Evaluating the impact of the enhanced Street Broadcast Reduction scheme using real maps in VANETs

Manuel Fogue, Piedad Garrido, Francisco J. Martinez

University of Zaragoza, Spain
Email: {m.fogue, piedad, f.martinez}@unizar.es

Juan-Carlos Cano, Carlos T. Calafate, Pietro Manzoni

Universitat Politècnica de València, Spain
Email: {jucano, calafate, pmanzoni}@disca.upv.es

Abstract

In traffic safety applications for *Vehicular ad hoc networks* (VANETs), some warning messages have to be urgently disseminated in order to increase the number of vehicles receiving the traffic warning information. In those cases, redundancy, contention, and packet collisions due to simultaneous forwarding (usually known as the broadcast storm problem) are prone to occur. In the past, several approaches have been proposed to solve the broadcast storm problem in multi-hop wireless networks such as *Mobile ad hoc Networks* (MANETs). Among them we can find counter-based, distance-based, location-based, cluster-based, and probabilistic schemes, which have been mainly tested in non-realistic simulation environments. In this paper, we present the *enhanced Street Broadcast Reduction* (eSBR), a novel scheme specially designed to increase the percentage of informed vehicles and reduce the notification time; at the same time, it mitigates the broadcast storm problem in real urban scenarios. We evaluate the impact that our scheme has on performance when applied to VANET scenarios based on real city maps, and the results show that it outperforms previous schemes in all situations.

Keywords:
Vehicular ad-hoc networks, warning message dissemination, broadcast storm, inter-vehicular communication, real maps.

1. Introduction

Vehicular ad hoc networks (VANETs) are wireless communication networks that do not require any sort of fixed infrastructures, offering a novel networking paradigm to support cooperative driving applications on the road. VANETs are characterized by: (a) constrained but highly variable network topology, (b) specific speed patterns, (c) time and space varying communication conditions (e.g., signal transmissions can be blocked by buildings), (d) road-constrained mobility patterns, and (e) no significant power constraints.

Many possible applications, ranging from inter-vehicle communication and file sharing, to obtaining real-time traffic information (such as jams and blocked streets), can benefit of the use of VANETs. In this work we focus on traffic safety and efficient warning message dissemination applications, where the objective is to reduce the latency and to increase the accuracy of the information received by nearby vehicles when a dangerous situation occurs, e.g., an accident, a traffic jam, etc.

In dense wireless vehicular environments (e.g., urban scenarios), an accident may cause many vehicles to send warning messages, and using a simple blind broadcast protocol will cause all vehicles within the transmission range, receiving the broadcast transmissions, to rebroadcast those messages. Hence, a broadcast storm (Tseng Y.-C. et al., 2002) may occur and any useful algorithm for information dissemination should incorporate mechanisms to avoid redundancy, contention and massive packet collisions due to simultaneous forwarding. In the past, several schemes have been proposed to avoid or alleviate the broadcast storm problem. However, they have been specifically proposed for MANETs and have only been validated using simple scenarios such as a highway (several lanes, without junctions) (Suriyapaibonwattana and Pomavalai, 2008; Suriyapaiboonwattana et al., 2009), or a Manhattan-style grid scenario (Korkmaz et al., 2004).

In this work, we propose a novel scheme called *enhanced Street Broadcast Reduction* (eSBR), which uses location and street map information to facilitate an efficient dissemination of warning messages in 802.11p (Task Group p, 2006) based VANETs. We evaluate the performance of our eSBR proposal in a realistic urban scenario, that is, obtained from real maps of existing cities, and demonstrate how our approach could benefit drivers on the road.

This paper is organized as follows: Section 2 reviews the related work on the broadcast storm problem in wireless ad hoc networks and delay-tolerant strategies proposed to improve message dissemination in intermittently connected networks. Section 3 describes our eSBR scheme and details its functionality using a real map scenario; for the sake of clarity, we also provide a formal definition of our proposal using set theory. Section 4 presents the simulation environment. Simulation results are then discussed in Section 5. Finally, Section 6 concludes this paper.

2. Related Work

2.1. On the broadcast storm problem in wireless networks

In VANETs, intermediate vehicles act as message relays to support end-to-end vehicular communications. For applications such as route planning, traffic congestion control, and traffic safety, the flooding of broadcast messages might be considered a straightforward approach to achieve a wide-spread dissemination. However, if flooding is done blindly, broadcast storms may arise, with several disadvantages to the dissemination process (Tseng Y.-C. et al., 2002):

- Many redundant rebroadcasts: a physical location may be covered by the transmission ranges of several hosts, making subsequent rebroadcasts unnecessary.
- Heavy channel contention: in dense networks, after a vehicle broadcasts a message and many of its neighbors decide to rebroadcast it, these transmissions will contend with each other since all neighbors are located near the sender.
- Long-lasting message collisions: in a CSMA/CA network (like the one studied), not using specific collision detection mechanisms causes collisions to be more likely to occur and cause more damage.

Over the years, several schemes have been proposed to address the broadcast storm problem in wireless networks. In Tseng Y.-C. et al. (2002) we can find some of the most interesting approaches, which are the following:

1. The *Counter-based scheme*. To mitigate broadcast storms, this scheme uses a threshold C and a counter c to keep track of the number of times the broadcast message is received. Whenever $c \geq C$, rebroadcast is inhibited.
2. The *Distance-based scheme*. In this scheme, authors use the relative distance d between vehicles to decide whether to rebroadcast a message or not. It is demonstrated that, when the distance d between two

vehicles is short, the *additional coverage* (AC) of the new rebroadcast is lower, and so rebroadcasting the warning message is not recommended. If d is larger, the additional coverage will also be larger.

3. The *Location-based scheme* is very similar to the distance-based scheme, though requiring more precise locations for the broadcasting vehicles to achieve an accurate geometrical estimation (with convex polygons) of the AC of a warning message. Since vehicles usually have GPS systems on-board, it is possible to estimate the additional coverage more precisely. The main drawback of this scheme is the high computational cost of calculating the AC, which is related to calculating many intersection areas among several circles.

Note that all these previous schemes alleviate the broadcast storm problem by inhibiting certain vehicles from rebroadcasting, reducing message redundancy, channel contention, and message collisions. In particular, they inhibit vehicles from rebroadcasting when the *additional coverage* (AC) area is very low. Overall, Tseng Y.-C. et al. (2002) demonstrated that a rebroadcast can only provide up to 61% additional coverage over that area already covered by the previous transmission in the best case (on average, the additional area is of 41%).

Additional efforts to find efficient solutions to the broadcast storm problem can be found in the following works:

1. The *weighted p-persistence*, the *slotted 1-persistence*, and the *slotted p-persistence* techniques presented in Wisitpongphan N. et al. (2007) are some of the few rebroadcast schemes proposed for VANETs. These three probabilistic and timer-based broadcast suppression techniques can mitigate the severity of the broadcast storms by allowing nodes with higher priority to access the channel as quickly as possible, but their ability to avoid storms is limited. These schemes are specifically designed for use in highway scenarios.
2. *The Last One* (TLO) scheme (Suriyapaibonwattana and Pomavalai, 2008) tries to reduce the broadcast storm problem by finding the most distant vehicle from the warning message sender, so that this vehicle will be the only one allowed to retransmit the message. This method uses GPS information from the sender vehicle and the possible receivers to calculate the distance. Although it brings a better performance than simple broadcast, this scheme is only effective in a highway scenario because it does not take into account the effect of obstacles (e.g., buildings) in urban radio signal propagation. More-

over, the scheme does not clearly state how a node knows the position of nearby vehicles at any given time.

3. The TLO scheme was extended using a protocol named *Adaptive Probability Alert Protocol* (APAL), which uses adaptive wait-windows and adaptive probability to transmit (Suriyapaiboonwattana et al., 2009). This scheme shows even better performance than the TLO scheme, but it is also only validated in highway scenarios.
4. A stochastic broadcast scheme is proposed by Slavik and Mahgoub (2010) to achieve an anonymous and scalable protocol where relay nodes rebroadcast messages according to a retransmission probability. The performance of the system depends on the vehicle density, and the probabilities must be tuned to adapt to different scenarios. However, the authors only test this scheme in an obstacle-free environment, thus not considering urban scenarios where the presence of buildings could interfere with the radio signal.
5. The *Cross Layer Broadcast Protocol* (CLBP) (Bi et al., 2010) uses a metric based on channel condition, geographical locations and velocities of vehicles to select an appropriate relaying vehicle. This scheme also supports reliable transmissions exchanging *Broadcast Request To Send* (BRTS) and *Broadcast Clear To Send* (BCTS) frames. CLBP reduces the transmission delay but it is only conceived for single-direction environments (like highway scenarios), and its performance in urban environments has not been tested.

It is easily noticeable that most existing solutions to the broadcast storm problem were only evaluated in obstacle-free environments, which are not comparable to real urban scenarios where plenty of obstacles can interfere with the signal, creating blind areas where vehicles will not receive the warning message unless intermediate forwarding nodes help to overpass the obstacle. This effect is shown in Figure 1, which includes an example of wireless signal propagation in a real city scenario obtained from Google Maps. If vehicle A is trying to broadcast a warning message, a basic radio propagation model will consider that all vehicles within its transmission range (vehicles B and C) would receive it. However, if we account for buildings as obstacles, there will be a blind area (dark area in the figure) that will impede vehicle C from receiving the message if vehicle B decides not to rebroadcast it.

The effect of obstacles in warning message dissemination has been addressed by other proposed schemes, specifically designed for information propagation in urban areas. Some of the most interesting pieces of work in this area are the following:

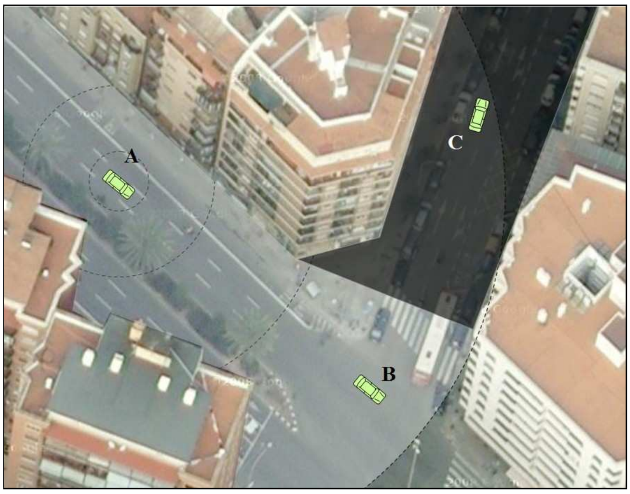


Figure 1: Example of wireless signal propagation in an urban scenario extracted from Google Maps. The lightest area represents the transmission range in a obstacle free environment, and the darkest area indicates the zone where the signal would not be propagated due to blocking by the nearby building.

