

# Secure Neighbor Position Discovery in VANETs

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**Abstract**—Many significant functionalities of vehicular ad hoc networks (VANETs) require that nodes have knowledge of the positions of other vehicles, and notably of those within communication range. However, adversarial nodes could provide false position information or disrupt the acquisition of such information. Thus, in VANETs, the discovery of neighbor positions should be performed in a secure manner. In spite of a multitude of security protocols in the literature, there is no secure discovery protocol for neighbors positions. We address this problem in our paper: we design a distributed protocol that relies solely on information exchange among one-hop neighbors, we analyze its security properties in presence of one or multiple (independent or colluding) adversaries, and we evaluate its performance in a VANET environment using realistic mobility traces. We show that our protocol can be highly effective in detecting falsified position information, while maintaining a low rate of false positive detections.

**Index Terms:** Vehicular ad hoc networks, neighbor position discovery, security in vehicular networks.

## I. INTRODUCTION

VANETs are envisioned to enable a range of applications, spanning from enhanced transportation safety and efficiency to mobile infotainment, while security and privacy enhancing technologies have been broadly accepted as prerequisites for the deployment of such systems. A number of on-going efforts have yielded a multitude of proposed schemes, including coordinated efforts such as those of the IEEE 1609 working group, the Car-to-Car Communication Consortium, the CAMP/VSC-2 project, and the SeVeCom project, which produced a full-fledged security architecture for vehicle-to-vehicle and vehicle-to-infrastructure communications.

Many aspects of security and privacy have already been addressed (e.g., in [1]–[3]) but no solution has been yet proposed for the secure discovery of the position of other nodes, in particular those within direct communication range. This is an important problem because vehicular nodes are location-aware, and location information is embedded in many VANET messages to support various applications; transportation safety and geographical forwarding (or GeoCast) are characteristic examples, while traffic monitoring and management, as well as access to location-based services are also closely related. In all such cases, nodes are required to reliably identify neighboring nodes and determine their positions. Nonetheless, adversarial or faulty nodes can falsify or alter such information, resulting in the disruption of system operations.

Secure discovery of the positions of neighbors cannot be achieved by any of the solutions in the literature. Secure localization techniques, which allow a reliable determination of own location, are a building block but not the solution to the problem at hand. Simply put, the reason is that an adversary could advertise a false position in any discovery protocol. The presence of trusted nodes would make the problem easier

to solve: road-side infrastructure or trustworthy specialized vehicles could help to securely localize other vehicles. In such case, techniques in the literature, designed for mobile ad-hoc networks, could be employed. However, this approach has severe limitations when applied to vehicular environments: the presence of road-side infrastructure is envisioned to be rather sparse and the presence of trustworthy nodes cannot be guaranteed at all times, whereas position discovery is needed at any time and location among any two or more vehicles.

To address this problem, we propose our Secure Neighbor Position Discovery (SNPD) protocol, which enables any node (i) to discover the position of its neighbors on-demand and in real-time; and (ii) to detect and discard faulty positions and, thus, ignore their originators. SNPD therefore allows any vehicular node to autonomously obtain a set of verified neighbor positions, leveraging the contributions of its peers to weed out wrong-doers, without any prior assumption about their trustworthiness.

In the rest of the paper, we first discuss related work and introduce the system and adversary model we adopt, then we describe our SNPD protocol in detail. A security analysis of SNPD follows, along with a performance evaluation based on realistic vehicular mobility traces.

## II. RELATED WORK

Secure neighbor position discovery for vehicular environments is, to the best of our knowledge, an open problem. Nevertheless, it relates to a number of other problems that have instead been addressed before, as discussed next. We emphasize that our SNPD protocol is compatible with state-of-the-art security architectures for vehicular networks, including those proposed by IEEE 1609.2 [4] and SeVeCom [5].

**Securing own location and time information** is orthogonal to our problem, as adversaries can acquire their own locations in a reliable manner, but then advertise false positions to their neighbors. Own positioning and time synchronization is thus a building block for SNPD, as it is for secure vehicular networking. In vehicular environments, self-localization is mainly achieved through Global Navigation Satellite Systems, e.g., GPS, whose security can be provided by cryptographic and non-cryptographic defense mechanisms [6]; alternatively, other terrestrial special-purpose infrastructure (beacons) could be used [7], along with techniques to deal with non-honest beacons [8]. In the rest of this paper, we assume that devices can determine securely their own position and time reference.

**Secure neighbor discovery (SND)**, that is, the discovery of directly reachable nodes (communicating neighbors) or nodes within a distance (physical neighbors) [9], is only a step towards the solution we are after. To put it simply, an adversarial node could be securely discovered as neighbor and

be indeed a neighbor (within some SND range), but it could still cheat about its position within the same range. SND is a subset of the SNPD problem, since it lets a node assess whether another node is an actual neighbor but it does not verify the location it claims to be at. Nonetheless, properties of SND protocols with proven secure solutions [10], [11], are useful in our context: as an example, signal Time of Flight-based and other distance measurements between two nodes can prevent relay attacks (i.e., malicious nodes relaying, stealthily and verbatim, messages of other correct nodes).

**Neighbor position verification** was investigated in the context of ad-hoc networks, with solutions relying on dedicated mobile or hidden base stations [12], or on the availability of a number of trustworthy devices [13]. Our SNPD protocol, instead, is a fully distributed solution that does not require the presence of any particular infrastructure or a-priori trusted neighbors. Also, unlike previous works, our solution targets highly mobile environments and it only assumes RF communication; indeed, non-RF communication, e.g., infra-red or ultra-sound, is unfeasible in VANETs, where non-line-of-sight conditions are frequent and car-to-car distances often are in the order of tens or hundreds of meters.

### III. SYSTEM AND ADVERSARY MODEL

We consider a vehicular network whose nodes communicate over a high-bit-rate data link through an RF interface. We assume that each node knows its own location with some maximum error  $\epsilon_p$ , and that it shares a common time reference with the other nodes in the network: both requirements can be met by equipping vehicles with GPS receivers, already a major trend in today's car manufacturing<sup>1</sup>. Also, nodes can perform Time of Flight (ToF)-based RF ranging using one message transmission, with a maximum error equal to  $\epsilon_r$ : as discussed in [13], [14], this is a reasonable assumption, although it requires modifications to the current off-the-shelf radio interfaces;  $\epsilon_p$  and  $\epsilon_r$  are assumed to be equal for all nodes.

Each node has a unique identity, and carries cryptographic keys that allow it to authenticate messages from other nodes in the network. Although there are various ways to enable authentication, here we only require that message authentication is done locally and we assume that each node  $X$  holds its own pair of private and public keys,  $k_X$  and  $K_X$ , respectively, as well as a set of one-time use keys  $\{k'_X, K'_X\}$ .  $X$  can encrypt and decrypt data with its key(s) and the public keys of other nodes; also, it can produce digital signatures with its private key. We assume that the binding between  $X$  and  $K_X$  can be validated by any node, as in state-of-the-art vehicular communication architectures.

Nodes either comply with the SNPD protocol (*correct*) or they deviate from it (*faulty* or *adversarial*). Adversarial nodes can advertise arbitrarily erroneous positions in messages they inject, to mislead other nodes about their position.

<sup>1</sup>With the help of GPS, user synchronization, fine time granularity and a relatively precise location information is available. Currently, small-footprint and low-cost GPS receivers are commercially available, which achieve low synchronization error and low localization error.

Adversaries are *external* or *internal*, depending on whether they lack or possess the cryptographic keys and credentials of system nodes, respectively. External adversaries can only relay or replay messages without changes, or jam the communication. Internal adversaries are more powerful in that they can fully participate in the protocol execution, forging arbitrary messages with faked own positions. Recall though that each adversary can inject messages only according to the cryptographic keys it possesses; it cannot forge messages on behalf of other nodes whose keys it does not have. Another classification of adversaries that is of interest to us is between *independent* and *colluding* adversaries: the former act without knowledge of other adversaries in the neighborhood, while the latter, by far the most dangerous, coordinate their actions by exchanging information.

