m1k}$	$\gamma_L^{1m21}$	...
$(p^2, c^1)$	$\gamma_L^{2111}$	...	$\gamma_L^{211k}$	$\gamma_L^{2121}$	...
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$

First, Eq. (2) selects the minimum element in each row. The minimum element of a row is the goodput value that will be achieved if we select the  $(p, c)$  pair of that row, and the adversaries' percentage happens to be the one in the minimizing column. If the adversaries' percentage is the right one (worst case scenario for the legitimate users), they can choose their sending rate to achieve the worst case goodput.

Then, among the minimum elements found, Eq. (2) selects the largest one by selecting the appropriate  $(p, c)$  pair. This way, we can guarantee the adversaries would not achieve a lower goodput, even if they could change their percentage.

In the second case, which we call the *optimistic* case, we know  $a$  but not  $r_A$ . So, for the given value of  $a$ , we choose  $p$  and  $c$  that maximize  $\gamma_L$  against the worst case reply  $r_A$ .

$$(p^*, c^*)(a) = \operatorname{argmax}_{(p,c)} \min_{r_A} \gamma_L(p, c, a, r_A) \quad (3)$$

Referring to the previous explanatory table, Eq. (3) now does the same minimization-maximization as Eq. (2), but operates on the columns corresponding to the known value of  $a$ . In either case, the adversaries choose their sending rate  $r_A$  to minimize  $\gamma_L$ , given the legitimate users' choice of  $p^*$  and  $c^*$ :

$$r_A^*(a) = \operatorname{argmin}_{r_A} \gamma_L(p^*, c^*, a, r_A) \quad (4)$$

$$r_A^*(a) = \operatorname{argmin}_{r_A} \gamma_L(p^*(a), c^*(a), a, r_A) \quad (5)$$

Note that the adversaries do not optimize over the percentage  $a$ , as they cannot change it.

### C. Performance Evaluation

AMA outperforms "check-all" and "check-nothing" strategies for all the considered values of  $a$ , regardless of the routing algorithm (CBF in Figure 4, CGGC in Figure 5). The curves in the figures are the mean value of 20 simulations and the error bars extend a standard deviation above and below the mean values. Note that the knowledge of  $a$  (which is not easy for the administrator to obtain) guarantees only a slight performance improvement (the pessimistic scheme performs almost as good as the optimistic).

As we can see from the figures, in the pessimistic case, which assumes no knowledge about the number of adversaries or their sending rate, the goodput of legitimate nodes  $\gamma_L$  improves up to 30% for CBF and up to 33% for CGGC.

In the case of CBF, the performance gain is due to the reduction in number of messages checked in the intermediate nodes. Our simulation data shows that the number of checked geocast messages drops up to 46% percent in this case.

Apart from the drop in the number of cryptographic operations, the performance of CGGC routing algorithm is affected by the beaconing processing load. Geocast messages now share the CPU time with beacons. Checking or not checking

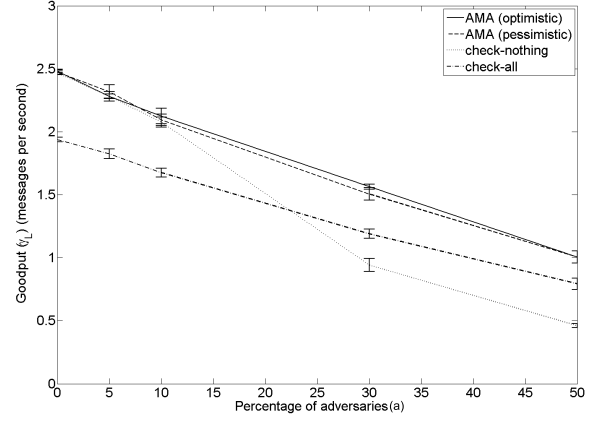


Fig. 4. Goodput  $\gamma_L$  obtained under (pessimistic and optimistic) AMA, "check-all", and "check-nothing" for the CBF routing algorithm.

