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# Performance Evaluation of Dissemination Protocols Over Vehicular Networks for an Automatic Speed Fine System

**DUSTIN CARRIÓN-OJEDA[1], (Student Member, IEEE), CRISTHIAN IZA[1], AND MÓNICA AGUILAR IGARTUA[2]**

[1]School of Mathematical and Computational Sciences, Yachay Tech University, Urcuquí 100650, Ecuador
[2]Department of Network Engineering, Universitat Politècnica de Catalunya (UPC), 08034 Barcelona, Spain

Corresponding author: Mónica Aguilar Igartua (monica.aguilar@upc.edu)

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**ABSTRACT** Vehicular accidents cause severe problems in our society including economic, material, and even life losses. The cause of those situations relies on several factors such as traffic density, vehicular flow, lack of traffic signaling and speed limit violations. Some of these problems cannot completely be eliminated but could be mitigated by proposing solutions such as people's awareness or intelligent radars to monitor speed limit violations. This work proposes a system to automatically generate fines in case of speed limit infractions. Our approach uses vehicular networks to monitor the vehicles' speed. We also propose a dissemination protocol to ensure the propagation and delivery of the generated fines at the road-side units, achieving a 94.99% and 99.91% fine delivery rate in urban scenarios with vehicles' densities of 30 and 200 vehicles per $km^2$, respectively.

**INDEX TERMS** Dissemination protocol, speed control system, speed limit infractions, vehicular networks.

## I. INTRODUCTION

Nowadays, transportation of people and goods is an essential service, and this is expected to continue in this way in the future. As a result, the number of vehicles circulating on the roads increases significantly every year, especially in the cities. Since traffic congestion has a significant impact on the frequency of road accidents [1], the number of traffic accidents increases year after year.

Road accidents are a significant problem in the world. According to [2], about 1.3 million people die per year because of a traffic accident and around 50 million people are seriously injured. Many factors affect the severity of road accidents. These factors include traffic speed, vehicles' density, traffic flow, alcohol intake, pedestrian misdirections, lousy visibility, among others [3]. Regardless of the variety of factors that can influence the severity of road accidents, the research done in [2] verified that exceeding the speed limit is the main factor that significantly influences the severity of crashes on streets and highways. For this reason, speed limit regulations should be enforced.

During the last years, there has been more research about the development of Intelligent Transportation Systems (ITS) to reduce the number of accidents; in general, ITS are capable of monitoring, communicating, and controlling their connected components [4]. One of the core functions performed by ITS is vehicle detection, which helps monitoring individual vehicles to hence derive crucial information such as their position or speed. Many ITS applications rely on vehicle detection, but one of the most studied applications is traffic management.

A specific application in traffic management is the development of smart traffic lights [5], which can warn vehicles about a danger of collision at an intersection. Besides, it has been proven that the simple installation of conventional traffic lights can reduce the number of road accidents [6]. Another case is the use of radars to measure vehicles' speeds. In this case, the prevention of accidents is tied to people's awareness, which is influenced by the infractions received by exceeding the speed limits.

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The motivation of the present work is to try to reduce the number of traffic accidents and their severity through an automatic system of detection and issuance of speeding fines. Currently, most speeding fines are issued by fixed speed cameras or, in some cases, mobile radars. However, by using those current options, many areas are left unmonitored. For this reason, the aim of using an automated system is to be able to monitor all vehicles in order to enforce drivers to be more cautious when driving.

In this article we propose an efficient model based on vehicular ad hoc networks (VANETs) where all vehicles can detect their own speed violations and those of nearby vehicles, can produce fines and can send them to the nearest road-side unit (RSU) for their final processing. In this work we make some assumptions:

1) We assume that there is some type of security system capable of detecting malicious vehicles that generate false fines. The design of such a system is out of the scope of this research work.
2) Although it may seem strange that a vehicle fines itself, we assume that all vehicles must do so, according to some regulations that require manufacturers to install such a device in vehicles in the near future.

The main contributions of this article are summarized as follows:

- We introduce an efficient new model for detecting speed limit violations and automatic generation of the corresponding fines.
- We propose a novel smart dissemination protocol to propagate the generated fines through the vehicular network towards an RSU.
- We carry out extensive simulations to evaluate the performance of our proposed dissemination protocol compared to other well-known dissemination protocols.

The remainder of the article is organized as follows. Section II presents a review of systems that automatically generate fines and also of dissemination protocols. Section III provides details of our proposed model and dissemination protocol. Afterward, the simulation environment's description is presented in Section IV, including a performance evaluation of some dissemination protocols. Finally, Section V concludes this article and points out future research.

## II. RELATED WORK

Since this work proposes (a) an architecture for detecting speed limit violations and (b) a data dissemination protocol, related works are divided into two sections regarding each topic.

### A. SPEED LIMIT VIOLATION DETECTION

One approach to try to reduce road accidents is the design of a framework able to recognize traffic signal violations. Generally, those systems are based on computer vision [7]–[9]. For instance, [9] proposed a method based on plate recognition able to send SMS feedback to the corresponding authorities. Their system employs optical character recognition. However, those systems have some crucial challenges, including image quality, which complicates the correct identification of the offending vehicle.

To develop more reliable systems, some researchers focus their attention on vehicular ad hoc networks [10], [11]. Using this approach, [12] developed a method for the detection of traffic violations. They used an accelerometer and a GPS transmitter in each vehicle to enable vehicle-to-infrastructure (V2I) communications. Each vehicle periodically sends a message to the closest RSU, where messages are processed. Each message received by an RSU contains the vehicle ID, location in the x- and y-axis, speed, and trajectory. The authors proposed a method to detect excessive vehicle speed above the limit and drunk driving behavior from analyzing these data.

Moreover, [13] proposed a method that enables a cop vehicle (CV) to issue fines about traffic violations to the offenders autonomously, once they are in the transmission range of that CV. They estimated by simulation the fine issuing delay, messaging cost, and percentage of violations detected for different numbers of violators vehicles, CVs and vehicles' speed. For their simulation, they created their own data structures to keep track of pending and received fines, violation entries and traffic rules. For creating a more realistic scenario, they also proposed an "unpatrolled area" without cop vehicles where no matter what infractions are committed, the vehicles do not receive a fine at that time but use the structure of pending fines to store them. Consequently, the pending fines will be issued as soon as the vehicle leaves the unpatrolled area and a cop vehicle detects it.

On the other hand, [14] proposed a system composed of an embedded unit installed on the vehicle, a violation event reader, an intelligent traffic light, and a wireless infrastructure. This infrastructure had to obtain the traffic violations, included speed exceeding committed by a vehicle, and send it to a central server in the traffic authority department. For securing the on-board unit from being bypassed or switched off, the author proposed connecting it to the vehicle's electric circuit, acting as a circuit-breaker. Consequently, if it is deliberately switched off or broken down, the vehicle will not run or start.

[15] proposed a framework using a variable speed limit (VSL) based model. This model adapts the speed limits according to different environmental factors, including weather conditions, accident-prone zones, condition surface of the road, and culture. They used road conditions, collision detection, and vehicle categorization as the dependent variables used by the VSL for fixing the speed limit. Finally, they used computer vision techniques for the vehicle recognition step, which uses the plate as the method's input.

### B. DATA DISSEMINATION PROTOCOLS

All works previously mentioned proposed approaches of how to control the speed violation problem. Nevertheless, there is another problem that should be addressed about the efficient dissemination of messages with a fine about the detected infraction to ensure efficient propagation of data packets between vehicles. This problem can be solved by implementing smart dissemination protocols that improve the packet delivery rate.