In this work, we focus primarily on internal adversaries with standard equipment (e.g., omnidirectional antennas, standard-compliant wireless cards, etc.). We distinguish them into (i) *knowledgeable*, i.e., adversaries that at any point in time know the exact positions of all their communication neighbors, and (ii) *unknowledgeable*, otherwise. In Section V, we will outline the threats which can be posed by both independent and colluding adversaries, and discuss possible additional threats carried out by adversaries using non-standard equipment (e.g., directional antennas).

### IV. SECURE NEIGHBOR POSITION DISCOVERY PROTOCOL

The SNPD protocol we propose allows any node in the network to discover and verify the position of its communication neighbors participating in the protocol message exchange. SNPD can be initiated in a reactive manner by any node, which we refer to as the *verifier*. Our solution is based on a *best-effort, cooperative approach* that leverages information collected by neighboring nodes thanks to the broadcast nature of the wireless medium. With such information, the verifier can compute, via ToF-based ranging, distances between pairs of neighbors, and then perform a sequence of tests that allow it to classify its communication neighbors as:

- *Verified*, i.e., nodes the verifier deems to be at the claimed position;
- *Faulty*, i.e., nodes the verifier deems to have announced an incorrect position;
- *Unverifiable*, i.e., nodes the verifier cannot prove to be either correct or faulty; due to insufficient information on these nodes or inconclusive test outcome.

The objective of our SNPD protocol is to be robust to adversarial nodes, i.e., to correctly identify and reject false positions and ignore their originators. In other words, it is necessary to minimize false negative and false positive outcomes, i.e., adversaries with positions deemed verified and correct nodes with positions deemed faulty, as well as the number of unverifiable nodes.

We stress that the SNPD protocol only verifies the position of those neighbors with which the message exchange takes place successfully. It therefore disregards nodes for which the protocol exchange prematurely ends, e.g., due to message loss or communication neighbors that refuse to take part in the

protocol. SNPD assumes that the nodes position does not vary significantly during one protocol execution, which is realistic if we consider that a complete message exchange takes no more than a few hundreds of milliseconds. Also, SNPD does not aim at building a consistent map of verified nodes, as every verifier autonomously tags its neighbors as verified, faulty or unverifiable.

Next, we detail the message exchange between the verifier and its communication neighbors, followed by a description of the security tests run by the verifier. Table I summarizes the notations used throughout the protocol description.

### A. Message exchange

We denote by  $t_X$  the time at which a node  $X$  starts a broadcast transmission and by  $t_{XY}$  the time at which a node  $Y$  starts receiving that same transmission;  $p_X$  is the current position of  $X$ , and  $\mathbb{N}_X$  is the current set of its communication neighbors. Consider a verifier  $S$  that initiates the SNPD protocol. The message exchange procedure is outlined in Algorithm 1 for  $S$ , and in Algorithm 2 for any of  $S$ 's communication neighbors.

The verifier starts the protocol by broadcasting a POLL whose transmission time  $t_S$  is stored locally (Alg. 1, lines 2-3). Such message is anonymous, since (i) it does not contain the verifier's identity, (ii) it is transmitted employing a fresh MAC address, and (iii) it contains a public key  $K'_S$  from a one-time use private/public key pair  $k'_S, K'_S$ , taken from a pool of anonymous keys which do not allow neighbors to map them onto a specific node. Including a one-time key in the the POLL also ensures that the message is fresh (i.e., the key acts as a nonce).

A communication neighbor  $X \in \mathbb{N}_S$  that receives the POLL stores its reception time  $t_{SX}$ , and extracts a random wait interval  $T_X \in [0, T_{max}]$  (Alg. 2, lines 2-5). After  $T_X$  has elapsed,  $X$  broadcasts a REPLY message using a fresh MAC address, and records the corresponding transmission time  $t_X$  (Alg. 2, lines 6-10). The REPLY contains encrypted information for  $S$ , namely the signed neighbor identity,  $Sig_X$ , and the POLL reception time: we refer to these data as  $X$ 's *commitment*,  $c_X$ . The hash  $h_{K'_S}$ , derived from the verifier's public key,  $K'_S$ , is also included to bind POLL and REPLY belonging to the same message exchange.

Upon reception of a REPLY message from a communication neighbor  $Y$ , the verifier  $S$  stores the reception time  $t_{YS}$  and the commitment  $c_Y$  (Alg. 1, lines 4-6). A different communication neighbor of  $S$ , e.g.,  $X$ , receives the REPLY message broadcast by  $Y$ , if  $Y$  is a communication neighbor of both  $S$  and  $X$ , i.e.,  $Y \in \mathbb{N}_S \cap \mathbb{N}_X$ . In such case,  $X$  too stores the reception time  $t_{YX}$  and the commitment  $c_Y$  (Alg. 2, lines 11-13). Note that also REPLY messages are anonymous, hence a node records all commitments it receives without knowing their origin.

After a time  $T_{max} + \Delta + T_{jitter}$ ,  $S$  broadcasts a REVEAL message;  $\Delta$  accounts for the propagation and contention lag of REPLY messages scheduled at time  $T_{max}$ , and  $T_{jitter}$  is a random time added to thwart jamming efforts on this message. Through the REVEAL, the verifier  $S$  (i) unveils its identity by including its signature and its public key to decrypt it, and

(ii) proves to be the author of the original POLL. The latter is achieved by attaching the encrypted hash  $E_{k'_S}\{h_{K'_S}\}$  (Alg. 1, lines 7-9).

Once the identity of the verifier is known, each neighbor  $X$ , which received  $S$ 's original POLL, unicasts to  $S$  an encrypted and signed REPORT message containing its own position, the transmission time of its REPLY, and the list of pairs of reception times and commitments referring to the REPLY broadcasts it received (Alg. 2, lines 14-17). Commitments are included 'as they are', since only  $S$  can decrypt them and match the identity of the nodes that created the commitments with the reported reception times.

### B. Position verification

Once the message exchange is concluded,  $S$  decrypts the received data and acquires the position of all neighbors that participated in the protocol, i.e.,  $\{p_X, \forall X \in \mathbb{N}_S\}$ .  $S$  also knows the transmission time of its POLL and learns the transmission time of all subsequent REPLY messages, as well as the corresponding reception times recorded by the recipients of such broadcasts. Applying a ToF-based technique,  $S$  can thus compute its distance from each communication neighbor, as well as the distances between pairs of communication neighbors that happen to share a link. In particular, denoting by  $c$  the speed of light, we define  $d_{XY} = (t_{XY} - t_X) \cdot c$ , i.e., the distance that  $S$  computes from the timing information it collected about the broadcast message sent by  $X$ . Similarly, we define  $d_{YX} = (t_{YX} - t_Y) \cdot c$ , i.e., the distance that  $S$  computes using the information related to the broadcast by  $Y$ . Exploiting its knowledge, the verifier can run verification tests to fill the set  $\mathbb{F}_S$  of faulty communication neighbors, the set  $\mathbb{V}_S$  of verified nodes, and the unverifiable set  $\mathbb{U}_S$ .

The first verification is carried through the **Direct Symmetry (DS)** test, detailed in Algorithm 3, where  $|x|$  denotes the modulus of  $x$  and  $\|p_X - p_Y\|$  is the Euclidean distance between locations  $p_X$  and  $p_Y$ . For direct links between the verifier and each of its communication neighbors,  $S$  checks whether reciprocal ToF-derived distances are consistent (i) with each other, (ii) with the position advertised by the neighbor, and (iii) with a proximity range  $R$ . The proximity range  $R$  upper bounds the distance at which two nodes can communicate, or, in other words, corresponds to the maximum nominal transmission range.