1. **Costa et al. (2006) presented an approach where a message propagation function encodes information about target areas and preferred routes for the message dissemination. Selecting different functions produces different routing protocols accounting for connected and disconnected situations between vehicles. These protocols show a remarkable performance in simple grid-like scenarios with low and high density of vehicles, but real maps are not used in their simulations. Moreover, this scheme requires to define target zones for the messages to obtain optimal results, which is not always possible.**
2. **The UV-CAST (Urban Vehicular broadCAST) protocol (Viriyasitavat et al., 2010) allows reducing the broadcast storm problem while solving disconnected network problems in urban VANETs. It defines a region of interest for each VANET application, and the propagation is adapted to maximize the number of informed vehicles in this region. Despite showing good results in a scenario obtained from the city of Pittsburgh, this scheme is not compared with other protocols that could produce similar results. In addition, the density of ve-**

hicles studied is relatively low and the authors do not study its performance when there are more than 50 vehicles/km^2.

3. **The RPB-MD protocol (Liu and Chigan, 2012) is a message dissemination (MD) approach with a relative position based (RPB) addressing model that allows defining the intended receivers in the zone of relevance. Simulation results show high delivery ratio and low data overhead; however, the scenario used is a single bidirectional highway, and the Radio Propagation Model selected is the deterministic Two-Ray Ground. Hence, we consider that this proposal should be revised to ensure that results are comparable to real ones obtained from existing urban scenarios.**

Overall we find that, even if the utility of these schemes is proven, none of them is designed to improve the dissemination and reduce the warning notification time by making use of the topology of the area where the propagation takes place, since they only use basic metrics such as the distance or the relative angles between vehicles. Our work includes additional knowledge about the roadmap to determine the optimal set of relaying vehicles.

2.2. VANETs as Delay-Tolerant Networks (DTN)

The vehicles in a VANET are, typically, sparsely spread across the roadmap, forming time-varying clusters of nodes due to the distance between vehicles and the effect of building blocking the wireless signal. This environment is subject to disruption, disconnection and long delay. Hence, there is not always a complete path of forwarding nodes from the source to every possible destination. Hence, VANETs can be considered a *Delay-Tolerant Network* (DTN) where routes must be found over intermittently-connected hops. Routing strategies for DTNs can be divided into two main groups: flooding strategies and forwarding strategies.

In the flooding family, each node delivers multiple copies of each message to other nodes, which act as relays, without using prior information about the network structure. Jones and Ward (2006) present some examples of these protocols, such as *Direct Contact* (data transmitted in one hop), *Two-Hop Relay*, and *Tree-Based Flooding* (more than two hops). In epidemic routing (Vahdat and Becker, 2000), all nodes will eventually receive all messages, obtaining a maximum delivery ratio at the cost of consuming network resources (channel, buffer, etc.) heavily.

Algorithms in the forwarding family require to add some knowledge about the network that is used to select the best path from the source to the destination. The simplest approach is using a distance metric to estimate the cost of delivering messages between nodes (*Location-Based Routing*). Other more sophisticated schemes such as the *Per-Hop Routing*, where the forwarding decision is made by the intermediary node which determines the next hop, and the *Per-Contact Routing*, where the routing table is recomputed each time a contact is available, are presented in Jones et al. (2005).

Again, all the existing DTN schemes have been only tested in simple scenarios, where all the nodes are in line-of-sight, and the decision whether to transmit a message or not is taken only based solely on the presence of other nodes, not on the specific layout. Including information about the scenario could help at improving the warning dissemination process, especially when integrated maps are available in the vehicles. In addition, the amount of resources needed to implement these strategies are not necessary in our proposal, since it does not store any message in queues or buffers for future relays.

Finally, our work is mainly focused on improving traffic safety by rapidly informing as many vehicles as possible. A high delay between the time when a dangerous situation takes place and its notification time makes the system become useless; thus, typical delay-tolerant schemes do not fulfill our requirements.

3. The enhanced Street Broadcast Reduction scheme in real maps

In this section, we present the *enhanced Street Broadcast Reduction scheme* (eSBR) - our novel proposal which takes into account the effect that buildings have over the signal propagation to improve message dissemination in real urban scenarios. At the frequency of 5.9 GHz (i.e., the frequency band adopted by the 802.11p standard), radio signals are highly directional and will experience a very low depth of penetration in urban scenarios. Hence, in most cases, buildings will absorb radio waves at this frequency, making communication only possible when vehicles are in line-of-sight.

In our model, vehicles operate in either *warning* or *normal* mode. Normal mode represents a default behavior; however, when a vehicle detects a dangerous condition, it will start operating in warning mode. Warning mode vehicles inform other vehicles about abnormal situations by sending warning messages periodically (every T_w seconds) using the highest priority at the MAC layer. We consider abnormal situations as any condition that could affect the traffic security and probably cause an accident, e.g., slippery

Algorithm 1: eSBR_Send()

```
P_w = AC3;    // set the highest priority
P_b = AC1;    // set default priority
ID = 0;       // initialize sequence number of messages
while (1) do
    if (vehicle_i is in warning mode) then
        create message m;
        set m.priority = P_w;
        set m.seq_num = ID++;
        broadcast warning message (m);
        sleep (T_w);
    else
        create message m;
        set m.priority = P_b;
        broadcast beacon (m);
        sleep (T_b);
```

road, a previous accident where the involved vehicles are an obstacle for the normal traffic flow, works on the road, etc. Only messages representing this situations will be produced using the highest priority, while messages for comfort and entertainment applications will be sent using lower priorities. Normal mode vehicles enable the diffusion of these warning packets and, periodically (every T_b seconds), they also send *beacons* with non-critical information such as their positions and speed. Normal messages have lower priority than warning messages, and they are not propagated by other vehicles. With respect to warning messages, each vehicle only propagates them once for each sequence number, i.e., older messages are dropped.

Algorithms 1 and 2 describe our eSBR scheme, where $vehicle_i$ identifies each vehicle in the scenario; m indicates each message sent or received by each vehicle; *warning* represents a warning message generated by a warning mode vehicle; *beacon* represents a normal message generated by a normal vehicle; T_w is the interval between two consecutive warning messages; T_b is the interval between two consecutive normal messages; P_w indicates the priority of the warning messages and P_b indicates the priority of the normal messages.

When $vehicle_i$ starts the broadcast of a message, it sends m to all its neighbors. When any nearby vehicle receives m for the first time, it rebroadcasts it by further relaying m to its neighbors. Depending on their charac-

Algorithm 2: eSBR_OnRecv()

```
for (every received message) do
    if (m is is a warning and m.seq_num received for the first time)
    then
        if (distance between sender and receiver > D or both vehicles
        are in different streets) then
            rebroadcast(m);
        else
            discard(m);
            /* warnings are only rebroadcasted when additional
            coverage area is high or they can be propagated to different
            streets */
    else
        discard(m);
        // duplicated warnings and beacons are not rebroadcasted
```

teristics, every vehicle repeats the *send*(*warning*) or the *send*(*beacon*) operations periodically with different periods (T_w and T_b, respectively). When a new message m is received, the vehicle tests whether m has already been received. To evaluate this condition, each vehicle maintains a list of message IDs. An incoming warning message ID is inserted in the list if m is received for the first time (i.e., its ID has not been previously stored in the list), and it is rebroadcasted to the surrounding vehicles only when the distance d between sender and receiver is higher than a distance threshold D, or the receiver is in a different street than the sender. We consider that two vehicles are in a different street when: (i) both are indeed in different roads (this information is obtained by on-board GPS systems with integrated street maps), or (ii) the receiver, in spite of being in the same street, is near to an intersection. Hence, warnings can be rebroadcasted to vehicles which are traveling on other streets, overcoming the radio signal interference due to the presence of buildings. If the message is a *beacon*, it is simply discarded since we are not interested in the dissemination of beacons.

Figure 2 shows an example in a real map scenario. When vehicle A broadcasts a warning message, it is only received by neighboring vehicles B, C, and D because buildings interfere with the radio signal propagation. In this situation, if we use distance or location-based schemes, vehicles B, C, and D will rebroadcast the message only if distances $d1$, $d2$ and $d3$, respectively, are large enough (i.e., the distance is larger than the distance

Figure 2: The enhanced Street Broadcast Reduction scheme: example scenario taken from the city of Valencia in Spain.

threshold D), or its additional coverage areas are wide enough (i.e., the AC is larger than the coverage threshold A). Supposing that only vehicle B meets this condition in our scenario, the warning message could still not be propagated to the rest of vehicles (i.e., E, F, and G).

Our eSBR scheme improves this situation as follows. In eSBR, vehicle D will rebroadcast the warning message since vehicle D is in a different street than vehicle A. The warning message will then arrive to all the nearby vehicles (in our scenario) in only three hops. In modern *Intelligent Transportation Systems* (ITS), vehicles are equipped with on-board GPS systems containing integrated street maps. Hence, location and street information can readily be used by eSBR to ease the dissemination of warning messages. When the additional coverage area is wide enough, vehicles will rebroadcast the received warning message. However, when the additional coverage area is very low, vehicles will rebroadcast warning messages only if they are in a different street. Note that distance and location-based schemes can be very restrictive, especially when buildings interfere with radio signal propagation. Without eSBR, warning messages will not arrive to vehicles E, F and G due to the presence of buildings.

One of the strengths of our algorithm, compared to existing protocols based on Delay-Tolerant Networks, is its low resource requirements. The eSBR scheme does not need specific buffers to store messages in the relaying nodes until a specific condition is satisfied, since all the transmissions in eSBR are performed using direct rebroadcasts when a new message arrives. New vehicles arriving to the affected area will be informed with subsequent warning messages, which are generated periodically (see Algorithm 1).