The work presented in [16] introduces a dissemination protocol based on the neighbors' locations. The main characteristic of this protocol is the distinction between dense and sparse scenarios. When a vehicle has more neighbors than a defined threshold, it is considered a dense scenario. In this case, when a vehicle has a message to be disseminated, farther vehicles are preferred to disseminate the message than closer vehicles, seeking to incur a shorter delay. If a vehicle receives a duplicated message, the forwarding of that message is canceled to avoid unnecessary data redundancy. In sparse scenarios, vehicles broadcast the data only if they are inside a specific area of interest.

On the other hand, [17] proposed a different approach for standard dissemination protocols. They used an Adaptive approach for Information Dissemination (AID), avoiding the traditional use of a fixed counter to manage the broadcasting of messages in VANETs. Their method consists of a decentralized distribution of information. Each node can dynamically decide to rebroadcast a message according to the number of messages received from its neighbors during a time interval. This approach adjusts the local parameters' values by using location information to avoid using extra information such as distance, position, or number of surrounding nodes.

Most of the state-of-the-art dissemination protocols use additional information along with the position to create more complex and efficient protocols. For instance, [18] introduces two protocols, the Timer-based Backbone Network dissemination protocol (TBN) and the Distance-based forwarding hop count protocol (DBF). The main characteristic of both protocols is the inclusion of an inhibition rule based on a timer to prevent all vehicles from disseminating the same message. Conversely, only the best positioned vehicles do so. The difference between TBN and DBF is the way used for setting up the timer. Additionally, the authors developed a probability-based version of both protocols [19] in which a vehicle will not forward a received message with a certain probability $p$. This approach decreases the network overhead specially in dense scenarios.

Another protocol is Data dissemination pRotocol In VEhicular networks (DRIVE) proposed by [20]. This protocol provides an efficient solution to the broadcast storm problem. One of the most significant advantages of this protocol is that it maximizes the data dissemination capability across the network in a region of interest without using neighbors' tables. The basis of this protocol is the store-carry-forward approach and the inclusion of Sweet Spots inside the area of interest. The sweet spots are areas where a vehicle is best positioned to perform data dissemination.

A common characteristic of most data dissemination protocols is using a fixed interval for beacon exchange. However, [21] designed the Adaptive data dissemination protocol (AddP) aimed at providing reliability to message dissemination efficiently. This protocol dynamically adjusts the beacon periodicity by considering the number of one-hop neighbors to mitigate the broadcast storm problem. A vehicle with many neighbors will broadcast at a lower rate than a vehicle with fewer neighbors. Furthermore, in their protocol, a vehicle only sends the same message once and selects a target one-hop vehicle for each message; nevertheless, if the target vehicle does not disseminate the message, any other vehicle does it to avoid losing a message.

Although several recently published articles [16], [22] have addressed the challenges of dissemination protocols in VANET, few studies [21], [23] have been reported on application performance measurements using the proposed dissemination protocol. In [23] a scheme called Adaptive Distributed Diffusion (ADD) protocol was proposed as a decentralized stochastic solution to the broadcast data diffusion problem. The authors evaluate their proposal for a video-streaming application, showing clear benefits compared to other proposals in terms of frame delivery ratio and peak signal to noise ratio (PSNR).

In general, different approaches for developing systems for speed limit detection and automatic fine generation have been proposed. One of these systems' challenges is the effective dissemination of the fines to the corresponding control centers. According to our state-of-the-art review, most of the systems use designated vehicles or RSUs to detect the infractions and general dissemination protocols to transmit them. In this study, we propose a novel architecture in which all vehicles in the vehicular network are used to detect speed infractions, generate the corresponding fines, and send them towards the nearest RSU to be delivered to the traffic management entity in the city, where it will be properly processed. Further, we proposed a smart multimetric dissemination protocol specifically developed for this application as it is explained in Section III-B.

In the next section, we explain in detail our proposed architecture and our proposal of dissemination protocol to be used.

## III. PROPOSED ARCHITECTURE AND DISSEMINATION PROTOCOL

In this section, we present the details of our proposed model and of our proposal of dissemination protocol. First, we describe our proposed architecture highlighting the importance of implementing an efficient dissemination protocol. Then, the details of the proposed dissemination protocol are explained.

### A. PROPOSED ARCHITECTURE

The proposed architecture delimits specific zones within the map, where each zone has its specific speed limit. This work uses rectangular zones, but the proposed architecture can work with zones of any shape. The objective of delimiting the map in zones is to simulate a realistic environment in which there are different speed limits depending on the zone, e.g., a scholar zone has a lower speed limit than a big avenue. Taking into account the division of the environment into zones, the system architecture is composed of two principal components: vehicles and RSUs.

### 1) VEHICLES

In the proposed architecture, each vehicle has an on-board unit (OBU) with GPS and a transmitter in charge of maintaining the communication within the network. Thanks to the GPS, the vehicles' speed can be estimated by computing the distance traveled on a time interval. Consequently, each vehicle can detect speed limit violations and generate the corresponding fines. However, as the speed measured with the GPS can be affected by different factors such as rapid speed changes or circular tracks [24], in this study, we consider a speed limit violation when the approximated speed is 20% above of the speed limit. The 20% depends on the zone on which the infraction is committed. Thus, the position extracted from the GPS is used to determine in which zone the vehicle is currently located. Then, the speed limit of that zone is compared with the current vehicle's speed, and if it exceeds the limit by more than a 20%, a speeding fine is issued.

For this reason, the OBU stores the information concerning the zones with their speed limits and the RSUs location. This architecture manages two types of messages: *beacon* and *fine*. Each vehicle periodically (e.g., once per second) broadcasts a beacon message within its transmission range; the information contained in the beacon message depends on the dissemination protocol. Basically, it contains the vehicle's ID (unique identifier), location (X and Y coordinates extracted from the GPS), and speed. This information is gathered in a neighbors' table (NT) to be available for the dissemination protocol. The position of the neighbors recorded in the NT is used to calculate the distance from the vehicle to each one of its neighbors listed in the NT. In this work we use the Euclidean distance.

Each time a vehicle receives a beacon message from a neighboring vehicle, it verifies the sending vehicle's speed and compares it with the speed limit of the corresponding area. If the issuing vehicle is committing a speed limit violation, the receiver vehicle generates a message with the corresponding fine, which contains the following information:

- Offending vehicle's ID. It can be the vehicle's plate or any other unique identifier of the offending vehicle.
- Detector vehicle's ID. It can be the vehicle's plate or any other unique identifier of the vehicle that detects the infraction.
- Offending vehicle's speed. It corresponds to the speed at which the offending vehicle went when the infraction was detected.
- Offending vehicle's zone. It is the zone in which the infraction was committed.
- Zone's speed limit. It is the speed limit of the specific zone in which the infraction was committed.
- Timestamp. It corresponds to the exact timestamp in which the fine was generated.

The fine message includes the detector vehicle's ID to tackle the problem of anonymous fines produced by malicious vehicles. In addition, this ID could be used in future applications dedicated to providing security to the proposed protocol. For example, if an RSU receives multiple fines generated from the same ID and it does not receive these fines from another vehicle, it may indicate that a malicious vehicle could actually have generated the fines. In addition, if two or more RSUs receive messages from the same ID at similar times, the distance between these RSUs and the speed of the issuing vehicle could be analyzed to identify the legitimacy of the fines. On the other hand, future versions of our proposal should send the information encrypted to avoid possible retaliation against the detecting vehicle, since currently, the real ID of the detector vehicle is part of the fine message.

After the fines are generated, the dissemination protocol should propagate them from the vehicle to the RSU, maximizing the fine delivery rate. Notice that instead of a dissemination protocol we could have used a unicast routing protocol, since the goal is to transmit the fine to the closest RSU. However, we have chosen to design a smart dissemination protocol (not just a naive flooding) to ensure a high delivery rate of the fine messages. In addition, using a suitable dissemination protocol we could warn surrounding vehicles to alert them about a fast vehicle around.