The first check is performed by comparing the distances  $d_{SX}$  and  $d_{XS}$  obtained from ranging, which shall not differ by more than twice the ranging error (Alg. 3, line 4). The second check verifies that the position advertised by the neighbor is consistent with such distances, within an error margin equal to  $2\epsilon_p + \epsilon_r$  (Alg. 3, line 5). This check is trivial but fundamental, since it correlates positions to verified distances: without it, an attacker could fool the verifier by simply advertising an arbitrary position along with correct broadcast transmission and reception timings. Finally,  $S$  verifies that  $d_{SX}$  is not larger than  $R$  (Alg. 3, line 6), and declares a neighbor as faulty if a mismatch surfaced in any of these checks<sup>2</sup>.

<sup>2</sup> The latter two checks are performed on both  $d_{SX}$  and  $d_{XS}$ , however in Algorithm 3 they are done on  $d_{SX}$  only, for clarity of presentation.



The **DS** test implies *direct* verifications that compare trusted information collected by the verifier against data advertised by each neighbor. The content of the messages received by  $S$ , however, allows also *cross*-verifications, i.e., checks on the information mutually gathered by each pair of communicating neighbors. Such checks are done in the **Cross-Symmetry (CS)** test, in Algorithm 4.

The **CS** test ignores nodes already declared as faulty by the **DS** test (Alg. 4, line 6) and only considers nodes that proved to be communication neighbors between each other, i.e., for which ToF-derived mutual distances are available (Alg. 4, line 7). Then, it verifies the symmetry of such distances (Alg. 4, line 9), their consistency with the positions declared by the nodes (Alg. 4, line 10), and their feasibility with respect to the proximity range (Alg. 4, line 11). For each communication neighbor  $X$ , a link counter  $l_X$  and a mismatch counter  $m_X$  are maintained. The former is incremented at every new cross-verification on  $X$ , and records the number of links between  $X$  and other communication neighbors of  $S$  (Alg. 4, line 8). The latter is incremented every time at least one of the cross-checks on distances and positions fails (Alg. 4, line 12), and identifies the potential for  $X$  being faulty.

Once all neighbor pairs have been processed, a node  $X$  is added to the unverifiable set  $\mathbb{U}_S$  if it shares less than two neighbors with  $S$  (Alg. 4, line 17). Indeed, in this case the information available on the node is considered to be insufficient to tag the node as verified or faulty (see Sec. V for more details). Otherwise, if  $S$  and  $X$  have two or more common neighbors,  $X$  is declared as faulty, unverifiable, or verified, depending on the percentage of mismatches in the cross-checks it was involved (Alg. 4, lines 18-22). More precisely,  $X$  is added to  $\mathbb{F}_S$ ,  $\mathbb{U}_S$  or  $\mathbb{V}_S$ , depending on whether the ratio of the number of mismatches to the number of checks is greater than, equal to, or less than a threshold  $\delta$ .

We point out that the lower the  $\delta$ , the fewer the failed cross-checks needed to declare a node as faulty, while the higher the  $\delta$ , the higher the probability of false negatives. In the following, we set  $\delta = 0.5$  so that a majority rule is enforced: the verifier makes a decision on the correctness of a node by relying on the opinion of the majority of shared communication neighbors. If not enough common neighbors are available to build a reliable majority, the node is unverifiable. As shown in the next section, this choice makes our SNPD protocol robust to attacks in many different situations.

The third verification, the **Multilateration (ML)** test, is detailed in Algorithm 5. The **ML** test searches the verified set determined through the **DS** and **CS** algorithms for suspicious situations, in which nodes in  $\mathbb{V}_S$  declare a high number of asymmetric links. When a suspect node is found, the **ML** test exploits as anchors other nodes in  $\mathbb{V}_S$ , and multilaterates the actual position of the node under verification.

The **ML** test looks for each verified neighbor  $X$  of the initiator  $S$  that did not notify a link instead reported by another party  $Y$  (Alg. 5, line 7). When such a node is found, it is added to a *waiting set*  $\mathbb{W}_S$  (Alg. 5, line 8) and a curve  $L_X(S, Y)$  is computed. Such curve is the locus of points that can generate a transmission whose Time Difference of Arrival (TDoA) at  $S$  and  $Y$  matches that measured by the two nodes, i.e.,

$|t_{XS} - t_{XY}|$ . It is easy to verify that the curve is a hyperbola, which is added to the set  $\mathbb{L}_X$  (Alg. 5, line 9).

Once all couples of verified nodes have been checked,  $\mathbb{W}_S$  is filled with suspect neighbors. For each node  $X$  in  $\mathbb{W}_S$ ,  $S$  exploits the hyperbolae in  $\mathbb{L}_X$  to multilaterate the position of  $X$ , referred to as  $p_X^{ML}$ , similarly to what is done in [13] (Alg. 5, line 14). Note that  $\mathbb{L}_X$  must include at least two hyperbolae for  $S$  to be able to compute the position  $X$  through multilateration, and this implies the presence of at least two shared neighbors between  $S$  and  $X$  (Alg. 5, line 13). The resulting position  $p_X^{ML}$  is then compared against that advertised by  $X$ ,  $p_X$ . If the difference exceeds a given error margin, neighbor  $X$  is moved from the verified set to the faulty one (Alg. 5, lines 15-17).

## V. SECURITY ANALYSIS

We analyze the security properties of the proposed scheme in presence of adversarial nodes, whose objective is to make the verifier believe that the fake positions they advertise are correct. We consider scenarios of increasing complexity: we start by discussing the basic workings of the SNPD protocol in presence of a single adversary and different shared neighborhoods; we then move to the case of multiple adversaries, at first assuming they act independently and, then, that they cooperate to perform the attack; finally, we examine the resilience of the scheme to a number of well-known attacks.

### A. Single adversary, no common neighbors

Consider a verifier  $S$  that starts the SNPD protocol in presence of an adversary  $M$ , with which it shares no common neighbor. In order to bring a successful attack,  $M$  must tamper with the data  $S$  uses for ranging, so that the resulting distance confirms its fake advertised position. To this end,  $M$  can forge at its convenience the time information in the messages it generates. In particular, let  $p'_M$  be the fake position that  $M$  wants to advertise; we denote by  $t'_{SM}$  the fake timing that  $M$  introduces in its REPLY, and by  $t'_M$  the fake timing inserted in its REPORT (in addition to  $p'_M$ ).

The **DS** test (Alg. 3) run by  $S$  on  $M$  checks the consistency between distances, by verifying that  $|d_{SM} - d_{MS}| \leq 2\epsilon_r$ , or:

$$|(t'_{SM} - t_S) \cdot c - (t_{MS} - t'_M) \cdot c| \leq 2\epsilon_r \quad (1)$$

and that positions are also coherent with the distances, i.e.,  $\|p_S - p'_M\| - d_{SM} \leq 2\epsilon_p + \epsilon_r$ , or, equivalently:

$$\|p_S - p'_M\| - (t'_{SM} - t_S) \cdot c \leq 2\epsilon_p + \epsilon_r \quad (2)$$

Thus, the adversary must forge  $t'_M$  and  $t'_{SM}$ , so that (1)–(2) still hold after its real position  $p_M$  is replaced with  $p'_M$ . Solving the equation system obtained by setting the error margin to zero in (1)–(2), we obtain:

$$t'_M = t_{MS} - \frac{\|p_S - p'_M\|}{c} = t_M + \frac{\|p_S - p_M\|}{c} - \frac{\|p_S - p'_M\|}{c} \quad (3)$$

$$t'_{SM} = t_S + \frac{\|p_S - p'_M\|}{c} = t_{SM} - \frac{\|p_S - p_M\|}{c} + \frac{\|p_S - p'_M\|}{c} \quad (4)$$

Note that  $p'_M$  is chosen by  $M$ , and that  $M$  knows  $t_M$  in (3) (since this is the actual transmission time of its own **REPLY**) and  $t_{SM}$  in (4) (since this is the time at which it actually received the **POLL** from  $S$ ). We therefore have a system of two equations that  $M$  can solve, in the two unknowns  $t'_M$  and  $t'_{SM}$ , only if it is aware of  $p_S$ , i.e., it is a knowledgeable adversary. We stress that, for  $M$  to be knowledgeable, two conditions must hold: first,  $M$  must have previously run the **SNPD** protocol to discover the identity and position of its neighbors; second, the verifier's position must have not changed since such discovery procedure. Clearly, as  $M$  cannot foresee when  $S$  starts the **SNPD** protocol, such conditions are extremely hard to fulfill, especially in a highly dynamic environment such as the vehicular one.