As shown, the proposed scheme relies on GPS locations to decide the next forwarding nodes. Modsching et al. (2006) discovered that average urban scenarios (like those used to validate our system) produce a mean error on GPS location of about 15 meters when the street presents high buildings at both sides, but the error is reduced to just 2 meters on average when there is a clearer view of the sky (since more satellites could be used to estimate the position). Additionally, using the information contained in the in-built street maps to correct the current location of the receptor (e.g., avoiding impossible positions inside of buildings) helps to reduce the mean error to just 5 meters. Moreover, Closas et al. (2007) focused on statistical computation to improve the positioning accuracy, generating maximum likelihood estimators under multipath conditions which are able to reduce the maximum error to 10 meters. Hence, even if the current location of the vehicle may present some degree of error, it is possible to achieve a good performance of the system.

To cope with GPS location errors, our simulations also use some defined thresholds to consider when a vehicle is near a junction, which allows reducing the influence of positioning errors. In addition, in order to ensure that at least one vehicle forwards a received warning message when it is near a junction of the roadmap and to reduce the influence of GPS errors, all vehicles within the range of a junction start a time counter with 1 second of duration after a warning message is received. If no rebroadcasted message is detected at the end of this interval, the vehicle will rebroadcast it on its own. Figure 3 summarizes the eSBR function, where v_s is the sender vehicle, v_r is the receiver vehicle, j is a junction of the roadmap, d represents a geographical distance function, d_{min} is the minimum rebroadcast distance and th_j is the threshold representing a junction's influence range.

3.1. eSBR Formal Definition

In order to obtain a clearer definition of the eSBR scheme, we now formally define it using set theory. This analysis provides a mathematical basis for the proposed scheme, which could be used for validation and analytical prediction of its behavior on a particular scenario, prior to actual simulation. Most existing schemes are not formally defined and it could lead to ambiguities, making it difficult to properly implement them, and achieve adequate comparisons with other proposed schemes.

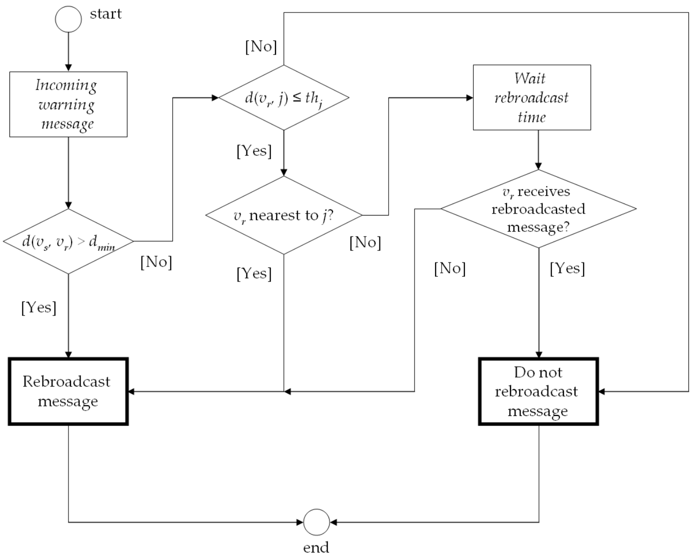


Figure 3: eSBR algorithm flow chart.

Using the street layout to improve the warning message dissemination has not received too much attention from the academia up to now. However, due to the significant impact of buildings and other obstacles on the wireless signals present in urban scenarios, it could help overpass obstacles and reach new areas of the topology that would remain hidden otherwise. This condition is represented in the following analysis, where we focus on the streets instead of single vehicles. The objective is to determine which streets are potentially able to disseminate the message, as this will be later applied to the vehicles located on them. The results will determine the influence of the roadmap on the message diffusion.

Let us define three different sets (V, S, and J) where V represents the set of vehicles, S represents the set of streets, and J represents the set of junctions between streets. Each street is defined as a straight line linking two junctions: j_{start} and j_{end}, and thus we define two functions, *start* and *end*, that return the start and end junction's position of a street. Other defined functions are *dist*, which computes the Euclidean distance between two points of the map; $have\_common\_junction$ to determine if two streets have a junction in common; and ang_diff that computes the angular difference between two streets (angle formed between the vectors representing the streets).

We call $\Omega_{j,t}$ the set of streets which are visible from the position of vehicle j (v_j) on time t. This set can be calculated as follows:

$$\Omega_{j,t} = \underbrace{\Phi_{j,t} \cup \Psi_{j,t}}_{streets\_located} \cup \underbrace{\Theta_{j,t} \cup \Xi_{j,t}}_{reachable\_streets} \tag{1}$$

We can decompose this set in a series of subsets:

- $\Phi_{j,t}$: set of streets in which v_j is located due to its position in the map.
- $\Psi_{j,t}$: set of streets in which v_j is located due to its proximity to a junction. A vehicle is near a junction when the distance between the junction and the vehicle is below a given threshold (th_c).

$$\begin{aligned}\Psi_{j,t} = \{\psi_i : \psi_i \in S \ \wedge \ (dist(pos(v_{j,t}), start(\psi_i)) < th_c \ \vee \\ dist(pos(v_{j,t}), end(\psi_i)) < th_c)\}\end{aligned} \tag{2}$$

- **$\Theta_{j,t}$: set of streets reachable by v_j (i.e., it has visibility) because they are adjacent (have one junction in common) to the streets where the vehicle is located (s_k in Equation 3) and the angular difference between these streets and the previous ones is below a threshold (th_a).**

$$\begin{aligned}\Theta_{j,t} &= \{\theta_i : \theta_i \in S \ \wedge \ (\exists s_k | s_k \in (\Phi_{j,t} \cup \Psi_{j,t}) \ \wedge \\ &\quad have\_common\_junction(\theta_i, s_k) \wedge ang\_diff(\theta_i, s_k) < th_a)\}\end{aligned} \tag{3}$$

- **$\Xi_{j,t}$: set of streets reachable by v_j because there is a chain of streets linked by common junctions (subset of streets S' in Equation 4) where the first street is visible by the vehicle (street s'_{vis}), and the angular difference between any pair of streets (s'_i and s'_j) in the chain is below a threshold (th_a).**

$$\begin{aligned}\Xi_{j,t} &= \{\xi_i : \xi_i \in S \ \wedge \ \exists S' \mid S' \subseteq S \wedge \ \xi_i \in S' \ \wedge \\ &\quad (\forall s'_i \mid s'_i \in S' \Rightarrow (\exists s'_j | s'_j \in S' \wedge s'_j \neq s'_i \ \wedge \\ &\quad have\_common\_junction(s'_i, s'_j))) \ \wedge \\ &\quad (\exists s'_{vis} \mid s'_{vis} \in S' \wedge s'_{vis} \in (\Phi_{j,t} \cup \Psi_{j,t} \cup \Theta_{j,t})) \ \wedge \\ &\quad (\forall s'_i, s'_j \mid s'_i \in S' \wedge s'_j \in S' \Rightarrow ang\_diff(s'_i, s'_j) < th_a))\}\end{aligned} \tag{4}$$

Given two vehicles, v_s and v_r, where v_s is the sender and v_r is the receiver, and supposing that the radio signal is strong enough to reach v_r, the eSBR scheme will rebroadcast an incoming warning message only if the following condition is satisfied concerning the streets where the sender and the receiver are located (i.e., ω_s and ω_r respectively):

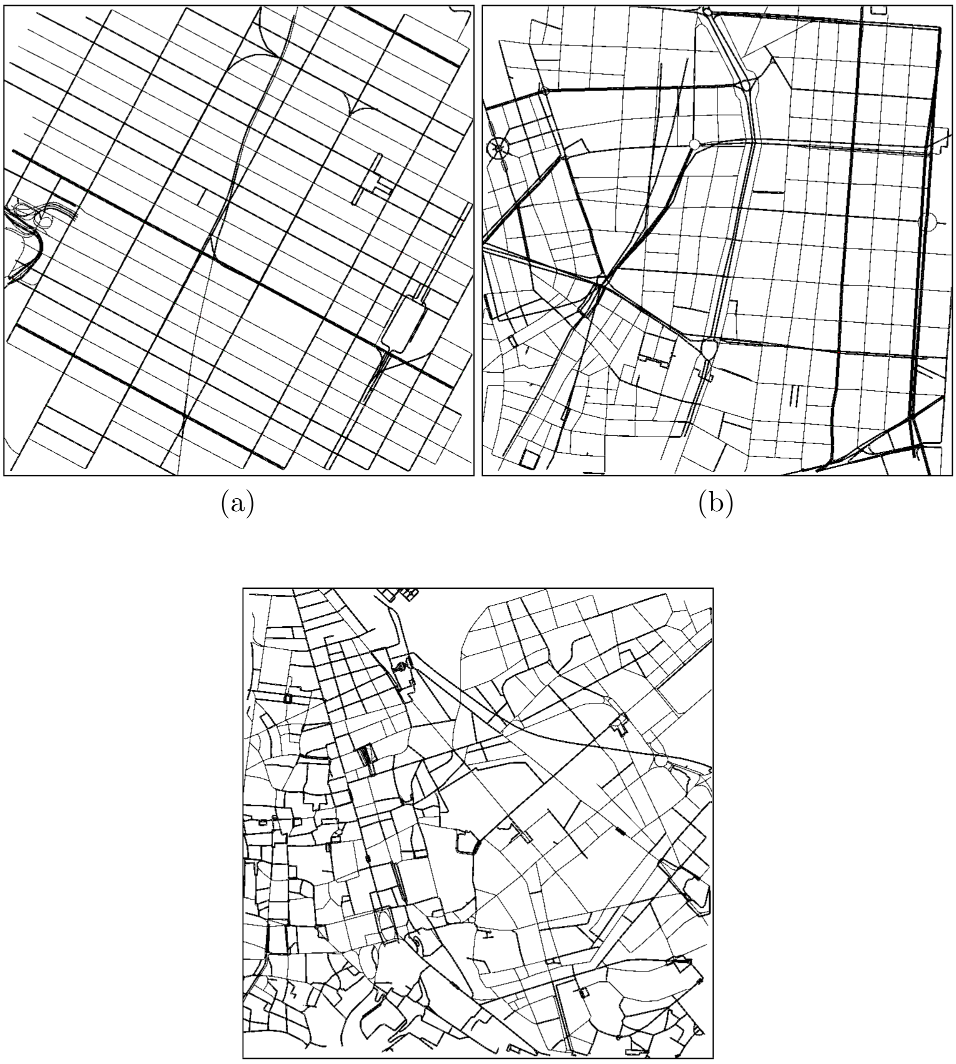
$$\begin{aligned} \exists \omega_s, \omega_r \mid \omega_s \in (\Phi_{s,t} \cup \ \Psi_{s,t}) \wedge \omega_r \in (\Phi_{r,t} \cup \ \Psi_{r,t}) \wedge \omega_r \notin \Omega_{s,t} \ \vee \\ (\exists j \mid j \in J \wedge (start(\omega_r) = j \vee end(\omega_r) = j) \ \wedge \\ (\forall v_i | v_i \in V \wedge v_i \neq v_r \Leftrightarrow dist(pos(v_i, t), j) \geq dist(pos(v_r, t), j))) \end{aligned} \tag{5}$$

which means that the eSBR scheme is activated (i.e., it allows that receiver to rebroadcast) when (a) the receiver is able to reach new streets unreachable for the sender ($\omega_r \notin \Omega_{s,t}$), or (b) the receiving vehicle is near to a junction (j) and it is the nearest vehicle to the center of the junction. This situation represents, in practice, the highest likability to reach new areas of the roadmap, thus informing new vehicles about dangerous situations.