For avoiding undetected infractions, each vehicle also monitors its location and speed and generates the corresponding fine if it is the case. When a vehicle detects its own infraction, the offending vehicle's ID and the detector vehicle's ID are equal. Of course, we assume that such a device is compulsory by regulation and manufacturers install them in the vehicles from factory. Additionally, each vehicle stores the generated fines for a specified time interval to avoid generating the same fine twice. This period can vary depending on the regulations of each city or country. In this work, for a simulation time of 100 seconds, 45 seconds are devoted for this purpose so vehicles store generated fines during 45 seconds.

In this study, we assume the existence of a mechanism to enforce speed limit detection, fine generation, and fine propagation. Since the correct functioning of the proposed architecture relies on the OBU, a viable mechanism is the one mentioned in Section II in which if the OBU is deliberately switched off or broken down, the vehicle will not run or start. However, as this mechanism has not been analyzed in this study, it should be further analyzed to verify whether it is safe to be used in a real scenario and analyze other alternative mechanisms.

### 2) ROAD-SIDE UNITS

In this architecture, RSUs work as the control center. Their function is to process the incoming fines from the vehicles, eliminate duplicates, and send this information to the specific

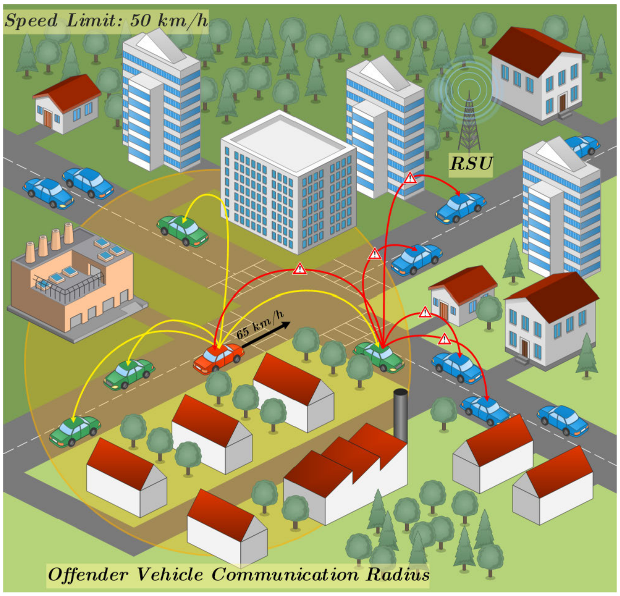


**FIGURE 1. Proposed architecture to detect speed limit violation and generate corresponding fines. The red vehicle exceeds the speed limit and a fine is disseminated towards the RSU.**

traffic authorities. All the RSUs share a structure for storing the fines, which allows them eliminating any duplicates. It is worth mentioning that for separating the functions between the architecture components, in this work we assume that RSUs do not detect speed limit violations or produce fines; they just receive them.

Fig. 1 illustrates the proposed architecture over which we have analysed our proposals. In this figure, the red vehicle commits a speed violation by exceeding the 50 km/h limit by more than 20% (65 km/h), the green vehicles are those that are within the communication radius of the offending vehicle, and the blue ones are those outside that transmission range. The yellow lines correspond to the beacons periodically broadcasted by the offending vehicle. Only those beacons are shown to simplify the visualization, although actually all vehicles and RSUs periodically emit beacons. On the other hand, when a vehicle receives the offender's beacon, it detects the speeding violation and broadcasts the corresponding fine message. The red lines illustrate this process. The fine message is emitted by all green vehicles and also the offending vehicle itself. In the picture, we show only the broadcasting of the fine message from a single vehicle to facilitate the visualization.

### B. 3DP: SMART DISSEMINATION PROTOCOL BASED ON DISTANCE, DENSITY AND POSITION

The proposed smart dissemination protocol for propagating fines from vehicles to RSUs is developed considering the nature of the application. Thus, this protocol is focused on maximizing the fine delivery rate regardless of other factors, such as delay or security. The proposed multimetric dissemination protocol relies on three metrics: distance, vehicles' density, and vehicles' position. According to our dissemination protocol, vehicles rebroadcast each fine only once for mitigating the broadcast storm issue. It also performs the store-carry-forward scheme for remaining its robustness even in low vehicular density scenarios. This protocol has three ways of broadcasting a fine message: (i) sending the fine directly to an RSU; (ii) sending the fine to another vehicle; and (iii) rebroadcasting a received fine. Each fine message is composed of a vector of fines and a target. If the sender vehicle cannot send the fine directly to an RSU, the target corresponds to the ID of the vehicle best suited for continuing the dissemination process towards any RSU, i.e., the neighbor vehicle closest to an RSU. On the contrary, if the sender vehicle can send the fine directly to an RSU, the target is null, meaning that no vehicle will rebroadcast the message any more to avoid saturating the network.

Our proposal, called **D**issemination protocol based on **D**istance, **D**ensity, and **P**osition (**3DP**), uses a neighbors' table which stores the following information regarding each neighbor: vehicle's ID, vehicles' density, vehicle's position, and vehicle's speed. The vehicles' density corresponds to the number of one-hop vehicles that the vehicle has in its NT. All the information inside the NT is stored for time $t_n$ and time $n_{-1}$ where $t_n$ corresponds to the time when the last beacon was received and $t_{n-1}$ is the time when the second last beacon was received ($t_n > t_{n-1}$). The information of both $t_n$ and $t_{n-1}$ is essential for this protocol because it is used as part of the target selection process. The target next-hop vehicle is intended to be the vehicle furthest from the issuer vehicle, closest to an RSU, and with the highest vehicles' density, since all those factors can increase the possibility of delivering the generated fines to an RSU. Notice that even though only one vehicle is selected to continue with the propagation of the message carrying fines, broadcasting is a fundamental part of our protocol since the vehicles that receive the message and are not the target can store the received fine and later disseminate it when they are close to an RSU. This way, we reduce the possibility of fines not being delivered at any RSU. In general, 3DP deploys an efficient receiver-based relay node selection technique to avoid overhead and high delay in the network. Moreover, it is important to mention that when a message arrives late at the RSU, it will be discarded or processed depending on whether there are duplicates or not, respectively.

#### 1) SENDING A NEW GENERATED FINE DIRECTLY TO AN RSU

A vehicle can directly send information to an RSU if it is within its sweet spot (SS), which is a specific zone inside of the area of interest (AOI), i.e., the transmission range of an RSU, and its distance to the RSU is less than a specified threshold ($dt$). 3DP uses the SS introduced by [20]. Fig. 2 shows the graphic representation of the AOI and the SS used in this work. The simulation results in [25]–[27] indicate that the maximum communication distance for IEEE 802.11p transceivers is 700 m for highway scenarios and 400 m for urban scenarios. After analyzing an exhaustive number

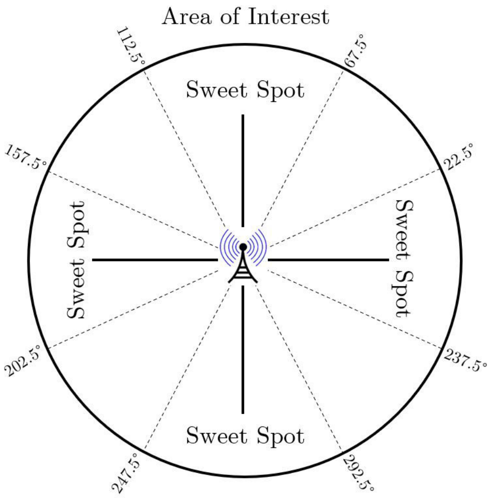


**FIGURE 2.** Area of interest (AOI) and sweet spot (SS) of an RSU.

of representative simulations, we found that the maximum communication distance in typical urban scenarios goes from 400 m to 500 m. Therefore, for this study, *dt* was set as half of the SS radius to maximize the probability that the RSU will receive the fine message.