Nevertheless, if  $M$  is aware of  $S$ 's location, the advertised position  $p'_M$  will pass the **DS** test provided that it is within the proximity range  $R$ , as shown in Fig. 1. Given such potential weakness, the **SNPD** protocol marks isolated neighbors as unverifiable in the **CS** test, even if they pass the **DS** test.

### B. Single adversary, one common neighbor

We now add to the previous scenario a node  $X$ , which is a correct neighbor, common to  $S$  and  $M$ . Recall that, in bringing its attack,  $M$  can forge messages with altered information, but it cannot modify the content of messages sent by other nodes, since they are all encrypted and signed.

The discussion in Sec. V-A applies again, since the fake position advertised by  $M$  needs to pass the **DS** test:  $M$  must be aware of  $S$ 's current position and must forge  $t'_M$  and  $t'_{SM}$  according to  $p_S$  and  $p'_M$ . However, the presence of the common neighbor introduces two additional levels of security.

First, the **POLL** and **REPLY** messages are anonymous, hence  $M$  does not know if the verifier is  $S$  or  $X$  upon reception of such messages. However, if it wants to take part in the protocol,  $M$  is forced to advertise the fake **POLL** reception time  $t'_{SM}$  in its **REPLY** message, before receiving the **REVEAL** and discovering the verifier's identity. The only option for  $M$  is then to randomly guess who the verifier is, and properly change  $t_{SM}$  into  $t'_{SM}$ , as in (4), and this implies a 0.5 probability of failure in the attack.

Second, the **CS** test on the pair  $(M, X)$  requires that  $|d_{XM} - d_{MX}| \leq 2\epsilon_r$  and  $|||p_X - p_M|| - d_{XM}| \leq 2\epsilon_p + \epsilon_r$ . Exactly as before, to pass these checks,  $M$  is forced to advertise the fake timings:

$$t'_M = t_M + \frac{\|p_X - p_M\|}{c} - \frac{\|p_X - p'_M\|}{c} \quad (5)$$

$$t'_{XM} = t_{XM} - \frac{\|p_X - p_M\|}{c} + \frac{\|p_X - p'_M\|}{c} \quad (6)$$

If  $M$  knows  $X$ 's current position  $p_X$ , it can solve (6) and announce the forged  $t'_{XM}$  in its **REPORT** to  $S$ . However, (5) introduces a second expression for  $t'_M$ , whereas  $M$  can only advertise one single  $t'_M$ . In order to pass both **DS** and **CS** tests,  $M$  needs to announce a  $t'_M$  that satisfies (3) and (5), which implies:

$$\|p_S - p_M\| - \|p_S - p'_M\| = \|p_X - p_M\| - \|p_X - p'_M\| \quad (7)$$

In other words,  $M$  is constrained to choose locations with the same distance increment (or decrement) from  $S$  and  $X$ . In (7),  $p_S$ ,  $p_X$ , and  $p_M$  are fixed and known, hence distances between  $p_S$  and  $p_M$ , and between  $p_X$  and  $p_M$  can be considered as constant. Since  $p'_M$  is variable over the plane, we rewrite (7) as  $\|p_X - p'_M\| - \|p_S - p'_M\| = k$ , which is the equation describing a hyperbola with foci in  $p_S$  and  $p_X$ , and passing through  $p_M$ . It follows that only positions on such hyperbola satisfy the four constraints in (3), (4), (5), and (6), and  $p'_M$  must lie on that curve in order to pass all tests. Examples of this condition are shown in Fig. 2.

Summarizing, the presence of a common neighbor  $X$  drastically reduces the vulnerability of the verifier to attacks, since  $M$  is now required (i) to be knowledgeable, (ii) to correctly guess the verifier's identity, and (iii) to advertise a fake position only along a specific curve. However, since some space for successful attacks remains, the **CS** test marks as unverifiable nodes that passed the **DS** test but share only one neighbor with the verifier. We also stress that, if  $M$  tweaks the timings so as to pass the **DS** test and does not care about the matching with  $X$ , it will still be tagged as unverifiable.

### C. Single adversary, two or more common neighbors

In the case of two or more common neighbors, we split the discussion into the two following cases: (i) a generic network topology and (ii) collinear nodes.

(i) *Generic network topology.* When a second correct neighbor  $Y$  is shared between  $S$  and  $M$ <sup>3</sup>, the discussion in Sec. V-B can be extended as follows. We noting that, as before, the adversary  $M$  has to be knowledgeable, but a second common neighbor reduces to 0.33 the probability that  $M$  correctly guesses the verifier's identity. More importantly, by applying the same reasoning as in Sec. V-B,  $M$  has now to forge four time values, i.e.,  $t'_M$ ,  $t'_{SM}$ ,  $t'_{XM}$ , and  $t'_{YM}$ , so that six equations are satisfied, i.e., (3), (4), (5), (6), and the two equations corresponding to the cross-check with the second common neighbor  $Y$ <sup>4</sup>.

To fulfill the constraints on  $t'_M$ , now  $M$  has to announce a position  $p'_M$  that is equally farther from (or closer to)  $S$ ,  $X$  and  $Y$  with respect to its actual location  $p_M$ . The point satisfying such condition lies at the intersection of three hyperbolae with foci in  $p_S$  and  $p_X$ ,  $p_S$  and  $p_Y$ ,  $p_X$  and  $p_Y$ , respectively, and such single point actually corresponds to the real position of the adversary,  $p_M$ .

Accordingly, in presence of two common neighbors, the **CS** test marks a node with no mismatches as verified. The majority rule (i.e.,  $\delta = 0.5$ ) results instead in the adversary being tagged as faulty when mismatches are recorded with both common neighbors. Finally, the adversary is added to the unverifiable set if it is capable of fooling  $S$  and either  $X$  or  $Y$ , since that leads to one mismatch over two links checked.

We stress that deceiving  $S$  and one of the common neighbors requires, beside the knowledge of their current positions

<sup>3</sup>Note that we do not make any assumption on the connectivity between  $X$  and  $Y$ .

<sup>4</sup>The latter two equations can be obtained from (5)–(6) by replacing  $p_X$ ,  $t_{XM}$  and  $t'_{XM}$ , respectively, with  $p_Y$ ,  $t_{YM}$  and  $t'_{YM}$ .

and a correct guess on the verifier’s identity, also the pinning of which `REPLY` comes from which neighbor (i.e.,  $M$  must randomly map  $t_{XM}$  onto  $p_X$  and  $t_{YM}$  onto  $p_Y$  for the computations on the hyperbolae to work). Thus, the guess taken by  $M$  in the hope of being marked as unverifiable has a success probability of 0.165, jointly given by the probability of guessing the right verifier (0.33) and the probability of guessing the right mapping (0.5) of `REPLY` reception times onto neighbor positions.