4. Simulation Environment

Simulation results presented in this paper were obtained using the ns-2 simulator. We modified the simulator to follow the upcoming *Wireless Access in Vehicular Environments* (WAVE) standard closely. VANET simulations must account for some extra characteristics that are specific to vehicular environments (Martinez F. J. et al., 2009b), and so we have extended the ns-2 simulator to implement IEEE 802.11p, which is a draft amendment to the IEEE 802.11 standard that defines enhancements to support *Intelligent Transportation Systems* (ITS) applications.

In terms of the physical layer, the data rate used for packet broadcasting was fixed at 6 Mbit/s, i.e., the maximum rate for broadcasting in 802.11p when assuming a 20 MHz channel. The MAC layer is based on the IEEE 802.11e *Enhanced Distributed Channel Access* (EDCA) *Quality of Service* (QoS) extensions. Therefore, application messages are categorized into different *Access Categories* (ACs), where AC0 has the lowest, and AC3 the highest priority. The contention parameters used for the *Control Channel* (CCH) are shown in Eichler (2007). In our proposed eSBR scheme, warning messages have the highest priority (AC3) at the MAC layer, while *beacons* have lower priority (AC1).



(a) (b) (c)

Figure 4: Scenarios used in our simulations as street graphs in SUMO: (a) fragment of the city of New York (USA), (b) fragment of the city of Madrid (Spain), and (c) fragment of the city of Rome (Italy).

Moreover, since we are simulating real city maps with buildings, we have modified the ns-2 simulator to model the impact of distance and obstacles in signal propagation. The Radio Propagation Model selected was the *Real Attenuation and Visibility Model* (RAV) (Martinez et al., 2010), a model which proved to increase the level of realism in VANET simulations using real urban roadmaps as scenarios where buildings act as obstacles. RAV implements the signal attenuation due to the distance between vehicles based on real data obtained from experiments in different streets of the cities of Valencia and Teruel (Spain). The test were performed using D-Link DWL-AG132 (D-Link Systems, Inc., 2011) wireless adapters, configured to use the IEEE 802.11a standard in the 5.9 GHz frequency band (the same band as 802.11p), obtaining a maximum transmission range of 400 meters. This model also accounts for the presence of buildings to determine if two vehicles are in line-of-sight, and otherwise the angular difference between the streets and the proximity to a junction are computed to approximate the effects of diffraction and reflection of the signal from the buildings.

To perform realistic simulations, it is specially important that the chosen mobility generator could obtain a detailed microscopic traffic simulation importing network topologies from real maps. Our mobility simulations are performed with SUMO (Krajzewicz and Rossel, 2007), an open source traffic simulation package which has microscopic traffic capabilities such as: collision free vehicle movement, multi-lane streets with lane changing, junction-based right-of-way rules and traffic lights. SUMO can also import maps directly from map databases such as OpenStreetMap (2011) and TIGER (2011).

Our simulation scenarios are based on three different roadmaps, which were obtained from real cities using OpenStreetMap. The three selected locations represent real scenarios having different streets densities and average street lengths. The chosen scenarios were the South part of the Manhattan Island from the city of New York (USA), the area around Paseo de la Castellana in the city of Madrid (Spain), and the area located at the North of the Colosseum in the city of Rome (Italy). All the selected maps have an extension of 4 km^2 (2 km $\times$ 2 km). Figure 4 depicts the street layouts used in SUMO to represent the selected scenarios, and Table 1 includes the main features of the chosen areas of the cities. As we can see, the New York map presents the longest streets, arranged in a Manhattan-grid style. The city of Rome represents the opposite situation, with short streets in a highly irregular layout, and the city of Madrid shows an intermediate layout, with a medium density of streets in a less irregular arrangement compared to Rome.

Table 1: Main features of the selected maps

Selected city map	New York (USA)	Madrid (Spain)	Rome (Italy)
Total streets	700	1387	2780
Total junctions	500	715	1193
Avg. street length	$122.54m$	$83.08m$	$45.88m$
Avg. lanes/street	1.57	1.27	1.06

To generate the movements for the simulated vehicles, we used the Krauss mobility model (Krauss et al., 1997) available in SUMO with some modifications to allow multi-lane behavior (Krajzewicz et al., 2002). This model is based on collision avoidance among vehicles by adjusting the speed of a vehicle to the speed of its predecessor using the following formula:

$$v(t+1) = v_1(t) + \frac{g(t) - v_1(t)}{\tau(t) + 1} + \eta(t), \tag{6}$$

where v represents the speed of the vehicle, v_1 is the speed of the leading vehicle, g is the gap to the leading vehicle, τ is the driver's reaction time (set to 1 second in our simulations) and η is a random variable with a value between 0 and 1.

Our mobility simulations also account for areas with different vehicle densities. In a real town, traffic is not uniformly distributed; there are downtowns or points of interest that may attract vehicles. Hence, we include the ideas presented in the *Downtown Model* (Martinez F. J. et al., 2008) to add points of attraction in realistic roadmaps. The simulated scenarios include a square area of 1 km^2 in the center of the map where the probability to attract vehicles is 50%. This means that about 50% of the vehicles will be moving around this area on average, while the other 50% will be spread over the remaining 3 km^2 area.

5. Simulation Results

In this section, we perform a detailed analysis to evaluate the impact of the proposed eSBR scheme on the overall system performance. Since performance results highly depend on the selected scenarios, and due to the random nature of the mobility model, we performed thirty simulations to obtain reasonable confidence intervals. All the results shown here have a 90% confidence interval. Each simulation lasted for 450 seconds, and in

Table 2: Parameter values for the simulations

Parameter	**Value**
number of vehicles	$100, 200, 300, 400$
map area size	$2000m \times 2000m$
number of warning mode vehicles	3
warning packet size	$256bytes$
normal packet size	$512bytes$
interval between consecutive messages	2 *seconds*
warning message priority	$AC3$
normal message priority	$AC1$
MAC/PHY	802.11p
Radio Propagation Model	RAV
maximum transmission range	$400m$
eSBR distance threshold (D)	$200m$

order to achieve a stable state, we only started to collect data after the first 60 seconds.

We evaluated the following performance metrics: (a) percentage of vehicles informed, (b) warning notification time, (c) number of packets received per vehicle, and (d) reception overhead. The percentage of vehicles informed is the percentage of vehicles receiving the warning messages sent by warning mode vehicles. The warning notification time is the time required by normal vehicles to receive a warning message sent by a warning mode vehicle (a vehicle that broadcasts warning messages). The reception overhead measures the average number of duplicate warning messages received at any vehicle. Table 2 shows the simulation parameters used.

For comparison purposes, we evaluated the performance of our eSBR proposed scheme with respect to several existing proposals. We chose a location-based scheme and a distance-based scheme from Tseng Y.-C. et al. (2002), which are proven to provide reasonable performance in obstacle-free environments, but their results on urban environments were not tested by the authors. From Costa et al. (2006), we selected the *Function Driven Probabilistic Diffusion* (FDPD) algorithm, a probabilistic scheme that uses the distance between sender and receiver to determine the forwarding

vehicles and reduce the broadcast storm problem. Finally, we also compared our approach with respect to the more recent UV-CAST algorithm (Viriyasitavat et al., 2010), especially designed for disconnected networks but with the additional cost of using more memory structures to implement a *Store-Carry-Forward* (SCF) approach. Despite some of these schemes were designed for urban environments, none of them use the information of the topology map to improve message dissemination, like our proposed eSBR algorithm.

In our study, we also vary the density of vehicles ranging from 100 vehicles (25 vehicles/km^2) to 400 vehicles (100 vehicles/km^2). The impact of other parameters affecting warning message dissemination, such as the density of vehicles and the priority and periodicity of messages, was previously studied in Martinez F. J. et al. (2009a).

5.1. Warning notification time and percentage of vehicles informed

Figure 5 shows the impact that the selected scenario has over the warning notification time (vehicle density is 50 vehicles/km^2). The first noticeable conclusion about the results is that our proposed eSBR scheme outperforms the other four dissemination schemes in terms of both percentage of vehicles informed and warning notification time. **In addition, when the eSBR scheme is used we obtain more stable results. Tseng Y.-C. et al. (2002) demonstrated that the location-based scheme was more efficient than the distance-based scheme, since it reduces redundancy without compromising the number of vehicles receiving the warning message. The main drawback of using the location-based scheme is the high computational cost involved in evaluating the additional coverage. However, although its effectiveness is proved in obstacle-free environments, our simulations show that the location-based scheme is too restrictive in urban scenarios. Many of the vehicles which could rebroadcast the message to reach new streets of the roadmap will in fact refrain from doing so in most cases. The UV-CAST algorithm obtains very similar results to the location-based dissemination, increasing at the same time the computational complexity and the amount of memory required. The FDPD scheme is the closest one to our eSBR in terms of warning notification time, although it is not able to outperform our proposal in any of the tested scenarios.**

Another important effect that may be observed is that the percentage of vehicles informed is highly dependent on the specific selected scenario.