If a vehicle that can directly send information to an RSU detects a speed limit infraction, the vehicle broadcasts the corresponding fine and any other stored fine. This way, the disseminated fine or fines will reach in 1-hop the RSU. After the message is sent, the vehicle clears its record of stored fines. The pseudo-code shown in Algorithm 1 describes the main steps performed by a vehicle when it has fines to disseminate, it is inside the SS of an RSU and its distance to the RSU is less than $dt$. In this case, the input for the algorithm corresponds to the fine of the detected infraction.

**Algorithm 1** The Source Vehicle Detecting a New Speed Limit Infraction or Receiving a Fine Message, Sends Fine/Fines Directly to an RSU Located Within Its Transmission Range (1-Hop)

**Data:**
*v*: Current vehicle.
*p*: Position of the current vehicle.
*dt*: Distance threshold for considering direct sending.

**Input:** New fine generated (*gf*) in the current vehicle, or new fine/s (*rfs*) received at the current vehicle.

```
1:  if p is inside SS of any RSU and distance from v to its
    closest RSU < dt then
2:    if v has stored fines then
3:      if the new gf or rfs are not stored yet then
4:        store the new gf or rfs;
5:      end if
6:      broadcast a fine message including all the stored
        fines (without any target receiver);
7:      clear the stored fines;
8:    else
9:      broadcast a fine message including the new gf or rfs
        (without any target receiver);
10:   end if
11: else
12:   forward the new gf or rfs to another vehicle (see
      Alg. 2);
13: end if
```

### 2) SENDING A NEW GENERATED FINE TO ANOTHER VEHICLE

Algorithm 2 shows the main steps followed by a vehicle that detects a speed limit infraction, and it is not inside the SS of any RSU. When a vehicle that is not in the SS of any RSU detects a speed limit infraction, it generates the corresponding fine, but before broadcasting it, the vehicle checks if it has not previously broadcasted the same fine (see Line 1).

If the fine has already been transmitted, there are two possible scenarios described between Lines 4 and 10. In the first scenario, the fine was not currently stored and has not previously been sent directly to any RSU (see Line 5). In this scenario, the generated fine is stored but not disseminated (see Line 6). The reason why the fine is stored is that 3DP considers that a fine can be eliminated from the buffer only if there is a high degree of certainty that an RSU received it, i.e., the fine was sent directly to an RSU. Otherwise, the fine is stored until the vehicle is in an optimal position to disseminate it. This way we increase the fine delivery rate, while mitigating the broadcast storm problem. The second scenario is when the fine is currently stored or has previously been sent directly to an RSU, in which case the generated fine is discarded (see Line 8).

On the other hand, if the generated fine has not been previously broadcasted, the vehicle that detected the speed limit infraction selects the next-hop target candidates following Algorithm 3 (see Line 2). After analyzing the target candidates with Algorithm 4, the source vehicle chooses the best target vehicle under its transmission range to continue the dissemination of the fine towards any RSU and broadcasts the corresponding fine message with the new generated fine (see Line 3).

According to Algorithm 3, for selecting the target vehicle, first, the sender vehicle refreshes its neighbors' table by eliminating all neighbors from which a message has not been received in the last three seconds (see Line 1). Vehicles share their beacons every 1 second, so 3 seconds proved to be a good timeout in our tests to detect neighbors leaving the transmission range of a vehicle. If there are no neighbors, the generated new fine is stored only if it is not currently stored and has not previously been sent directly to any RSU (see Lines 22 to 26). On the contrary, if there are neighbors the vehicle analyzes them for selecting three types of candidate targets: possible target inside SS (*ptSS*), possible target inside AOI (*ptAOI*), and possible target outside AOI (*pt*). The target selection process is shown from Line 3 to Line 21.

**Algorithm 2** The Source Vehicle Detecting a New Speed Limit Infraction or Receiving a Fine Message, Forwards the Fine/Fines to Another Vehicle in Its Neighborhood. The Target Next-Hop Vehicle Is Chosen According to Alg. 3 and Alg. 4

**Input:** New *fine generated* (*gf*) in the current vehicle, or new *fine/s received* (*rfs*) at the current vehicle.

```
if the new gf or rfs were not previously broadcasted then
    select next-hop candidate targets (see Alg. 3);
    select the final target next-hop vehicle and broadcast a
    fine message with the new gf or rfs (see Alg. 4);
else
    if the new gf or rfs are not stored and have not yet been
    sent directly to any RSU then
        store the new gf or rfs;
    else
        discard the new gf or rfs;
    end if
end if
```

The *ptSS* is the neighbor that is closest to an RSU and it is inside the SS. Similarly, the *ptAOI* is the neighbor that is closest to an RSU and it is inside the AOI. Finally, the *pt* is the neighbor located outside the AOI with the maximum gain ($g$). We define a gain $g_i$ associated to each candidate (vehicle$_i$) to be a target vehicle, as follows:

$$g_i = \alpha \cdot Dis_i + \beta \cdot Dens_i + \gamma \cdot Pos_i, \tag{1}$$

where $\alpha, \beta, \gamma \in [0, 1]$ and $\alpha + \beta + \gamma = 1$ to respectively weight the impact of the distance ($Dis_i$), the density ($Dens_i$), and the position factor ($Pos_i$) over the gain ($g_i$).

The distance ($Dis_i$) is the relation of the distance between the sender of the fine message and a potential receiver (vehicle$_i$) of that message within its transmission range:

$$Dis_i = \frac{\text{distance between the current fine sender and the potential next forwarder (vehicle}_i\text{) of the fine}}{\text{vehicle's transmission range}}. \tag{2}$$

The vehicles' density ($Dens_i$) is computed as the relation between the number of neighboring vehicles of a potential receiver (vehicle$_i$), and the maximum vehicles' density of the vehicles within transmission range:

$$Dens_i = \frac{\text{vehicles' density of the potential next forwarder (vehicle}_i\text{) of the fine}}{\text{maximum vehicles' density within the transmission range}}. \tag{3}$$

Finally, the vehicle' position factor ($Pos_i$) is computed as the relation between the distance from the potential next forwarder (vehicle$_i$) of the fine to its closest RSU, and its maximum value within transmission range:

$$Pos_i = 1 - \frac{\text{distance from the potential next forwarder (vehicle}_i\text{) of the fine to its closest RSU}}{\text{maximum distance to closest RSU within the transmission range}}. \tag{4}$$

Notice that $Dis_i$, $Dens_i$ and $Pos_i$ are defined in the range [0, 1]. The idea is that we prefer vehicles farther away from the current vehicle sending the fine message ($Dis_i \rightarrow 1$), with a higher vehicles' density ($Dens_i \rightarrow 1$) and closest to any RSU ($Dens_i \rightarrow 1$).

Since the gain defined in eq. (1) is a multimetric score where each metric has its weight ($\alpha, \beta, \gamma$), instead of using fixed weights, the Dynamic Self-configured Weights (DSW) algorithm [28] is used to select them dynamically. By dynamically selecting the weights, the current sender vehicle will select the best possible target accurately among its neighbors. For simplifying the explanation about the dynamically selection of the weights, the metrics *Dis*, *Dens*, and *Pos* will be referred as $u_1$, $u_2$, and $u_3$, respectively.