When three or more common neighbors are present between  $S$  and  $M$ , the chances of a successful attack drop to zero. Indeed, not only the probability of guessing the right originators of the different messages shrinks as the size of the common neighborhood grows, but the majority rule dooms the adversary to insertion in the faulty set, even when all random guesses are exact. By extending the above analysis on the hyperbolae, we observe that, with a threshold  $\delta = 0.5$ , when  $S$  and  $M$  share  $n \geq 3$  communication neighbors, the mismatch-to-links ratio is  $\frac{n-1}{n} > \delta$ .

A summary of the security of the SNPD protocol, in presence of a single adversary and in a generic network topology, is presented in Tab. II, where different rows identify different behaviors of the neighbor  $X$  under verification by  $S$ . The columns represent the number of correct neighbors shared by  $S$  and  $X$ . For each combination, we report the set to which  $X$  is assigned by  $S$ , possibly with a probability value due to the adversary’s random guessing on the roles of neighbors.

(ii) *Collinear nodes*. When the majority of common neighbors is collinear to  $S$  and an adversary  $M$ , and lies on the same side as  $S$  with respect to  $p_M$ , a degree of freedom exists for the attacker. Indeed,  $M$  is verified if it announces a fake position that is collinear with  $p_M$  and  $p_S$ , within a distance  $R$  from  $S$ , and such that the majority of the common neighbors still lies on the same side as  $S$  with respect to  $p'_M$ . This case, however, hardly leads to an advantage for the adversary, since  $p'_M$  must remain aligned with the positions of the other nodes, must respect the ordering with the majority of them, and cannot exceed  $S$ ’s proximity range.

#### D. Multiple independent adversaries

We now consider the presence of multiple uncoordinated adversaries. It is easy to see that independent attackers damage each other, by announcing false positions that reciprocally spoil the time computations discussed in the previous sections. Cross checks on couples of non-colluding adversaries will always result in mismatches in the `CS` test, increasing the chances that such nodes are tagged as faulty by the initiator.

Where multiple independent attackers can harm the system is in the verification of correct neighbors. As a matter of fact, a node is ruled verified if it passes the strict majority of cross controls it undergoes. A correct node surrounded by several adversarial neighbors could thus be marked as faulty (unverifiable), if it shares with the initiator a number of adversarial nodes greater than (equal to) the number of correct nodes. An example is provided in Fig. 3. However, it is to be said that, under the assumption that the percentage of attackers among all nodes in the network is small, situations

where a correct node shares mostly uncoordinated adversarial neighbors with the initiator are very unlikely to occur.

#### E. Multiple colluding adversaries, basic attack

Coordinated attacks carried out by colluding adversaries are obviously harder to counter than those independently led by individual adversarial nodes. The SNPD protocol is resistant to coordinated attacks, unless the presence of colluding adversaries in the neighborhood of the initiator node is overwhelming.

The goal of adversarial nodes remains that of inducing the initiator  $S$  into trusting the fake positions they announce. The basic way they can cooperate to that end is by mutually validating the false information they generate. Indeed, colluding adversaries can advertise to  $S$  reception times (of reciprocal `REPLY` messages) forged so that the values derived through ToF-based ranging confirm the positions they made up in the `CS` test. In other words, a perfect cooperation results in the colluding adversaries’ capability of “moving” all links among them without being noticed by the initiator. Our SNPD protocol can counter the basic attack from colluders, as long as 50% *plus one* of the neighbors in common to the verifier and an adversary are correct. Indeed, a strict majority of correct shared neighbors allows the identification of attackers through the `CS` test. An example with three colluding attackers is provided in Fig. 4.

#### F. Multiple colluding adversaries, hyperbolae-based attack

A more sophisticated version of the basic coordinated attack can be organized by colluding adversaries as follows. Having received the `POLL` message, the attackers not only agree on the identity of the initiator  $S$ , but also pick a common neighbor  $X$  that they share with  $S$ : each colluder determines the hyperbola with foci  $S$ ,  $X$ , and passing through its own actual position, and announces a fake position on such curve. This allows the adversaries to announce correct links (i) with the initiator  $S$ , (ii) with the selected neighbor  $X$ , and (iii) among themselves. Node  $X$  becomes an involuntary allied in the attack: in order to work properly, the `CS` test, based on the majority rule, needs that more than 50% *plus three* of the common neighbors between the initiator and communicating node are correct. The two additional correct neighbors are required to counter the effect of  $X$  becoming an unintentional colluder during the cross verification.

#### G. Multiple colluding adversaries, `REPLY`-disregard attack

A second variation to the attack presented in Sec. V-E relies on a coordinated action against `REPLY` messages received from correct nodes. As a matter of fact, the `CS` test can control the symmetry of links between couples of neighbors only if ToF-based ranging is performed in both directions. Thus, by intentionally excluding from their `REPORT` the commitments received from correct nodes while including all those received by colluding nodes, adversaries can selectively avoid cross symmetry tests with correct nodes, so that no mismatches are found. We refer to this as a `REPLY`-disregard attack and stress



that it requires at least three colluding nodes forming a clique, or the adversaries would result unverifiable to the initiator, since they would share less than two (bidirectional) neighbors with it.

The SNPD protocol is robust to REPLY-disregard attacks, thanks to the controls run in the **ML** test. More precisely, an adversary carrying out a disregard attack together with  $N$  colluders can safely advertise up to  $N - 1$  wrong reception times from correct nodes, being still tagged as verified by the majority rule. This means that there must be at least  $N + 1$  correct neighbors, shared by an adversary and the initiator, for the adversary to be forced to disregard one or more REPLY, and for two correct shared neighbors to be in the condition of participating in the **ML** test and identify the colluder. This means that 50% *plus two* of the shared neighbors must be correct for our SNPD protocol to work properly.

As a final remark on coordinated attacks, we comment on the significant resources and a strong effort they require from the colluding adversaries. Colluders have to share out-of-band links through which they can exchange information to coordinate the attack, upon reception of the POLL message. Exploiting such links, they first have to agree on the initiator's identity, either by a shared random guess or by employing a multilateration technique to disclose it. Then, colluders have to inform each other about the fake positions they will announce, and about the estimated transmission time of their REPLY messages: this way, each cooperating adversary is able to recognize the anonymous REPLY of a colluder node and to compute a reception time that is consistent with the fake position advertised by such colluder. Finally, this exchange of information must occur in a very limited time interval after the POLL message has been broadcast, so that colluders can transmit their REPLY messages well before the  $T_{max}$  deadline.

#### H. Denial of Service (DoS) attacks

**Jamming.** An adversary  $M$  may jam the channel and erase REPLY or REPORT messages. To successfully perform such an attack,  $M$  should jam the medium continuously for a long time, since it cannot know when exactly each of the nodes will transmit its REPLY or REPORT message. Or,  $M$  could erase the REVEAL message, but, again, jamming should cover the entire  $T_{jitter}$  time; jamming a specific REPLY transmission is not straightforward either as the REPLY transmission time is randomly chosen by each node. Overall, there is no easy point to target; a jammer has to basically jam throughout the SNPD execution, an action that is possible for any wireless protocol and orthogonal to our problem.

**Clogging.** An adversary could induce SNPD traffic in an attempt to congest the wireless channel, e.g., by initiating the protocol multiple times in a short period and getting repeated REPLY and REPORT messages from other nodes. REPORT messages are large and unicast, and generated in a short period after the reception of the REVEAL message. They are thus likely to cause the most damage. However, SNPD has a way of preventing that: the initiator must unveil its identity before such messages are transmitted by neighbors. An exceedingly frequent initiator can be identified and rate-limited, its excessive REVEAL messages ignored. Conversely,

REPLY messages are small in size, they are broadcast (and thus require no ACK) and they are spread over the time interval  $T_{max}$ . Their damage is somewhat limited, but their unnecessary transmission is much harder to thwart. Indeed, REPLY messages should be sent following an anonymous POLL message; such anonymity is a requirement that is hard to dismiss, since it is instrumental to keeping adversaries unknowledgeable. As a general rule, correct nodes can reasonably self-limit their responses if POLLS arrive at excessive rates. Overall, clogging DoS have only local effect, within the neighborhood of the adversary, which could anyway resort to jamming and obtain the same effect.