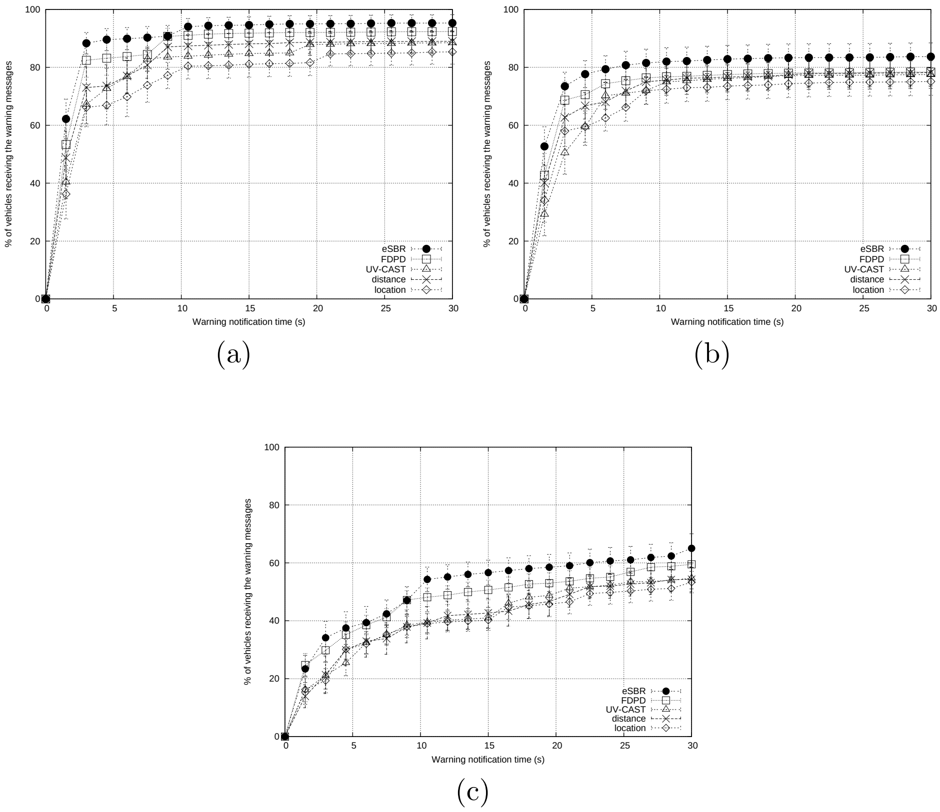


Figure 5: Average notification time and percentage of vehicles informed obtained when simulating 200 vehicles and varying the simulation scenario: (a) New York, (b) Madrid, and (c) Rome.

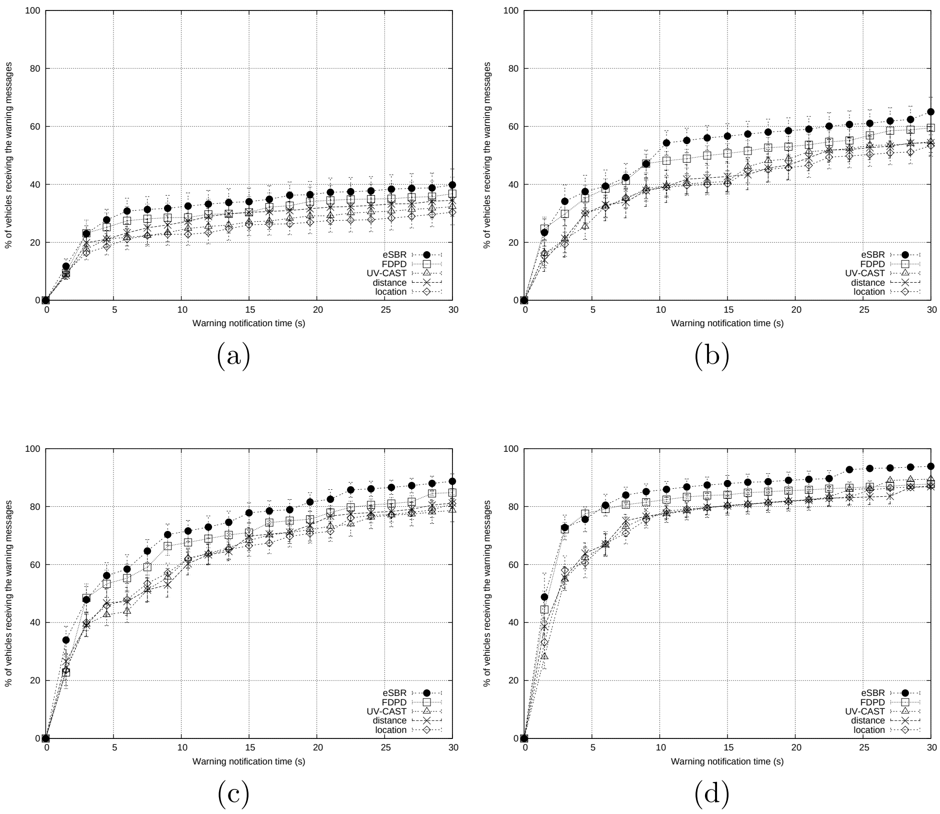


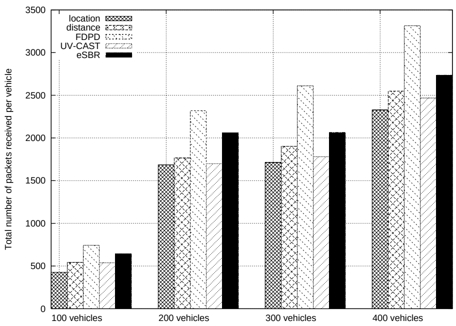
Figure 6: Average notification time and percentage of vehicles informed obtained in the Rome scenario and simulating: (a) 100 vehicles, (b) 200 vehicles, (c) 300 vehicles, and (d) 400 vehicles.

In scenarios with long streets arranged orthogonally, like New York, our proposal is able to inform more than 95% of the vehicles, while in scenarios with high density of short streets only about 70% of vehicles can be informed. Using the eSBR scheme notably increases the percentage of vehicles informed, presenting a similar behavior in all scenarios where eSBR allows informing at any moment of time about 10-15% more vehicles compared to the distance-based scheme, and about 15-20% compared to the location-based and UV-CAST algorithms. The message propagation speed is also higher for eSBR, mainly during the first seconds of the dissemination process.

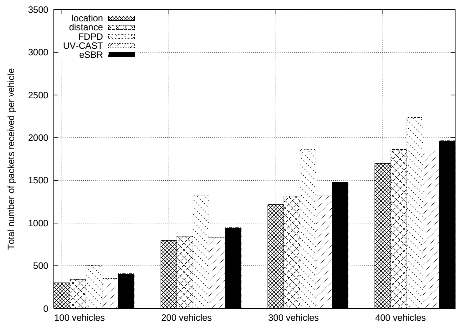
Figure 6 evaluates the impact that the network density has on the performance metrics. We vary the vehicle density from 100 to 400 vehicles, and the selected scenario is Rome. **The trend is similar independently of the vehicle density, i.e., by using eSBR there is a higher number of informed vehicles, while the location-based and the UV-CAST schemes are not able to find suitable rebroadcast nodes in the selected environment. As the number of vehicles in the scenario grows, the advantage of our eSBR scheme remains evident, and so the warning notification time is reduced while the percentage of informed vehicles increases. When we select 300 vehicles, the location-based, distance-based, and UV-CAST algorithms need about 10 seconds on average to reach 60% of the simulated vehicles, the FDPD scheme requires more than 7 seconds, and the eSBR scheme only needs 6 seconds. If the number of vehicles raises to 400, it takes 4 seconds for the location-based, distance-based, and UV-CAST schemes to inform 60% of vehicles, whereas eSBR and FDPD are able to reach the same percentage in only 2.5 seconds.**

5.2. Messages received per vehicle

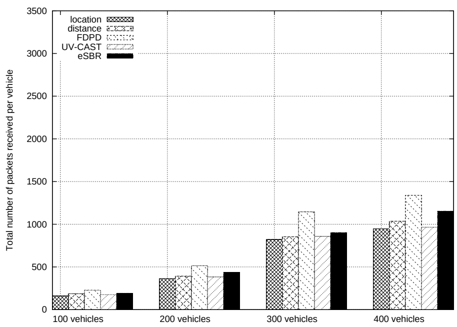
The results achieved in terms of number of messages (including beacons) received per vehicle appear in Figure 7. As shown, scenarios like New York, with long streets arranged in a regular way, are prone to increase the number of messages received, mainly when the vehicle density is high since many of the vehicles in the roadmap are in line-of-sight. **The differences between the five schemes are not very remarkable in this scenario when the vehicle density is not very high, with 5-10% more messages received using eSBR compared to the distance-based and**



(a)



(b)



(c)

Figure 7: Average number of messages received per vehicle in the different scenarios: (a) New York, (b) Madrid, and (c) Rome.

UV-CAST schemes, and about 10-15% compared to the location-based scheme. The number of messages received using the eSBR scheme slightly increases due to the higher probability for a vehicle to rebroadcast a message when they are close to a junction. However, these vehicles are forwarding nodes since they are the most suitable ones to increase the percentage of informed vehicles, reducing the warning notification time without notably increasing the number of messages. The FDPD algorithm introduces the highest amount of messages in the system, (up to 25% more messages than eSBR) increasing the risk of broadcast storms.

When Simulating scenarios like Madrid, the number of messages is reduced by 20-40% in all cases, and the decrement is even more noticeable in the Rome scenario where the dissemination process only produces less than half of the messages obtained in the New York scenario. The reduction of the number of messages also decreases the differences between the five schemes, and thus the eSBR scheme is specially suitable in environments with medium and high density of streets, where the amount of messages received is low and a slight increase of the number of messages is not likely to produce broadcast storms.

These results also lead to a significant conclusion: our proposed eSBR scheme is specially suitable for situations where the density of vehicles is not too high, mostly due to its ability to inform as many vehicles as possible without notably increasing the number of messages. This situation is likely to occur during the first steps of the mass implantation of wireless devices in vehicles, when the market penetration rate will be low, and only a reduced number of vehicles will be able to communicate with each other.

5.3. Reception overhead

The reception overhead is a measure of the average number of duplicate messages received by any vehicle involved in our simulations. This metric is useful to determine if a protocol can effectively solve or mitigate the broadcast storm problem. Duplicate messages also represent an ineffective use of the channel bandwidth, so they must be avoided whenever possible. We include both warning messages and control beacons in our results.

Figure 8 shows the reception overhead measured for the different tested dissemination algorithms in a scenario with 200 vehicles (50 vehicles/km^2). As can be seen, the obtained results are again

highly dependent on selected roadmap: maps with long and regular streets (e.g., New York) are prone to produce broadcast storm problems even in situations with low density of vehicles, thus producing a higher level of reception overhead. Irregular scenarios like Rome reduce the number of duplicate messages received by the vehicles since the wireless signal finds more obstacles during its propagation.