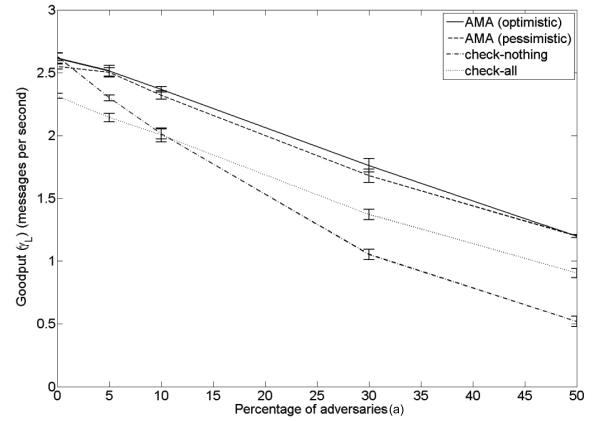


Fig. 5. Goodput  $\gamma_L$  obtained under (pessimistic and optimistic) AMA, "check-all", and "check-nothing" for the CGGC routing algorithm.

a geocast message or a group of messages can make the difference between an immediate check of arriving geocast message and its prolonged stay in an intermediate node due to the CPU busy period introduced by beacons. The same applies to forged messages, as their increased number in the incoming queue can make valid messages wait for a period of time before being checked and relayed. This is the main reason why the performance of "check-nothing" strategy drops with the increase in the number of adversaries in the network.

The introduction of other CPU tasks (not related to forwarding) would make this effect even more visible. In case the security unit is not a stand-alone unit and has to share the CPU time with other tasks, the moment when an incoming message gets its share of CPU becomes extremely important. A single forged message or an unnecessary check of a legitimate message can make the arriving geocast message wait for additional few hundred milliseconds due to the CPU multitasking.

In the pessimistic case, the optimal values of  $p$  and  $c$  obtained as explained in VI-B are  $p = 0.2$  and  $c = 40$  for both CGGC and CBF. In the optimistic case, the obtained values for  $p$  and  $c$ , for both considered algorithms, are shown in Table I.

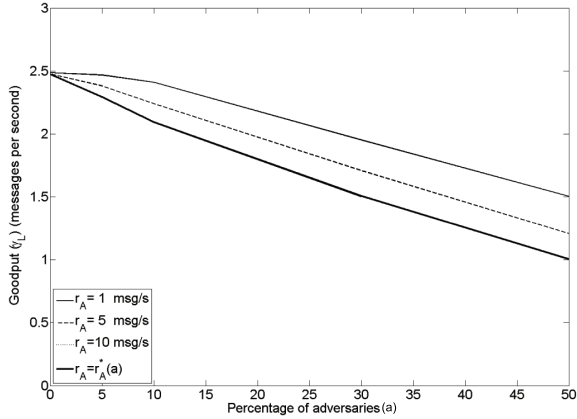


Fig. 6. Goodput  $\gamma_L$  obtained for various adversarial sending rates  $r_A$  under pessimistic AMA for the CBF routing algorithm. The thick line corresponds to the optimal sending rate  $r_A^*$ .

Percentage of adversaries	CBF		CGGC	
	$p$	$c$	$p$	$c$
$a = 0$	0.05	60	0.2	80
$a = 5$	0.05	20	0.05	80
$a = 10$	0.2	100	0.3	80
$a = 30$	0.3	100	0.2	40
$a = 50$	0.2	40	0.2	40

TABLE I  
THE OPTIMAL PARAMETERS  $p$  AND  $c$  FOR *optimistic* AMA.

If the adversaries have less knowledge than what we have assumed (i.e., if they do not know the  $p^*$  and  $c^*$ ), they may choose a sending rate other than the computed optimal  $r_A^*$ . In Figures 6 (for CBF) and 7 (for CGGC) we plot the resulting  $\gamma_L$ - $a$  curves for all sending rates  $r_A$  for the pessimistic choice of  $p^*$  and  $c^*$ . We see that a suboptimal selection of the sending rate by the adversaries results in improved performance for our scheme. The thick line in the figures corresponds to the optimal (for the adversaries) sending rate  $r_A^*$  and represents the worst case scenario (i.e. the lower bound for the goodput).

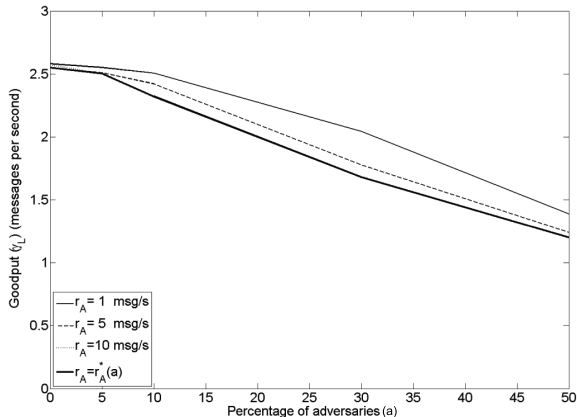


Fig. 7. Goodput  $\gamma_L$  obtained for various adversarial sending rates  $r_A$  under pessimistic AMA for the CGGC routing algorithm. The thick line corresponds to the optimal sending rate  $r_A^*$ .