#### I. Adversarial use of directional antennas

Assume that adversarial nodes are equipped with directional antennas and multiple radio interfaces. Then, as a correct node  $S$  starts the SNPD protocol, a knowledgeable adversary  $M$  can send REPLY messages through the different interfaces at different time instants, so as to fool the communication neighbors shared by  $M$  and  $S$ : a correct neighbor  $X$  would record a time  $t'_{MX}$ , which is compliant with the fake position,  $p'_M$ , announced by  $M$  and, thus, can pass the corresponding cross check in the **CS** test. If the adversary is able to fool a sufficient number of neighbors, it succeeds and is tagged as verified; however, we stress that the adversary needs as many directional antennas and radio interfaces as the number of neighbors it wants to fool. Moreover, it must hope that no two such neighbors are within the beam of the same antenna. The complexity, cost, and chances of failure make this attack hardly viable.

## VI. PERFORMANCE EVALUATION

To test our SNPD protocol, we selected a real-world road topology that consists of a  $5 \times 5$  km<sup>2</sup> portion of the urban area of the city of Zurich [15]. These traces describe the individual movement of cars through a queue-based model calibrated on real data: they thus provide a realistic representation of vehicular mobility at both microscopic and macroscopic levels. We extracted 3 hours of vehicular mobility, in presence of mild to heavy traffic density conditions; the average number of cars in the area at a given time is 1200.

Traces have a time discretization of 1 s. Thus, given a trace, every second we randomly select 1% of the nodes as verifiers. For each node, we consider that all devices within the proximity range  $R$  are communication neighbors of the node. Clearly, the larger the  $R$ , the higher the number of neighbors taking part in the same instance of the SNPD protocol: for example for  $R$  equal to 50 m and 500 m, the average node degree is 8 and 104.8 and the variance is 5.9 and 71.8, respectively. Also, we set  $\epsilon_r$  to 6.8 m and  $\epsilon_p$  to 5 m [14].

Since *unknowledgeable* adversaries are always tagged as faulty in the **DS** test, in the following we present results considering that all adversaries are always *knowledgeable*. We stress that this is a very hard condition to meet in dynamic networks, hence all results are to be considered as an upper bound to the success probability of an attack.

When independent adversaries are considered, we randomly select a ratio (a varying parameter in our analysis) of the nodes as attackers. In case of colluders, instead, we randomly select some nodes as adversaries, and for each we further randomly identify neighbors who will collude with it so as to form an attackers group of size  $\sigma$  (or up to the number of neighbors available). We assume that colluding adversaries perform hyperbolae-based attacks, which, as previously discussed, are the hardest to contrast. For every scenario under study, we statistically quantify the outcome of the verification test and compare it to the actual behavioral model of the nodes (namely, correct or adversary).

We first report results in terms of probabilities that the tests return false positives and false negatives (Figs. 5(a) and 5(c)) as well as of probability that a (correct or adversary) node is tagged as unverifiable (Figs. 5(b) and 5(d)). The former gauge the reliability of our scheme, while the latter is a mark of the protocol accuracy. The plots showing the false positives and false negatives, when the ratio of adversaries varies and  $R=250$  m, confirm that our scheme errs on the side of caution: indeed, as the number of adversaries increases, it is more likely for a correct node to be mislabeled than for an adversary to be verified (the latter probability amounting to less than 0.02). Instead, widening the proximity range with a fixed adversary ratio, namely 0.05, only plays into the verifier's hands, thanks to the greater number of nodes (the majority of which are correct) that can be tested. As for the probability that a node is unverifiable, while little sensitivity to the ratio of adversaries is observed, a small  $R$  (hence fewer neighbors) affects the protocol capability to reach a conclusive verdict on either correct or adversary nodes. We also estimated that the degree of freedom that a successful adversary has in setting its fake position, for  $R=250$  m and a ratio of 0.05 attackers, is such that, on average, the fake and actual positions of a verified adversary are collinear and differ by 40 m.

We then fix the adversaries ratio to 0.05 and  $R$  to 250 m and we consider the presence of colluders. Figs. 6(a) and 6(b) show the excellent performance of our scheme as the colluder group size  $\sigma$  varies. The impact of colluders on the results appears to be negligible, mainly thanks to the large number of neighbors defeating even big groups of colluders.

Finally, we comment on the overhead introduced by SNPD, in terms of number and size of messages. SNPD generates at most  $2N + 2$  messages for one execution initiated by a verifier with  $N$  communication neighbors. This is twice the cost of an unsecured NPD protocol that would consist of one poll and  $N$  position replies from neighbors. Moreover, SNPD messages are relatively small in size: with SHA-1 hashing and ECDSA-160 encryption [16], the length of signatures is 21 bytes (with coordinates compression). Assuming that messages include headers with 4-byte source and destination identifiers and 1-byte message type field, POLL, REPLY, and REVEAL are all less than 100 bytes in size (to be precise, 26, 71, and 67 bytes, respectively). The REPORT length is variable, depending on the number of commitments it carries: e.g., for 5 commitments, its size is only 295 bytes, and up to 28 commitments can fit in a single 1500-byte IP packet. Obviously, the on-demand nature of the protocol

makes it best suited to event-triggered applications, such as safety and tolling ones. In these scenarios, SNPD induces very low overhead in the network. The limited number and the small size of messages make the proactive use of the protocol feasible, for relatively low rate execution, e.g., once in a few tens of seconds.

## VII. CONCLUSION

We proposed a lightweight, distributed scheme for securely discovering the position of communication neighbors in vehicular ad hoc networks. Our solution does not require the use of a-priori trustworthy nodes, but it leverages the information exchange between neighbors. Our analysis showed the scheme to be very effective in identifying independent as well as colluding adversaries. Results derived using realistic vehicular traces confirmed such ability and highlighted the good performance of our solution in terms of both false negatives/positives and uncertain neighbor classifications.

Future work will aim at assessing the performance of the proposed secure neighbor position discovery protocol when adversaries have partial or out-of-date knowledge on the other nodes' positions, and at adapting our scheme to a high-frequency proactive utilization.

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**Algorithm 1:** Message exchange protocol: verifier node

```

1 node  $S$  do
2    $S \rightarrow * : \langle \text{POLL}, K'_S \rangle$ 
3    $S$  : store  $t_S$ 
4   when receive REPLY from  $Y \in \mathbb{N}_S$  do
5      $S$  : store  $t_{YS}, c_Y$ 
6   end
7   after  $T_{max} + \Delta + T_{jitter}$  do
8      $S \rightarrow * : \langle \text{REVEAL}, E_{k'_S} \{h_{K'_S}\}, K_S, Sig_S \rangle$ 
9   end
10 end

```

**Algorithm 2:** Message exchange protocol: neighbor node

```

1 forall  $X \in \mathbb{N}_S$  do
2   when receive POLL by  $S$  do
3      $X$  : store  $t_{SX}$ 
4      $X$  : extract  $T_X$  uniform r.v.  $\in [0, T_{max}]$ 
5   end
6   after  $T_X$  do
7      $X : c_X = E_{K'_S} \{t_{SX}, K_X, Sig_X\}$ 
8      $X \rightarrow * : \langle \text{REPLY}, c_X, h_{K'_S} \rangle$ 
9      $X$  : store  $t_X$ 
10  end
11  when receive REPLY from  $Y \in \mathbb{N}_S \cap \mathbb{N}_X$  do
12     $X$  : store  $t_{YX}, c_Y$ 
13  end
14  when receive REVEAL from  $S$  do
15     $X : \mathbb{t}_X = \{(t_{YX}, c_Y) \forall Y \in \mathbb{N}_S \cap \mathbb{N}_X\}$ 
16     $X \rightarrow S : \langle \text{REPORT}, E_{K_S} \{p_X, t_X, \mathbb{t}_X, Sig_X\} \rangle$ 
17  end
18 end