Concerning the dissemination algorithms, the FDPD scheme obtains the worst results in all simulated scenarios, and the differences increase in maps like New York. As previously shown, this algorithm presented the closest results to eSBR in terms of warning notification time. However, Figure 8 demonstrates that the FDPD scheme provokes a noticeable increase in the number of duplicate messages present in the network. The schemes that reduce the reception overhead in a higher degree are the location-based and the UV-CAST algorithms. Our proposed eSBR algorithm produces more reception overhead than these schemes, but this is only noticeable in the New York roadmap (where the increase is about 15%), whereas the differences are almost negligible in the other scenarios. Therefore, the eSBR scheme introduces little overhead compared to other more restrictive schemes, which is compensated by the reduction in terms of warning notification time and blind vehicles.

5.4. Performance under GPS inaccuracy

Our proposal is based on positioning data to determine the vehicles closest to the junctions of the roadmap to maximize the message propagation process in any urban area; thus, inaccuracy on GPS data could result in performance degradation. Modern GPS devices usually produce an average positioning error ranging from 10 to 15 meters, which could be reduce to less than 5 meters using correction techniques (as shown in Section 3). Despite current systems typically adopt these error correction techniques, we incorporated these errors to our simulations in order to represent extreme situations where the positioning device produces significant mistakes; our propose is to study the impact of the GPS error on the results obtained when the eSBR scheme is active.

In particular, the average error introduced in our experiments ranges from 0 meters (perfect location) to 50 meters, representing

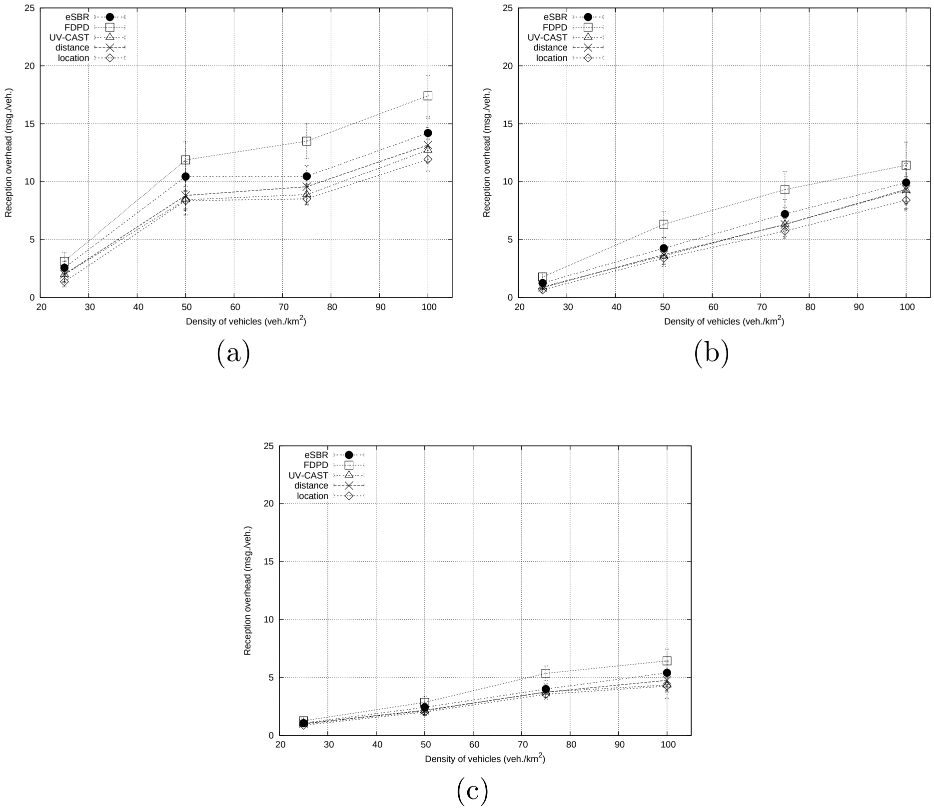


Figure 8: Average reception overhead in the different scenarios: (a) New York, (b) Madrid, and (c) Rome.

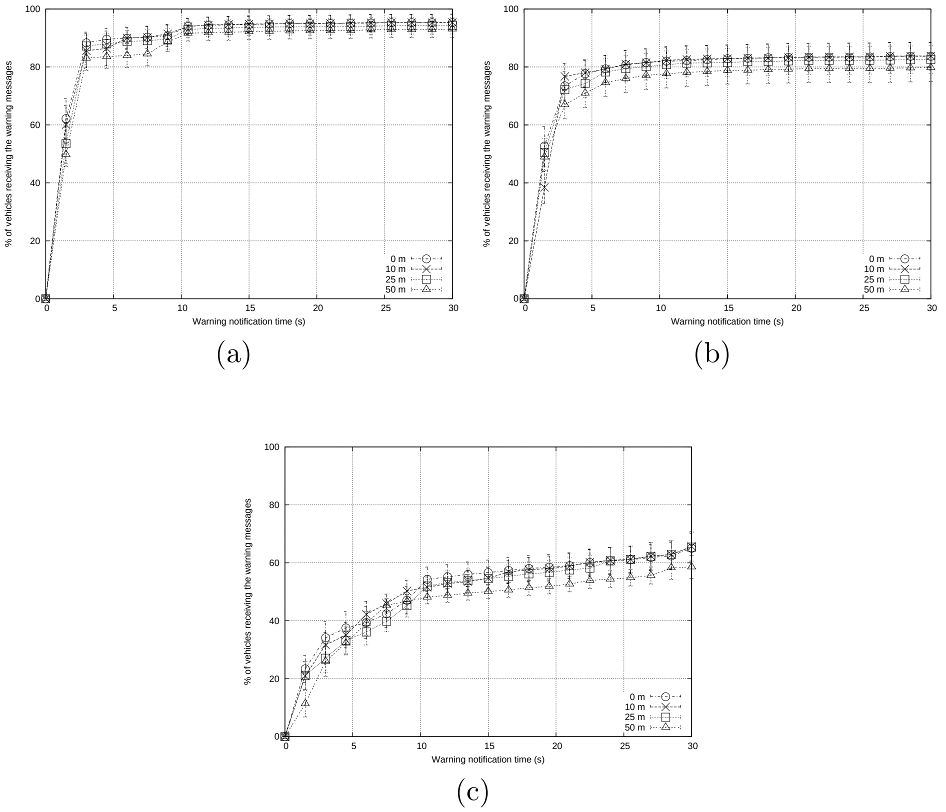


Figure 9: Average notification time and percentage of vehicles informed obtained when simulating 200 vehicles under different levels of GPS inaccuracy and varying the simulation scenario: (a) New York, (b) Madrid, and (c) Rome.

scenarios where the positioning is very difficult due to surrounding buildings or other urban structures. By applying these error margins in our simulations, we obtained the results presented in Figure 9.

As shown, errors on GPS location cause a variation on the performance of the algorithm, which becomes more noticeable as the error increases. However, the results are really similar in all the scenarios for average errors below 25 meters, and the performance is only slightly reduced when the error exceeds this threshold. The map where the differences are more noticeable is Rome, where a 50 meters error causes 10% less informed vehicles after the first

10 seconds. In Madrid, the performance is reduced by approximately 5% when comparing the perfect location scenario and the maximum error situation. Finally, in maps like the Manhattan area in New York, the differences are hardly noticeable even for the highest level of error.

To sum up, the eSBR scheme is robust enough to support positioning errors up to 25 meters without showing performance degradation. The impact on warning notification time is more evident on irregular maps (like Rome), since the GPS error impedes an optimal selection of vehicles for rebroadcasting, making it more difficult to reach certain areas of the topology occluded by buildings. In Manhattan-like scenarios, positioning error has little effect on the eSBR performance, and thus our algorithm can cope with errors produced by tall buildings and other urban structures, typical in city downtown areas.

5.5. Performance under background traffic

In a real deployment scenario, the warning message dissemination application may coexist with very different applications that generate additional traffic on the wireless channel. These applications are expected to receive less priority than the warning message dissemination process, but it is interesting to study how this additional traffic influences the propagation of warning information when sharing the same channel.

Some authors have already studied how a vehicular environment is affected by large amounts of traffic. Torrent-Moreno et al. (2004) quantified via simulation the probability of reception for the two-ray ground propagation model, as well as for the Nakagami distribution in saturated environments; Calafate et al. (2011) optimized content delivery performance by seeking the optimal packet size in urban scenarios with added infrastructure. In our case, we study how the eSBR scheme behaves in high traffic load scenarios that would increase the contention level in the wireless channel.

We designed an experiment with different levels of background traffic. In addition to messages related to warning message dissemination (beacons and warnings), vehicles also broadcast messages produced by other applications (road conditions, local traffic congestion, video captured by a car, etc.). We studied three different scenarios: (i) no background traffic (only the warning message dissemination is working), (ii) vehicles sending 5 messages per second

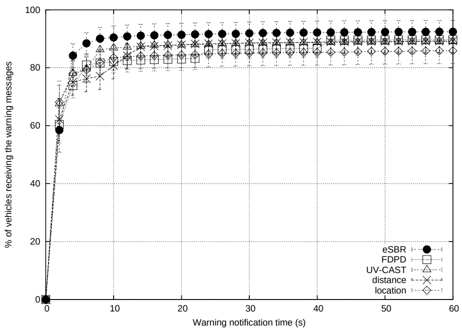
with 200 KB size each, producing 1 MB/s per vehicle, and (iii) vehicles sending 5 messages per second with 400 KB size each, producing 2 MB/s per vehicle. This additional messages have the same priority as the beacons sent by normal mode vehicles (AC0), while warning messages are broadcasted with priority AC3 (the highest). Also notice that the maximum broadcasting data rate is of 6 Mbit/s.

Figure 10 shows the simulation results for the three studied scenarios in the Madrid roadmap when simulating 400 vehicles (100 vehicles/km^2). As shown, the dissemination speed is reduced as we increase the amount of background traffic. However, when each vehicle sends 1 MB/s of additional traffic, the eSBR scheme is still able to outperform all other algorithms. It is interesting to note that simpler schemes, such as the distance-based one, is the closest to the eSBR, which means that more restrictive dissemination algorithms are better at avoiding channel saturation under very high background traffic load. This is confirmed when we increase the additional traffic to 2 MB/s per vehicle, where the distance-based and location-based schemes obtain the best performance. As the simulation progresses, our proposed eSBR gets closer to them, and the differences become negligible after 50 seconds, whereas the FDPD performance is reduced after the first 40 seconds. The UV-CAST algorithm achieves more stable results, but it is unable to outperform the distance-based scheme in all cases.