Let us define the vector $R = [R_1, R_2, R_3]$ as the variation value for each metric $m$ ($1 \le m \le 3$) between time $t1$ and time $t2$, where $t2 > t1$. The vector $R$ can be expressed as follows:

$$R = \begin{cases} R_1 = \dfrac{[u_1(t_2) - \overline{u_1}(t_2)] - [u_1(t_1) - \overline{u_1}(t_1)]}{2} \\ R_2 = \dfrac{[u_2(t_2) - \overline{u_2}(t_2)] - [u_2(t_1) - \overline{u_2}(t_1)]}{2} \\ R_3 = \dfrac{[u_3(t_2) - \overline{u_3}(t_2)] - [u_3(t_1) - \overline{u_3}(t_1)]}{2}, \end{cases} \tag{5}$$

where $0 \le u_m(t_1), u_m(t_2), \overline{u_m}(t_1), \overline{u_m}(t_2) \le 1 \ \forall \ m \in [1, 3]$. $u_m(t_1)$ and $u_m(t_2)$ are the current scores of each metric $m$ for times $t1$ and $t2$, respectively. $\overline{u_m}(t_1)$ and $\overline{u_m}(t_2)$ are the average score values of each metric $m$ computed for all the neighbors of the current forwarding node. If $R_m < 0$ means that metric $m$ is getting worst in the period of ($t2 - t1$). Consequently, $R_m$ should be set to zero. Due to $R_m$ is not guaranteed to be between [0, 1], the maximum value $R_{max} = R_x$ where $x \in [1, 3]$ is used to normalize this vector creating the normalized vector $S$ which is:

$$S = \left[\frac{R_1}{R_{max}}, \frac{R_2}{R_{max}}, \frac{R_3}{R_{max}}\right]. \tag{6}$$

Now, to ensure that the sum of all weights is equal to one, we calculate the parameter $\xi$ using the following equation:

$$\xi = \frac{1}{\sum_{i=1}^{3} S_i}. \tag{7}$$

Finally, the new normalized vector of weights $W$ is:

$$W = \begin{cases} \alpha = S_1 \times \xi \\ \beta = S_2 \times \xi \\ \gamma = S_3 \times \xi. \end{cases} \tag{8}$$

Thus, instead of using fixed values to $\alpha$, $\beta$, and $\gamma$, these values were calculated dynamically with eq. (8). It is

**Algorithm 3** Selection of Candidate Targets (i.e., Possible Vehicles) to Be Chosen (Using Alg. 4) as the Next-Hop to Forward the Fine Towards the Closest RSU

**Data:**
*NT*: Neighbors' table, i.e. list of vehicles within transmission range.
*ptSS*: Possible target vehicle (to forward the fine) inside the SS area.
*dSS*: Distance between the *ptSS* and its closest RSU.
*ptAOI*: Possible target vehicle (to forward the fine) located inside the AOI.
*dAOI*: Distance between the *ptAOI* and its closest RSU.
$g_i$: Current gain obtained if vehicle$_i$ is selected to forward the fine. Equation (1) shows how $g_i$ is calculated.
*mg*: Maximum gain present among the vehicles within the transmission range (inside *NT*).
*pt*: Possible target vehicle (to forward the fine) located outside the AOI and with the maximum gain (*mg*).

**Input:** New fine generated (*gf*) in the current vehicle, or new fine/s (*rfs*) received at the current vehicle.

refresh *NT*
**if** *NT* contains at least one vehicle **then**
  **for** vehicles$_i$ in *NT* **do**
    **if** vehicle$_i$ is in *SS* **then**
      **if** distance from vehicle$_i$ to closest RSU $<$ *dSS* **then**
        *dSS* $\leftarrow$ distance from vehicle$_i$ to its closest RSU;
        *ptSS* $\leftarrow$ vehicle$_i$'s ID;
      **end if**
    **else if** vehicle$_i$ is in AOI **then**
      **if** distance from vehicle$_i$ to closest RSU $<$ *dAOI* **then**
        *dAOI* $\leftarrow$ distance from vehicle$_i$ to its closest RSU;
        *ptAOI* $\leftarrow$ vehicle$_i$'s ID;
      **end if**
    **else**
      **if** $g_i > mg$ **then**
        $mg \leftarrow g_i$
        *pt* $\leftarrow$ vehicle$_i$'s ID
      **end if**
    **end if**
  **end for**
  **return** *dSS*, *ptSS*, *ptAOI*, and *pt*;
**else**
  **if** the new *gf* or *rfs* are not stored **and** have not yet been sent directly **then**
    store the new *gf* or *rfs*;
  **end if**
**end if**

important to mention that in the unlikely case that all the metrics for a specific neighbor are getting worst, we cannot give preferences to any metric, i.e., $\alpha = \beta = \gamma = 1/3$. Moreover, since DSW algorithm can be applied from $t2$, at $t1$ the values of the weights start from the equal values: $\alpha = \beta = \gamma = 1/3$.

**Algorithm 4** Selection of the Next-Hop Best Target Vehicle and Dissemination of the Fine/Fines

**Data:**
*dt*: Distance threshold for considering direct sending.
*fm*: Fine message.

**Input:** *dSS*, *ptSS*, *ptAOI*, *pt*, new fine generated (*gf*) in the current vehicle, or new fine/s (*rfs*) received at the current vehicle.

1: **if** the new *gf* or *rfs* are not stored yet **and** have not yet been sent directly to an RSU **then**
2:   store the new *gf* or *rfs*;
3: **end if**
4: **if** there is a *ptSS* **then**
5:   set *ptSS* as the target of the *fm*;
6:   **if** $dSS < dt$ **then**
7:     add all stored fines to the *fm*;
8:     clear the stored fines from current vehicle;
9:   **else**
10:     add only the new *gf* or *rfs* to the *fm*;
11:   **end if**
12: **else**
13:   **if** there is a *ptAOI* **then**
14:     set *ptAOI* as the target of the *fm*;
15:   **else**
16:     set *pt* as the target of the *fm*;
17:   **end if**
18:   add only the new *gf* or *rfs* to the *fm*;
19: **end if**
20: remove in the *fm* all the fines that have already been forwarded to avoid sending them twice;
21: the current vehicle broadcasts the *fm* that contains the fine/s that have not yet been forwarded;

Once the candidate targets (i.e., possible vehicles to forward the fine message) have been selected using Algorithm 3, Algorithm 4 describes how the final target vehicle is chosen to forward the fine in the next-hop towards an RSU. First, the vehicle stores the new fine if it is not stored yet and has not previously been sent directly to an RSU (see Lines 1 and 2). After that, the vehicle verifies if there is a *ptSS* since it will be the best-suited vehicle to continue the dissemination of the fine (see Line 4). If there is such a target vehicle, the current sender sets it as the target of the fine message (see Line 5). Additionally, the current sender checks the distance between that target vehicle and its nearest RSU (see Line 6). If this distance is less than a specified threshold ($dt$), then all the stored fines are added to the message (see Line 7), and then the stored fines are eliminated from the buffer of the current vehicle (see Line 8); otherwise, only the new fine currently generated is included in the message (see Line 10). However, if there is no *ptSS*, the target will be the *ptAOI* if it exists (see Line 14) or the *pt* if it does not (see Line 16), and only the new fine is added to the message (see Line 18). Finally, before broadcasting the fine message (see Line 21), the vehicle removes the fines that have already been forwarded from the message to avoid sending them twice (see Line 20).

#### 3) REBROADCASTING A RECEIVED FINE MESSAGE

As stated in Algorithm 5, when a vehicle receives a fine message, it checks if its ID is equal to the message's target (see Line 1). If its ID matches the target there are two cases: (i) the vehicle that receives the message is inside the SS of an RSU and its distance to the RSU is less than *dt* (see Line 2); or (ii) it is not the case (see Line 4). In the first case, the vehicle forwards the incoming message to its closest RSU following the process described in Algorithm 1 (see Line 3). On the other hand, if it is not inside the SS of any RSU, the vehicle follows Algorithm 2 to select the next-hop target vehicle to continue the dissemination of the received fine message until reaching an RSU (see Line 5). Finally, if its ID does not match the target, the vehicle stores all the fines of the message that were not stored yet and have not yet been sent directly to an RSU (see Lines 8 and 9).

**Algorithm 5** A Vehicle That Receives a Fine Message Continues the Dissemination Process

**Data:**
- *v*: Current vehicle.
- *p*: Position of the current vehicle.
- *dt*: Distance threshold for considering direct sending.