```

**Algorithm 3:** Direct Symmetry (DS) test

```

1 node  $S$  do
2    $S : \mathbb{F}_S \leftarrow \emptyset$ 
3   forall  $X \in \mathbb{N}_S$  do
4     if  $|d_{SX} - d_{XS}| > 2\epsilon_r$  or
5        $\| \|p_S - p_X\| - d_{SX} \| > 2\epsilon_p + \epsilon_r$  or
6        $d_{SX} > R$  then
7        $S : \mathbb{F}_S \leftarrow X$ 
8     endif
9   end
10 end

```

**Algorithm 4:** Cross-Symmetry (CS) test

```

1 node  $S$  do
2    $S : \cup_S \leftarrow \emptyset, \forall_S \leftarrow \emptyset$ 
3   forall  $X \in \mathbb{N}_S, X \notin \mathbb{F}_S$  do
4      $S : l_X = 0, m_X = 0$ 
5   end
6   forall  $(X, Y) \mid X, Y \in \mathbb{N}_S, X, Y \notin \mathbb{F}_S, X \neq Y$  do
7     if  $\exists d_{XY}, d_{YX}$  then
8        $S : l_X = l_X + 1, l_Y = l_Y + 1$ 
9       if  $|d_{XY} - d_{YX}| > 2\epsilon_r$  or
10         $\| \|p_X - p_Y\| - d_{XY} \| > 2\epsilon_p + \epsilon_r$  or
11         $d_{XY} > R$  then
12          $S : m_X = m_X + 1, m_Y = m_Y + 1$ 
13       endif
14     end
15   end
16   forall  $X \in \mathbb{N}_S, X \notin \mathbb{F}_S$  do
17     if  $l_X < 2$  then  $S : \cup_S \leftarrow X$ 
18     else switch  $\frac{m_X}{l_X}$  do
19       case  $\frac{m_X}{l_X} > \delta$  :  $S : \mathbb{F}_S \leftarrow X$ 
20       case  $\frac{m_X}{l_X} = \delta$  :  $S : \cup_S \leftarrow X$ 
21       case  $\frac{m_X}{l_X} < \delta$  :  $S : \forall_S \leftarrow X$ 
22     end
23   end
24 end

```

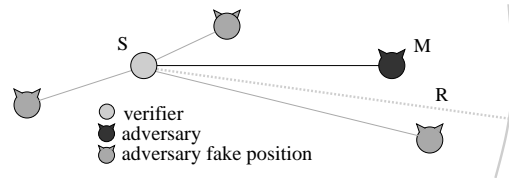


Fig. 1. If  $M$  knows  $S$ 's position, it can advertise any fake position, provided its distance from  $S$  is at most equal to  $R$ .

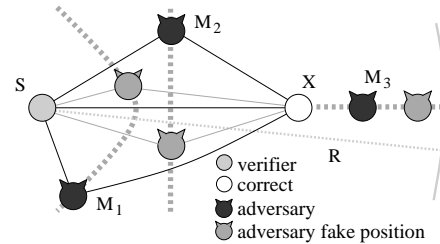


Fig. 2.  $M_1$ ,  $M_2$ , and  $M_3$  depict different situations in which a single adversary can be. In the general case (as  $M_1$ ), a knowledgeable adversary that correctly guessed the verifier's identity can pass all tests if its fake position is on a hyperbola with foci in  $S, X$ , passing by  $M_1$ . Particular cases that determine a degeneration of the hyperbola are: (i) the adversary is equidistant from  $S$  and  $X$  (as  $M_2$ ), constraining the fake position on the symmetry axis of  $S$  and  $X$ ; (ii) the adversary is aligned with  $S$  and  $X$  (as  $M_3$ ), and not between them; then, the fake location needs to be on the same line, between  $X$  and a point at distance  $R$  from  $S$ .

TABLE I  
SUMMARY OF NOTATIONS

Notation	Description
$k_X$ (resp. $K_X$ )	private (resp. public) key of node $X$
$k'_X$ (resp. $K'_X$ )	private (resp. public) one-time key of node $X$
$t_X$ (resp. $t'_X$ )	actual (resp. fake) transmission time of a message by node $X$
$t_{XY}$ (resp. $t'_{XY}$ )	actual (resp. fake) reception time at node $Y$ of a message sent by node $X$
$p_X$ (resp. $p'_X$ )	actual (resp. fake) position of node $X$
$d_{XY}$	distance between nodes $X$ and $Y$
$\epsilon_p$ (resp. $\epsilon_r$ )	position (resp. ranging) error
$R$	node proximity range
$\mathbb{N}_X$	current set of communication neighbors of node $X$
$T_X$	random wait interval after reception of POLL at node $X$
$Sig_X$	signed identity of node $X$
$c_X$	commitment of node $X$
$\mathbb{V}_X$	set of <i>verified</i> communication neighbors of node $X$
$\mathbb{U}_X$	set of <i>unverifiable</i> communication neighbors of node $X$
$\mathbb{F}_X$	set of <i>faulty</i> communication neighbors of node $X$

Algorithm 5: Multilateration (ML) test

```

1 node  $S$  do
2    $S : \mathbb{W}_S \leftarrow \emptyset$ 
3   forall  $X \in \mathbb{V}_S$  do
4      $S : \mathbb{L}_X \leftarrow \emptyset$ 
5   end
6   forall  $(X, Y) \mid X, Y \in \mathbb{V}_S, X \neq Y$  do
7     if  $\exists t_{XY}$  and  $\nexists t_{YX}$  then
8       if  $X \notin \mathbb{W}_S$  then  $S : \mathbb{W}_S \leftarrow X$ 
9        $S : \mathbb{L}_X \leftarrow L_X(S, Y)$ 
10    end
11  end
12  forall  $X \in \mathbb{W}_S$  do
13    if  $|\mathbb{L}_X| \geq 2$  then
14       $S :$ 
15       $p_X^{ML} = \arg \min_p \sum_{L_i, L_j \in \mathbb{L}_X} \|p - L_i \cap L_j\|^2$ 
16      if  $\|p_X - p_X^{ML}\| > 2\epsilon_p$  then
17         $S : \mathbb{F}_S \leftarrow X, \mathbb{V}_S = \mathbb{V}_S \setminus X$ 
18      end
19    end
20  end

```

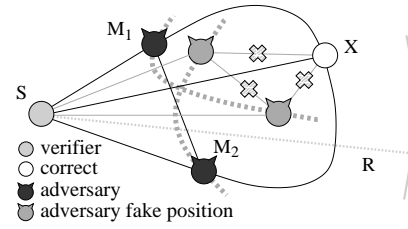


Fig. 3. Clique of four nodes: the verifier  $S$ , a correct neighbor  $X$ , and two adversaries ( $M_1, M_2$ ).  $M_1$  ( $M_2$ ) announces a fake position along a hyperbola with foci on  $p_S$  and  $p'_{M_2}$  ( $p'_{M_1}$ ). However, the latter information is fake, leading to a mismatch in the cross-check on  $(M_1, M_2)$ . Also, since each attacker can “move” at most one link other than that with  $S$ , the checks on  $(X, M_1)$  and  $(X, M_2)$  fail as well. Thus,  $M_1$  and  $M_2$  damage each other and are tagged as faulty.  $X$ , although correct, is added to  $\mathbb{F}_S$ , since all neighbors it shares with  $S$  happen to be adversaries.