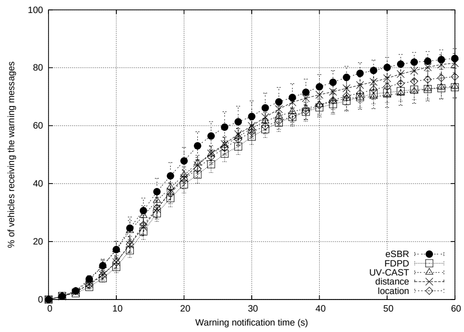
Therefore, we can conclude that the existence of background traffic could have a noticeable impact on warning message dissemination performance. For additional traffic load of about 1 MB/s produced by each vehicle, the eSBR is still able to obtain better results than the rest of schemes. However, higher levels of background traffic benefit simpler and more restrictive schemes, which are able to achieve good results in high contention scenarios.

5.6. Evolution of the warning message dissemination process

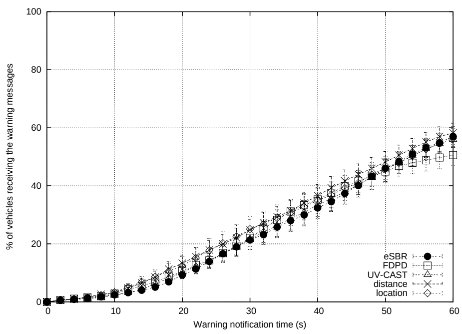
In order to better understand the warning dissemination process, Figures 11 to 14 offer a visual representation of the number of messages received in one of our simulations at different time instants. Each image was obtained by splitting the Madrid simulated scenario in a 100 $\times$ 100 grid, meaning that each cell depicted represents 400 m^2 (20 m $\times$ 20 m).



(a)



(b)



(c)

Figure 10: Average notification time and percentage of vehicles informed obtained when simulating 400 vehicles in the Madrid scenario under different levels of background traffic: (a) only warning message dissemination, (b) additional 1 MB/s broadcast by each vehicle, and (c) additional 2 MB/s broadcast by each vehicle.

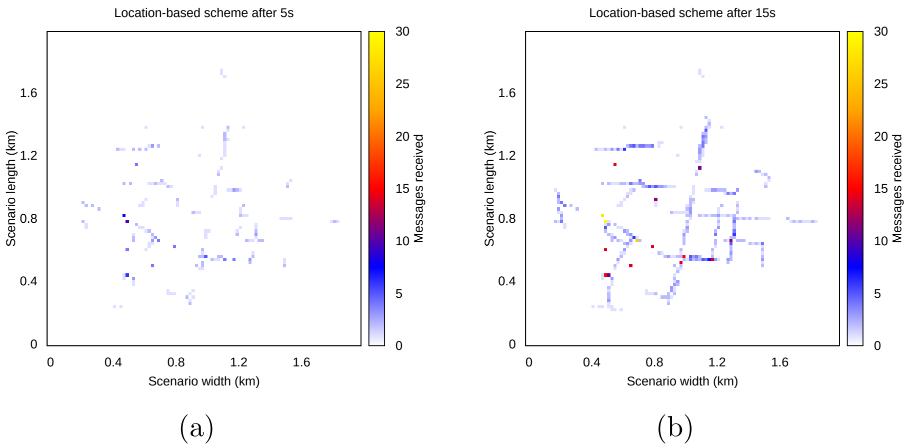
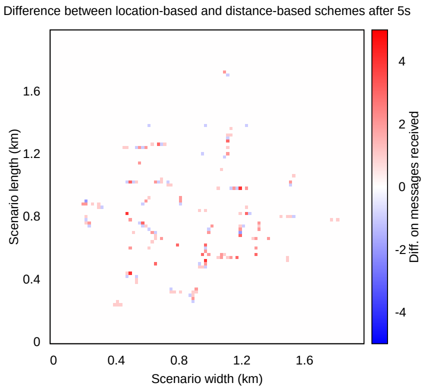


Figure 11: Evolution of the warning message dissemination process in the Madrid scenario simulating 100 vehicles and using a location-based scheme after (a) 5 seconds and (b) 15 seconds.

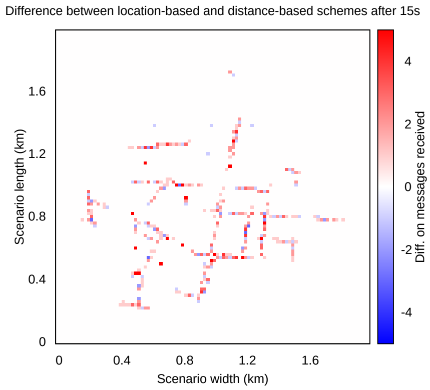
Figures 11 and 13 show the number of messages received in each area when simulating 100 and 400 vehicles, respectively, and a location-based dissemination scheme is selected. White areas indicate that no messages were received during the simulation (blind zones and buildings), whereas yellow areas represent locations where 30 or more messages were received. These results are used as a basis to illustrate the variations between the three dissemination schemes, and so the heatmaps found on Figures 12 and 14 show the differences in terms of number of messages per area for the distance-based and eSBR schemes with respect to the location-based scheme. Red areas indicate a higher number of messages received and blue areas represent fewer messages.

When only 100 vehicles are simulated (Figures 11 and 12), the location-based scheme presents a very slow progression. Our proposed eSBR is able to spread messages to a larger area compared to the other two schemes. In fact, the eSBR scheme is the only one that reaches a small area in the South-West part of the map. After 15 seconds, eSBR presents the highest percentage of areas of the city informed about the dangerous situation, reaching about 7% additional area compared to the distance-based scheme and 17% more area than the location-based scheme.

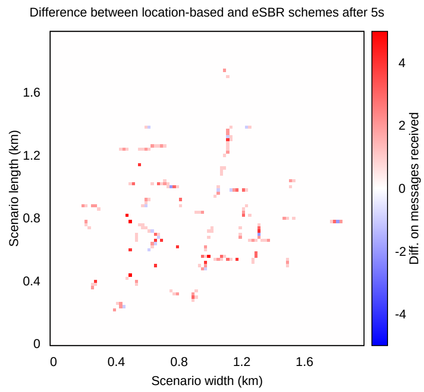
If the simulations include 400 vehicles (Figures 13 and 14), the three schemes are able to reach a wider area of the scenario since it is easy to find



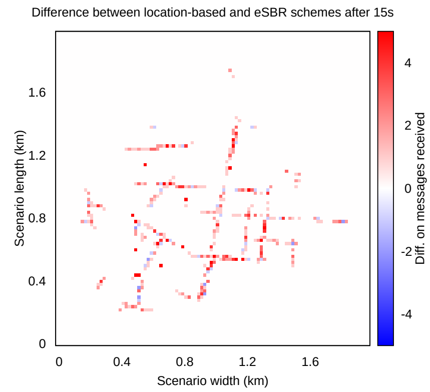
(a)



(b)

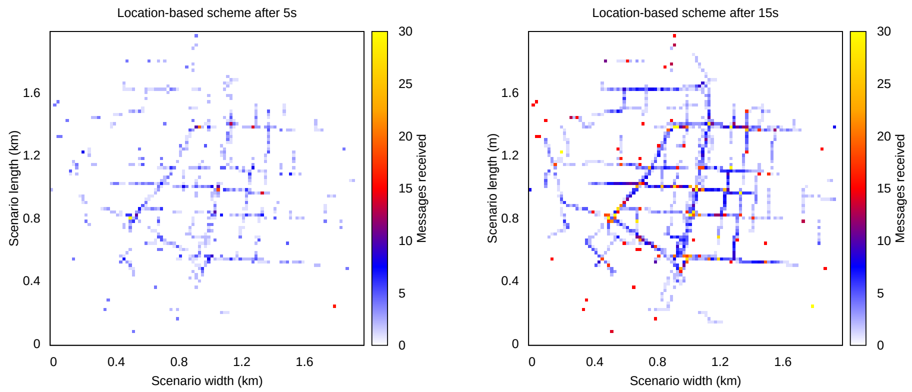


(c)



(d)

Figure 12: Differences in number of messages with respect to the location-based scheme simulating 100 vehicles in the Madrid scenario; using a distance-based scheme after (a) 5 seconds and (b) 15 seconds, and our proposed eSBR after (c) 5 seconds and (d) 15 seconds.



(a)

(b)

Figure 13: Evolution of the warning message dissemination process in the Madrid scenario simulating 400 vehicles and using a location-based scheme after (a) 5 seconds and (b) 15 seconds.

appropriate rebroadcasting nodes. The eSBR scheme presents the highest coverage area after 5 and 15 seconds (up to 12% and 8% additional area, respectively), especially when compared to the location-based scheme which inhibits too many nodes from forwarding in an urban scenario. Our results show that the differences between location-based and distance-based schemes when the density of nodes is high become less significant after the initial period of the simulation. However, the eSBR scheme works more efficiently from the beginning of the dissemination process, and thus this effect could be interesting to spread critical messages to neighbor vehicles as soon as possible without the risk of generating broadcast storms.