**Input:** New fine/s (*rfs*) received at the current vehicle.

```
1:  if target of received message == current vehicle's ID then
2:      if p is inside SS of any RSU and distance from v to its closest RSU < dt then
3:          follow the process described in Algorithm 1 using the new rfs as input;
4:      else
5:          follow the process described in Algorithm 2 using the new rfs as input;
6:      end if
7:  else
8:      if the new rfs were not stored yet and have not yet been sent directly then
9:          store the new rfs;
10:     end if
11: end if
```

## IV. PERFORMANCE EVALUATION

In this section, we carry out a set of comprehensive simulations to evaluate the performance of our proposed architecture using different dissemination protocols, including our approach 3DP. First, we present the simulation scenario followed by the discussion of the obtained simulation results.

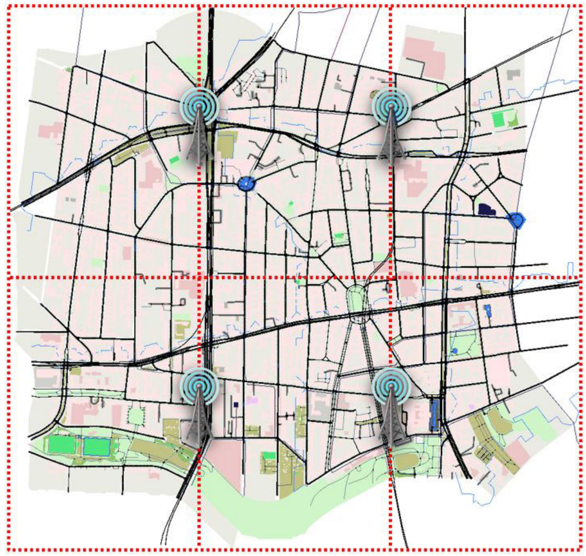

**FIGURE 3.** Map extracted from OpenStreetMap [31] corresponding to an area of 1.9 km × 1.6 km from Berlin, Germany.

### A. SIMULATION SCENARIO

To evaluate the performance of the proposed framework, we have used the vehicular network simulator OMNeT++ 5.5.1 [29]. In this simulation manager, we include the VEINS 5.0 simulator for vehicular networks [30]. For assessing the system in a realistic scenario, a real map of 1.9 km × 1.6 km from Berlin, Germany, was extracted from the OpenStreetMaps platform [31]. This map was chosen because it contains different kinds of roads, such as highways, urban areas and roundabouts. Moreover, for simulating real traffic, this study used the Simulator for Urban MObility 1.2.0 (SUMO) [32]. Finally, the map was divided into six rectangles of the same dimensions to control the speed limit by zones; each zone had a different speed limit. Fig. 3 illustrates the zones and the position of the four RSUs available in the map.

We tested the proposed system using two scenarios with four and five different vehicles' densities, respectively. The first scenario has low vehicles' densities with 10, 20, 30, and 40 vehicles per km$^2$. The second scenario evaluates the dissemination protocols' performance with higher vehicles' densities: 50, 100, 150, 200 and 250 vehicles per km$^2$. Every simulation was executed ten times to include 90% confidence intervals. At the beginning of each simulation, the vehicles' speed and position were randomly generated by SUMO to ensure randomness among the different simulations. Table 1 presents the details of the simulation settings.

In Table 1, the percentage of offending vehicles corresponds to the vehicles that exceed by at least 20% the speed limit. The main motivation of the simulations was to evaluate the proposed dissemination protocol and the proposed framework of an automatic speed fine system. To verify the efficiency of 3DP we compare its performance to the following dissemination protocols, described in Section II-B,

**TABLE 1. Simulation settings.**

| Protocol | Parameters | Values |
|---|---|---|
| General | Simulation time | 100 s |
| | Simulation runs | 10 |
| | Simulation area | 1.9 km $\times$ 1.6 km |
| | Vehicles distribution | Random |
| | Percentage of vehicles exceeding speed limit | 60% |
| | Vehicles' density (veh/km$^2$) | 10,20,30,40,50, 100,150,200,250 |
| | Total number of RSUs | 4 |
| | MAC Protocol | IEEE 802.11p |
| | Bit rate | 2 Mbps |
| | Transmission power | 20 mW |
| | Transmission range | 700 m |
| 3DP | Sweet Spot radius | 700 m |
| | Distance threshold for considering direct sending ($dt$) | 350 m |
| | $\alpha, \beta, \gamma$ | dynamically updated with DSW [28] |
| AddP [21] | Fixed minimum timeout to wait for a beacon ($P_f$) | 1 s |
| | Additional time added by each vehicle to the beacon timeout ($TpV$) | 0.02 s |
| | Minimum delay before rebroad-casting a fine message ($Ti$) | 1.1 s |
| | Influence of the distance and density over the gain ($w$) | 0.5 |
| DRIVE [20] | Sweet Spot Radius | 700 m |
| DBF [18] | Maximum delay for retransmission | 3 s |
| TBN [18] | Maximum delay for retransmission | 3 s |

since they share some features with our protocol: AID [17], DBF [18], TBN [18], DRIVE [20], and AddP [21].

### B. PERFORMANCE EVALUATION METRICS

Four key performance indicator (KPI) are used to assess our proposed smart multimetric dissemination protocol compared to the other protocols mentioned above:

- Total number of fines transmitted (FT): The total number of new fines detected and sent by the vehicles. We count the new fines produced by vehicles that detect a speed infraction committed by themselves or by a vehicle around within their transmission range.
- Fine delivery ratio (FDR): The percentage of fines received in the RSUs concerning the total number of infractions committed by the vehicles. This KPI will tell us how effective our proposal is, i.e., how much different fines were successfully delivered at any RSU to be further processed by the competent authority. Note that since an infraction could be detected by multiple vehicles which would send the same fine message, RSUs must be able to eliminate duplicate fines.
- Average percentage of packet collisions (PC): The total average percentage of packet collisions measured during the simulation. This KPI will tell us how efficient is our proposal of a smart multimetric dissemination protocol.
- Total number of packets transmitted (PT): The total number of packets transmitted by the vehicles during the simulation. This KPI includes packets carrying fines and re-transmitted packets due to collisions or losses.

The FT and FDR KPIs help us to evaluate the effectiveness of the proposed automatic speed fine framework, whereas the PC and PT KPIs help us to analyse the performance of the dissemination protocols in the MAC layer.

### C. SIMULATION RESULTS

This section discusses the performance of our proposed smart multimetric dissemination protocol 3DP compared to five well-known and highly used dissemination protocols. Fig. 4 shows the simulation results under low vehicles' densities. In Fig. 4(a), it can be seen that the total number of fines transmitted (FT) is almost the same for every protocol since, in our proposed architecture, each vehicle can detect its own as well as its neighbors' infractions. On the other hand, Fig. 4(b) shows how 3DP achieves the highest fine delivery ratio (FDR) under low vehicles' densities. Even with 20 vehicles per km$^2$, 3DP manages to achieve a good delivery rate above 80%, proving its robustness under sparse scenarios. On the contrary, the other evaluated protocols achieved similar results among them, but their FDR is around 10% lower than that of 3DP.

The average percentage of packet collisions (PC) is shown in Fig. 4(c). The results depicted in this figure show that 3DP is the protocol that produces fewer collisions under low vehicles' densities. Even with a density of 40 vehicles per km$^2$, 3DP produces just 0.14% of collisions, around 13 times less than the PC produced by AID, DRIVE, DBF, and TBN. In contrast, AddP was the protocol with the highest average percentage of packet collisions with 4.36%. Nevertheless, this result can be explained because AddP increases the frequency of beacons transmission in low vehicles' densities.