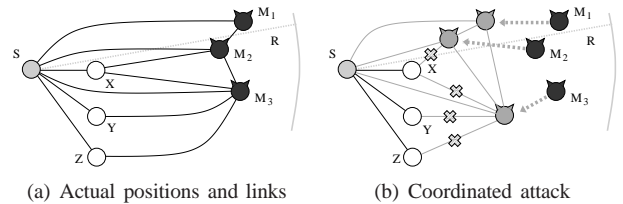


Fig. 4. Coordinated attack by  $M_1, M_2$ , and  $M_3$  against  $S$ . All links between adversaries appear consistent with the false positions they advertise, but links with correct neighbors  $X, Y$ , and  $Z$  result in mismatches in the CS test.  $M_1$ , sharing with  $S$  two colluders but no correct nodes, results as verified. The same holds for  $M_2$ , sharing with  $S$  two colluders and one correct node.  $M_3$  is instead marked as faulty, thanks to the three correct common neighbors.

TABLE II  
SUMMARY OF SECURITY ANALYSIS IN A GENERIC NETWORK TOPOLOGY

$X$	$ \mathbb{N}_S \setminus X $	0	1	2	3+
Correct		$\mathbb{U}_S$	$\mathbb{U}_S$	$\mathbb{V}_S$	$\mathbb{V}_S$
Unknowledgeable adversary		$\mathbb{F}_S$	$\mathbb{F}_S$	$\mathbb{F}_S$	$\mathbb{F}_S$
Knowledgeable adversary		$\mathbb{U}_S$	$\mathbb{U}_S$ (0.5) $\mathbb{F}_S$ (0.5)	$\mathbb{U}_S$ (0.165) $\mathbb{F}_S$ (0.835)	$\mathbb{F}_S$

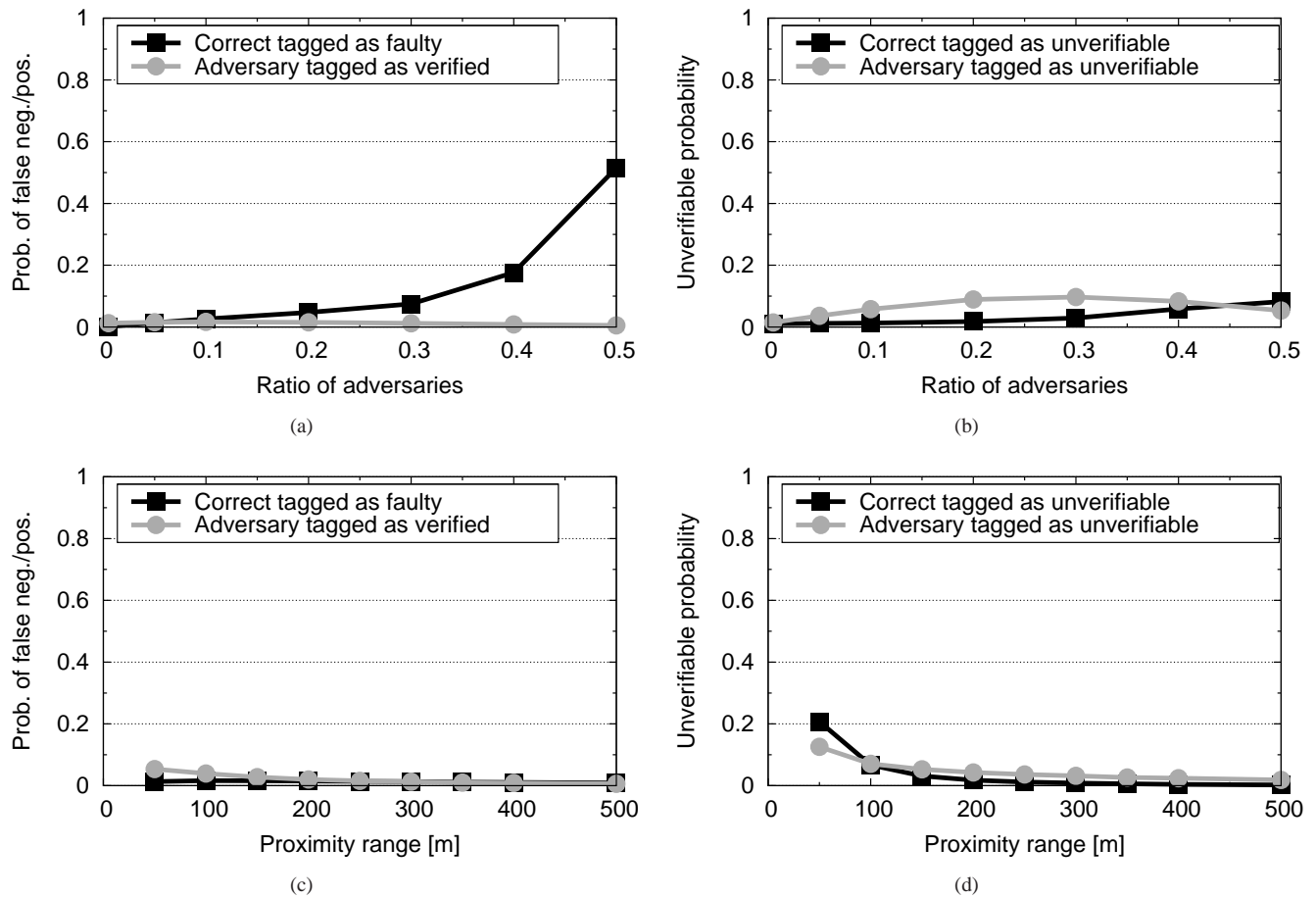


Fig. 5. Independent adversaries: probability of false negatives/positives and probability of classifying a neighbor as unverifiable. In (a) and (b),  $R = 250$  m while the ratio of adversaries varies; in (c) and (d), the ratio of adversaries is 0.05 and the proximity range  $R$  varies.

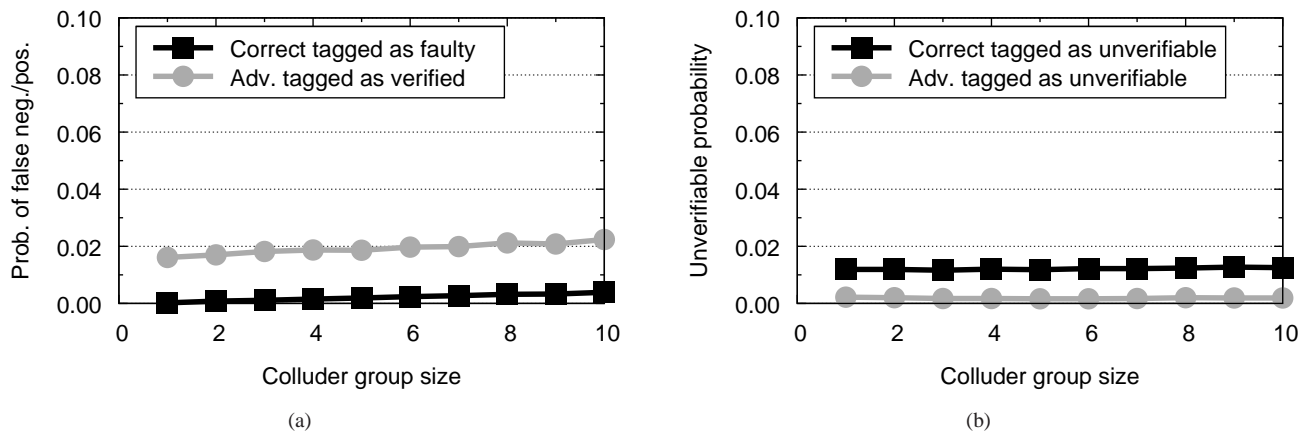


Fig. 6. Colluding adversaries: probability of false negatives/positives and probability of classifying a neighbor as unverifiable, for ratio of adversaries equal to 0.05,  $R = 250$  m, and varying group size  $\sigma$ .