6. Conclusion

Achieving efficient message dissemination is of utmost importance in vehicular networks to warn drivers about critical road conditions. However, the broadcasting of warning messages in VANETs can result in increased channel contention and packet collisions due to simultaneous message transmissions. **In this paper, we introduce the *enhanced Street Broadcast Reduction* (eSBR) scheme to improve the performance of the warning message dissemination process in real map urban scenarios. Simulation results show that eSBR outperforms other schemes in all**

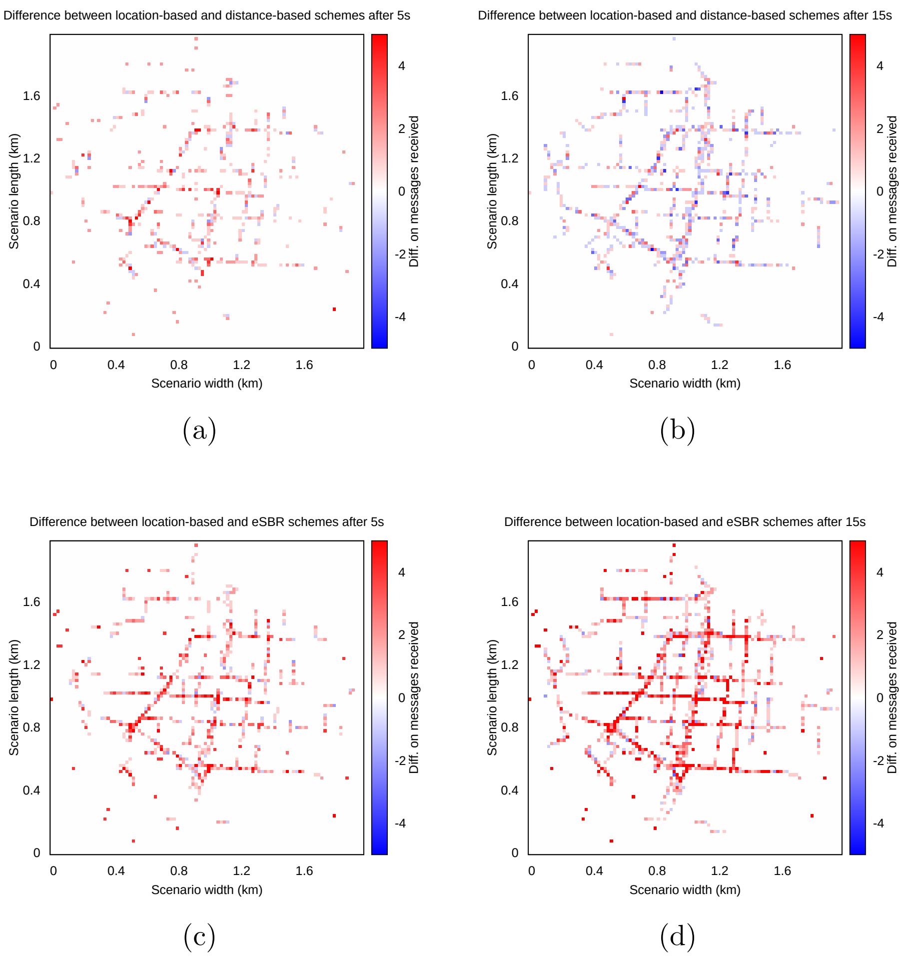


Figure 14: Differences in number of messages with respect to the location-based scheme simulating 400 vehicles in the Madrid scenario; using a distance-based scheme after (a) 5 seconds and (b) 15 seconds, and our proposed eSBR after (c) 5 seconds and (d) 15 seconds.

scenarios, yielding a higher percentage of vehicles informed, and a reduced warning notification time while not introducing broadcast storm problems; thus, we consider it suitable for real scenarios.

We find that using scenarios with different values for the density of streets and junctions, or average street length, may affect notably the results in terms of informed vehicles and messages received per vehicle. Roadmaps with irregular, short streets need a higher vehicle density for the dissemination to be effective, while using nearly orthogonal topology scenarios provides good results with very low vehicle densities. Hence, the dissemination system could be tuned to use a more or less restrictive broadcast scheme, depending on the features of the current scenario, to maximize performance.

The proposed eSBR scheme is specially suitable in situations where there are few vehicles able to forward messages, which can be due to either the low vehicle density or the low market penetration rate of wireless devices. Thus, the eSBR scheme may be successfully used during the first steps of the mass implantation of 802.11p compliant devices on vehicles. Moreover, by studying the time evolution of the message propagation process, we find that our proposal can be very useful to transmit critical messages that should be spread out as soon as possible; **in particular, we show that eSBR clearly outperforms all the studied proposals, i.e., the distance-based and location-based schemes, the Function Driven Probabilistic Diffusion algorithm, and the UV-CAST protocol in terms of warning notification time and percentage of blind nodes, while exhibiting a reduced overhead.**

Acknowledgments

This work was partially supported by the *Ministerio de Ciencia e Innovación*, Spain, under Grant TIN2011-27543-C03-01, and by the *Diputación General de Aragón*, under Grant "subvenciones destinadas a la formación y contratación de personal investigador".

References

Bi, Y., Cai, L., Shen, X., Zhao, H., May 2010. A Cross Layer Broadcast Protocol for Multihop Emergency Message Dissemination in Inter-Vehicle Communication. In: IEEE International Conference on Communications (ICC), 2010. pp. 1–5.

Calafate, C. T., Fortino, G., Fritsch, S., Monteiro, J., Cano, J.-C., Manzoni, P., 2011. An efficient and robust content delivery solution for ieee

802.11p vehicular environments. Journal of Network and Computer Applications (0), –.

Closas, P., Fernandez-Prades, C., Fernandez-Rubio, J., May 2007. Maximum Likelihood Estimation of Position in GNSS. Signal Processing Letters, IEEE 14 (5), 359–362.

Costa, P., Frey, D., Migliavacca, M., Mottola, L., 2006. Towards lightweight information dissemination in inter-vehicular networks. In: Proceedings of the 3rd international workshop on Vehicular ad hoc networks. VANET '06. New York, NY, USA, pp. 20–29.

D-Link Systems, Inc., 2011. DWL-AG132 Wireless 108AG USB Adapter. Available at http://www.dlink.com.

Eichler, S., September 2007. Performance evaluation of the IEEE 802.11p WAVE communication standard. In: Proceedings of the Vehicular Technology Conference (VTC-2007 Fall), Baltimore, MD, USA.

Jones, E. P., Li, L., Ward, P. A., 2005. Practical routing in delay-tolerant networks. In: Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking. WDTN '05. ACM, New York, NY, USA, pp. 237–243.
URL `http://doi.acm.org/10.1145/1080139.1080141`

Jones, E. P., Ward, P. A., 2006. Routing strategies for delay-tolerant networks. Submitted to ACM Computer Communication Review (CCR).

Korkmaz, G., Ekici, E., Ozguner, F., Ozguner, U., October 2004. Urban multi-hop broadcast protocols for inter-vehicle communication systems. In: Proceedings of First ACM Workshop on Vehicular Ad Hoc Networks (VANET 2004).

Krajzewicz, D., Hertkorn, G., Rssel, C., Wagner, P., September 2002. SUMO (Simulation of Urban MObility) - An open-source traffic simulation. In: Proceedings of the 4th Middle East Symposium on Simulation and Modelling (MESM2002). Sharjah, United Arab Emirates, pp. 183–187.

Krajzewicz, D., Rossel, C., 2007. Simulation of Urban MObility (SUMO). Centre for Applied Informatics (ZAIK) and the Institute of Transport Research at the German Aerospace Centre, available at http://sumo.sourceforge.net/index.shtml.

Krauss, S., Wagner, P., Gawron, C., 1997. Metastable states in a microscopic model of traffic flow. Physical Review E 55 (5), 5597–5602.

Liu, C., Chigan, C., 2012. RPB-MD: Providing robust message dissemination for vehicular ad hoc networks. Ad Hoc Networks 10 (3), 497–511.

Martinez, F. J., Fogue, M., Coll, M., Cano, J.-C., Calafate, C. T., Manzoni, P., July 2010. Assessing the Impact of a Realistic Radio Propagation Model on VANET Scenarios Using Real Maps. In: 2010 9th IEEE International Symposium on Network Computing and Applications (NCA). Boston, USA, pp. 132–139.

Martinez F. J., Cano J.-C., Calafate C. T., Manzoni P., May 2008. Citymob: a mobility model pattern generator for VANETs. In: IEEE Vehicular Networks and Applications Workshop (Vehi-Mobi, held with ICC), Beijing, China.

Martinez F. J., Cano J.-C., Calafate C. T., Manzoni P., October 2009a. A Performance Evaluation of Warning Message Dissemination in 802.11p based VANETs. In: IEEE Local Computer Networks Conference (LCN), Switzerland.

Martinez F. J., Toh C.-K., Cano J.-C., Calafate C. T., Manzoni P., October 2009b. A survey and comparative study of simulators for vehicular ad hoc networks (VANETs). Wireless Communications and Mobile Computing. DOI:10.1002/wcm.859.

Modsching, M., R., K., K., H., March 2006. Field trial on GPS Accuracy in a medium size city: The influence of built-up. In: 3rd Workshop on Positioning, Navigation and Communication 2006 (WPNC'06). Hannover, Germany.

OpenStreetMap, 2011. A collaborative project to create a free editable map of the world. Available at http://www.openstreetmap.org.

Slavik, M., Mahgoub, I., January 2010. Stochastic Broadcast for VANET. In: 2010 7th IEEE Consumer Communications and Networking Conference (CCNC). Las Vegas, USA, pp. 1–5.

Suriyapaibonwattana, K., Pomavalai, C., Oct. 2008. An effective safety alert broadcast algorithm for VANET. In: International Symposium on Communications and Information Technologies, 2008. ISCIT 2008. pp. 247–250.

Suriyapaiboonwattana, K., Pornavalai, C., Chakraborty, G., Aug. 2009. An adaptive alert message dissemination protocol for VANET to improve road safety. In: IEEE Intl. Conf. on Fuzzy Systems, 2009. FUZZ-IEEE 2009. pp. 1639–1644.

Task Group p, 2006. IEEE P802.11p: Wireless access in vehicular environments (WAVE). IEEE Computer Society.

TIGER, 2011. TIGER: Topologically Integrated Geographic Encoding and Referencing. Available at http://www.census.gov/geo/www/tiger.

Torrent-Moreno, M., Jiang, D., Hartenstein, H., 2004. Broadcast reception rates and effects of priority access in 802.11-based vehicular ad-hoc networks. In: Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks. VANET '04. ACM, New York, NY, USA, pp. 10–18.

Tseng Y.-C., Ni S.-Y., Chen Y.-S., Sheu J.-P., 2002. The broadcast storm problem in a mobile ad hoc network. Wireless Networks 8, 153–167.

Vahdat, A., Becker, D., July 2000. Epidemic routing for partially-connected ad hoc networks. Tech. rep., Duke University.

Viriyasitavat, W., Bai, F., Tonguz, O., dec. 2010. UV-CAST: An urban vehicular broadcast protocol. In: 2010 IEEE Vehicular Networking Conference (VNC). Amsterdam, The Netherlands, pp. 25–32.

Wisitpongphan N., Tonguz O.K., Parikh J.S., Mudalige P., Bai F., Sadekar V., 2007. Broadcast storm mitigation techniques in vehicular ad hoc networks. IEEE Wireless Communications 14, 84–94.