Finally, Figs. 4(d) depicts the total number of packets transmitted (PT) by each protocol. As in the previous results, AddP transmits the highest amount of packets because of the short delay time between each beacon. On the contrary, 3DP is the protocol that transmits the lowest amount of packets because it avoids sending the same message twice. This characteristic of 3DP is crucial for mitigating the broadcast storm problem.

On the other hand, Fig. 5 presents the simulation results under high vehicles' densities. Fig. 5(a) shows how as vehicles' density increases, the total number of transmitted fines (FT) begins to vary from one protocol to another. Even though AddP transmitted fewer fines than the other protocols, it does not mean that AddP detects fewer infractions. In fact, all protocols always detect 100% of the infractions. However, the variation occurs because, in high vehicles' densities, some vehicles do not receive their neighbors' beacons due to losses or collisions. Therefore, it is very important that each vehicle can detect its own infractions to guarantee the detection of all infractions in any scenario, i.e., either under low or high-density scenarios.

Fig. 5(b) shows that as with low vehicles' densities, 3DP achieves the highest fine delivery ratio (FDR). From

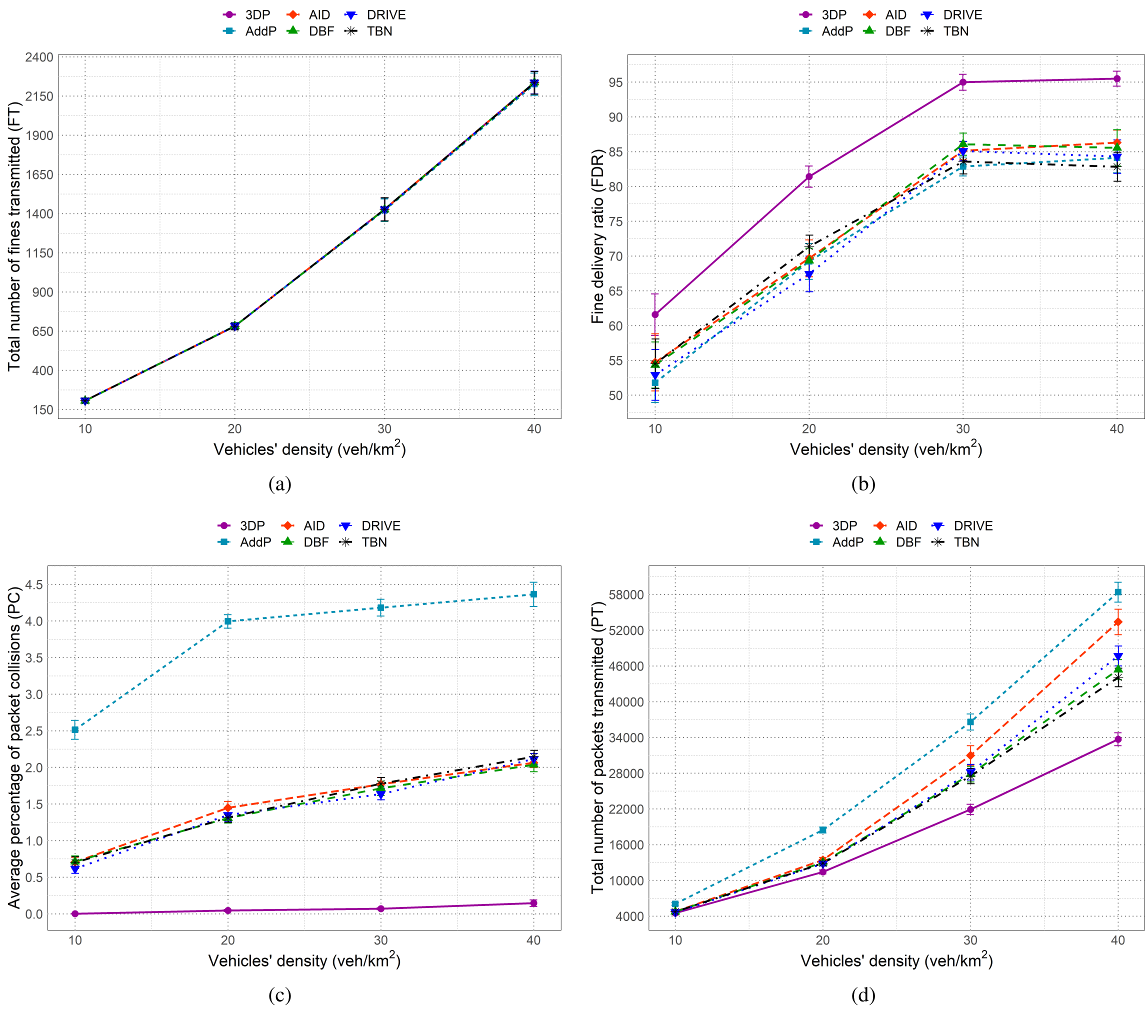


**FIGURE 4. Simulation results of all dissemination protocols under low vehicles' densities. (a) Total number of fines transmitted (FT). (b) Fine delivery ratio (FDR). (c) Average percentage of packet collisions (PC). (d) Total number of packets transmitted (PT).**

a density of 100 vehicles per km$^2$, the FDR of 3DP is almost 100%, with a maximum of 99.91% with a vehicles' density of 200 vehicles per km$^2$. As expected, increasing the vehicles' density decreases the difference between the 3DP FDR compared to the FDR obtained with the other protocols. Besides, from 200 vehicles per km $^2$, the FDR begins to decrease instead of increasing due to the channel's saturation produced by the high exchange of beacon messages.

Even under very high vehicles' densities, Fig. 5(c) shows how 3DP is capable of maintaining an average percentage of packet collisions (PC) less than 1.5%. On the other hand, although AddP was the worst protocol in terms of PC under low densities, DRIVE is the protocol that produces, on average, most collisions under high vehicles' densities. AddP improves its performance under high densities because as the vehicles' density increases, the delay between beacons also increases. On the contrary, DRIVE increases the PC because the number of vehicles within the SS increases at high densities. Since in DRIVE, the vehicles inside the SS are in charge of continuing the dissemination of the message, there will be a large emission of packets within the same area (SS), producing a higher probability of collision.

Finally, Fig. 5(d) illustrates the rapid increment in the total number of packets transmitted (PT) when the vehicles' density increases. As in low densities, 3DP manages to maintain a low number of packets transmitted in relation to the other protocols due to the fact that it avoids broadcasting the same fine twice. On the other hand, as explained above, the high number of packets transmitted using DRIVE is due to the high number of vehicles within the SS. In the case of AID, the high number of PT is because this protocol does not have a mechanism to prevent vehicles from sending the same message more than once; it only uses a re-transmission inhibition mechanism based on a dynamic counter. However, a high number of packets transmitted and a high average percentage of packet collisions does not imply a low FDR since AID and DRIVE have a high PT and PC; however,