## VII. DISCUSSION

We discuss two extensions for AMA that could improve performance at the expense of complexity. First, the transition between two modes of AMA can be smoother than jumping from a fixed checking probability  $p$  to 1. That is,  $p$  can increase when a forged message is detected, and decrease when a legitimate message is checked. Second, depending on the application's security requirements, not all messages need to be checked by their destinations. If AMA is also applied to the messages received in the destination zone, the network performance could improve.

## VIII. RELATED WORK

Three major efforts to design security and privacy enhancing solutions for VC have been undertaken in industry and academia, with the endorsement of authorities: the NoW project [9], the IEEE 1609.2 working group [8], and the SeVeCom project [10]. The basic ideas that transcend these efforts are: (i) their building on top of the currently accepted vehicular communication protocol stack that includes safety beaconing, (ii) their reliance on a *Certification Authority (CA)* and public key cryptography to protect V2V and V2I messages, with consensus on the use of Elliptic Curve DSA [25] (iii) their objective to satisfy requirements such as message authentication, integrity, and non-repudiation (albeit in a "lighter" manner for the IEEE effort) and (iv) their intention to protect private user information. We note that our scheme is oblivious to the exact use of certificates and public keys. As a result, AMA can remain fully operational and effective even if privacy enhancing algorithms with multiple certified public keys (pseudonyms) are implemented. Another recent, currently on-going effort in securing VC, is the Car-2-Car Communication Consortium (C2C-CC) Security Working Group. The baseline concepts and activities of the C2C-CC SEC WG can be found in the C2C-CC Manifesto [4].

Prior to these efforts, a number of works investigated different aspects of security and privacy of vehicular networks. They outlined challenges [5], [6], they described attacks [26], [27], [28], [7], and offered solutions [14], [29], [30], [12]. The last two works consider cryptographic mechanisms other than public key cryptography; in the former one, [30], symmetric key cryptography complements the public key operations to reduce overhead. The latter [12] uses group signature to complement public key cryptography. Investigating those variants, with the somewhat different processing loads, in the context of AMA would be an interesting point for future work. The reduction of overhead for transportation safety applications has been investigated in [12], with simple, context-agnostic overhead reduction schemes, and in [31], [32] that propose context-specific strategies for overhead reduction. The investigation of the vehicular communications security overhead and its effect on system/application performance is extended in [33], which considers both safety and efficiency applications and additional security mechanisms. These works are complementary to AMA and their joint investigation with AMA is another interesting point for future work.

Good surveys of geographic routing protocols can be found in [34], [35]. Regarding security aspects of geographical routing, Leinmüller *et al.* [36] analyze the effects of false position information on geographical routing and plausibility checks to reduce the impact of wrong position advertisements. More recently, a comprehensive design and performance evaluation for secure GeoCast, including experimental implementation, is provided in [19].

Finally, extensive work on security overhead reduction and optimistic validation can be found in closely related areas. A solution for overhead reduction for broadcast authentication in large sensor networks is proposed in [37]. In [38] security-throughput trade-off in wireless networks with adversaries was considered. Design tradeoffs between security and performance in wireless group communicating systems were analyzed in [39].

## IX. CONCLUSION

Strict security requirements for vehicular communications led to several proposals that consider authentication and integrity check of each relayed message as necessary conditions for secure multihop inter-vehicle communication. This default approach brings considerable security overhead. Complex cryptographic operations, such as signature verification, introduce non-negligible processing delays. We show that the measured processing times on low-end platforms can result in degradation of network performance. On the other hand, ignoring security can lead to DoS attacks and even more severe decrease in network performance.

In this paper, we demonstrate that a simple, yet adaptive, filtering scheme that allows nodes to judiciously decide when to check the received message that requires further relaying, and when to simply forward it without any delay, brings significant performance gain. The scheme, which we term AMA, treats multihop messages in reactive rather than proactive way and requires checking of relayed messages only in the presence of a threat. Our simulations with the state of the art in vehicular routing algorithms show that, as a result of security overhead reduction, the goodput of legitimate nodes increases up to 33%. We believe that, because of the significant gains possible, this approach is worthy of further investigation.

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