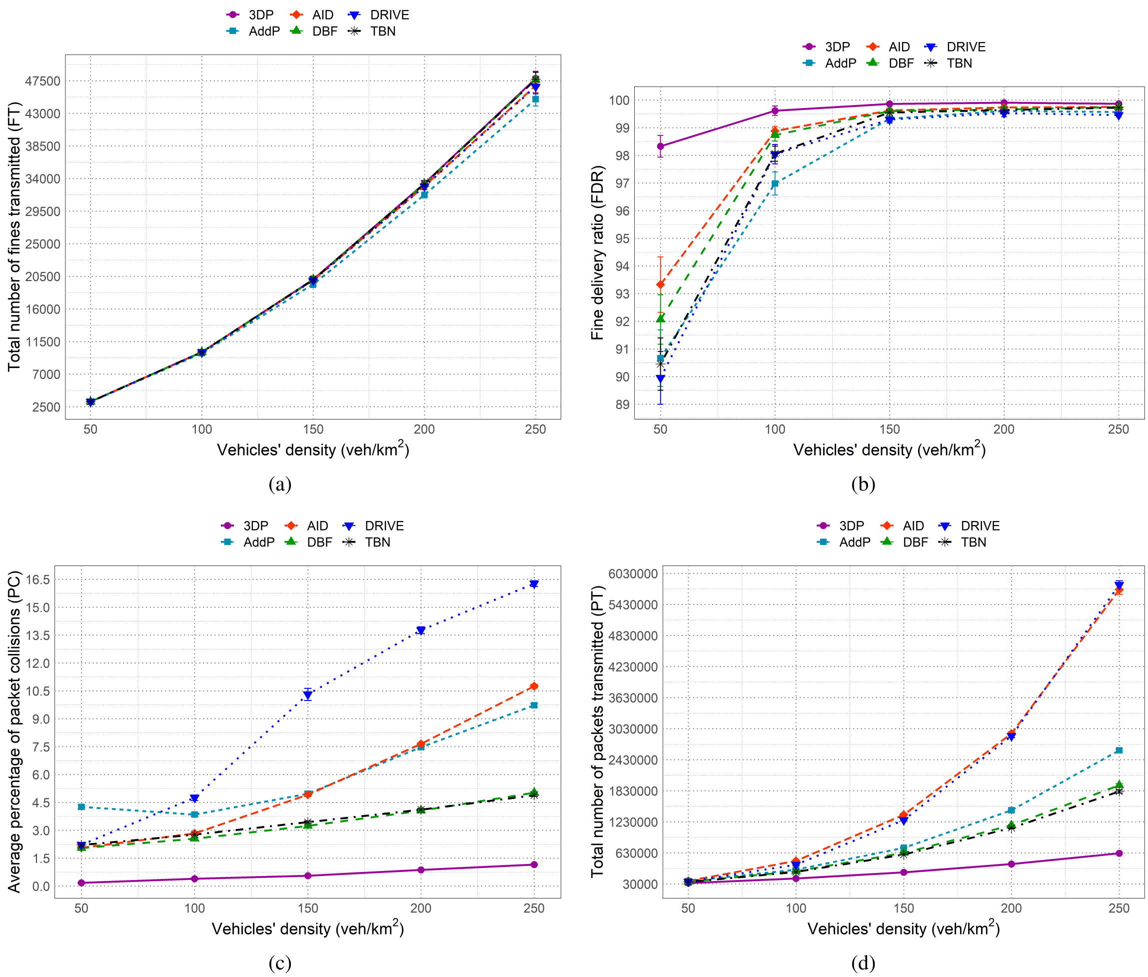


**FIGURE 5. Simulation results of all dissemination protocols under high vehicles' densities. (a) Total number of fines transmitted (FT). (b) Fine delivery ratio (FDR). (c) Average percentage of packet collisions (PC). (d) Total number of packets transmitted (PT).**

AID is the protocol with the highest FRD after 3DP, reaching 99.74% with 200 vehicles per km$^2$.

In general, the performance of 3DP is better in all the metrics with all the tested vehicles' densities. The results presented in Figs. 4 and 5 prove our protocol's efficiency in disseminating the generated fines across the vehicular network while keeping a low average packet collision without transmitting too many packets. The reasons for the success of 3DP are the store-carry-forward approach, sending a fine message only once, the direct transmission to the RSUs, and the target selection based on a multimetric combination of distance to candidates, vehicles' density, and position of candidates regarding the RSU.

### *D. IMPACT OF 3DP OVER THE FINES SYSTEM*

Our proposed system aims to generate fines when speed infractions are detected. According to the results shown in Figs. 4 and 5, our proposed dissemination protocol is the most suitable for being used with our proposed fine-detection architecture. With 20 veh/km$^2$, 3DP achieved a fine delivery rate of 81.42%; and with only 50 veh/km$^2$ its fine delivery rate increased to almost 100%, whereas the other tested protocols required around 100 veh/km$^2$ to achieve similar results.

Additionally, independently of the dissemination protocol, our proposed fine-detection architecture can detect, generate, and transmit the speed infractions from vehicles to RSUs. In our framework, all vehicles are used as radars capable of detecting their own and their neighbors' speed infractions, our system was able to detect 100% of the speed limit violations regardless of the vehicular density, taking into consideration that in this study, an infraction was considered if the vehicle speed exceeds the limit speed by at least 20%. Moreover, as the RSUs were only in charge of processing the received fines, they could be used to any other application without affecting the performance of the analysed fine-detection service. Finally, even though the speed limit zones in this study were established as rectangles for simplicity, they can be set to any other shape that best fulfills the scenario's requirements.

## V. CONCLUSION AND FUTURE WORK

In this article, we proposed an efficient system for automatic fine generation when speed limit infractions are detected.

The proposed system is composed of a specific architecture and a dissemination protocol. In the proposed architecture, all the vehicles work as radars generating the fines that the RSUs will process. Additionally, this architecture uses two types of messages: (1) beacon messages for detecting speed limit infractions and also for keeping updated a neighbors' table; and (2) fine messages used to disseminate the generated fines across the vehicular network till the fine message reaches an RSU. The proposed architecture has shown to be efficient regardless of the vehicles' density in terms of the total number of fines transmitted (FT), fine delivery ratio (FDR), the average percentage of packet collisions (PC), and the total number of packets transmitted (PT).

On the other hand, our proposed smart multimetric dissemination protocol 3DP, achieved a fine delivery ratio FDR = 99.91% with a density of 200 veh/km$^2$. Furthermore, this protocol was better than AID, DRIVE, DBF, TBN, and AddP in either low and high vehicles' densities. Also, the average percentage of packet collisions (PC) and the total number of packets transmitted were lower when using 3DP. Consequently, we conclude that our proposed architecture using our proposed smart multimetric dissemination protocol provides a robust fine generator system for a typical urban scenario.

Our future work includes integrating more traffic violations such as red-light infractions. Also, we plan to incorporate security into the architecture to check the legitimacy of the received fines on the RSUs for avoiding possible man-in-the-middle attacks. Moreover, an analysis of the efficiency of the proposed architecture and dissemination protocol on a highway environment will be performed.

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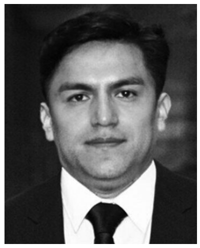
**DUSTIN CARRIÓN-OJEDA** (Student Member, IEEE) received the B.E. degree in information technology engineering from Yachay Tech University, Ecuador, in 2020. His research interests include artificial intelligence applications, electroencephalogram-based biometric systems, and vehicular networks.



**CRISTHIAN IZA** received the M.Sc. degree from the Universitat Autònoma de Barcelona (UAB), in 2017, and the Ph.D. degree in engineering from the Universitat Politécnica de Catalunya (UPC), in 2018. He was a Visiting Scholar with the research group of the École Normale Supérieure de Lyon, in 2017. He is currently a Full Professor at the School of Mathematical and Computational Sciences, Yachay Tech University. Since 2020, he serves as a member of the Scientific Computing Group, heading the Cooperative Mobile Systems Group, Department of Computer Science, Yachay Tech University. His research interests include data dissemination and privacy of vehicle-to-X communication in heterogeneous environments.

**MÓNICA AGUILAR IGARTUA** received the M.Sc. and Ph.D. degrees in telecommunication engineering from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 1995 and 2000, respectively. She is currently an Associate Professor at the Department of Network Engineering, UPC. She is the author of more than 25 journal articles, has chaired several conferences, and is a member of the Editorial Board of the *Ad Hoc Networks* journal. Her research interests include design and performance evaluation of routing protocols to distribute multimedia services over vehicular *ad-hoc* networks (VANETs). Lately, her research activity focuses on the integration of electric vehicles and autonomous vehicles in vehicular networks and their interaction with smart grids and smart cities.