Knowing Vehicles Location HELPs Avoiding Broadcast Packets Storm*

Roberta Fracchia, Michela Meo, Dario Rossi
Politecnico di Torino
name.surname@polito.it

Abstract

This paper proposes HELP, *a simple and distributed broadcast algorithm for warning delivery services in inter-vehicular ad hoc networks. Assuming that neighborhood location information is available from the routing layer, each node determines whether to re-broadcast the message based on i) the coverage zone of the received message and ii) the estimated position of its neighbors. Investigations are led using a popular microscopic traffic model, in order to ensure realism of the networking performance evaluation. Results show that the algorithm efficiently limits the number of broadcasted messages, which is very close to the optimal. Furthermore, robustness of the results in terms of the number of informed vehicles can also be achieved, provided that a safety error margin is considered in the position estimate.*

1 Introduction

The price paid for mobility in Europe is too high. In year 2000, road accidents killed over 40,000 people and injured more than 1.7 million: paradoxically, a "killer application" in inter-vehicular communications would be the one that actually helped in saving many human lives. Indeed, the intolerable human and social costs of road injuries is pushing governments and corporations to invest on the deployment of new applications for road safety, based on wireless technologies for inter-vehicle communications [1, 2].

In this context, Information and Warning Functions (IWF) [2] services consist in equipping vehicles with communication facilities so that, when dangerous situations are detected (either by specific on board devices or by drivers initiative), a warning message can be propagated to vehicles that follow by adopting ad hoc networking capabilities. However, despite the wireless technology is now mature enough to allow the development of such services, inter-vehicular networking poses a number of new challenges, as it has recently been highlighted [3]. Indeed, although vehicles can only drive along the road direction (which makes their movement pattern very regular), nevertheless rapid changes in the network topology are difficult to predict given the high speed (which makes the network prone to frequent fragmentation, leading to high variability of the connectivity). Moreover, the case of IWF is particularly critical due to the need for very short delay and high reliability in the information delivery; at the same time the channel utilization should be kept as low as possible to allow the contemporary deployment of other services. Hopefully, a handle to solve the problem could come from the requirement of commercial services. Indeed, robust and scalable inter-vehicle routing protocols are definitively needed for building successful services such as entertainment applications. Therefore, IWF may profitably exploit information that is readily available from the exchanged beacon messages, which are likely to include vehicle positions and traveling speeds [2, 4]. Based on this assumption, we propose a broadcast algorithm called HELLO-Estimated Location-based Procedure (HELP), that aims at meeting the IWF requirements by exploiting the location information available from the routing layer.

Besides, we stress that the effectiveness of a broadcast IWF algorithm strongly depends on the network topology and connectivity, which in their turn depend on the mobility model. Therefore, in order to evaluate the performance of the proposed broadcast algorithm, we adopt a realistic traffic model based on cellular automata research.

The reminder of the paper is organized as follows. Related works are discussed in Section 2, while Section 3 focuses on the IWF service; Section 4 describes the vehicular traffic model adopted to gather the simulation results reported in Section 5; Section 6 concludes the paper.

2 Related work

Inter-Vehicular Communications (IVC) received much attention in the last years: this section summarizes the research community findings that are more relevant to the purpose of our work.

We point out that the use of beacon (or HELLO) packets to discover and maintain neighbor relationships is gain-

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ing popularity in both *unicast* as well as *broadcast* inter-vehicular communications. Broadcast communications adopted the beaconing service essentially for the higher system reliability that can be achieved through the knowledge of neighborhood within a one- or two-hops radius [5].

Much of the research in unicast IVC derives from the more general Mobile Ad Hoc Network (MANET) context, where the beaconing information is used either in a *topology* based or a *position* based fashion. Topology based approaches use the information about the existing network *links* in order to build at each node the local perspective of the network graph: in other words, the *connectivity* is known but not the exact position of the neighbors. Topology based routing algorithm maintain information about available paths in the network. However, recent works [6] highlighted that topology-based approaches may not be suitable for vehicular MANET: indeed, given the high mobility of vehicles, the topology discover and maintenance task is very expensive and introduces an excessive amount of control message overhead.

Conversely, position-based routing relies on the knowledge of the *geographical position* of nodes in the network, which requires vehicles to be equipped with the Global Positioning System (GPS). The basic idea is to exploit more precise information (i.e., the position, the traveling direction) while avoiding to maintain more complex global topological information. Position based paradigm is a promising approach suitable for the IVC context, as its growing consensus in both academic [6] and corporate [2] research testifies. Based on this premises, in the following we assume that a position based routing protocol is adopted by the on-board IVC device, so that geographic information regarding the neighborhood is available to implement other services, such as the broadcast IWF proposed in this paper.

3 Information and Warning Functions

As reference scenario we consider a highway-like traffic, where the high speed of vehicles increases the importance of a timely warning propagation in hazardous situations. At any moment and at any point of the highway, sensors on board of vehicles may detect a potential danger, such as an accident. In this case, the system automatically triggers the propagation of a warning message: the objective of the warning delivery service is to advertise all vehicles in a region closed to the detected danger and called *security area*. Vehicles outside this area, instead, never relay the warning, so that the medium remains available for other possible communication services.

The IWF task is accomplished by forwarding the warning message over the security area, exploiting multi-hop ad hoc broadcast communications. That is, IWF does not make use of any routing service, but uses the neighborhood location information gathered by the routing layer. We assume that a position-based routing protocol, relaying on beaconing service, is implemented by the on-board IVC device: thus, we adopt the common HELLO packet format and the standard beaconing procedure described in the literature. To be more precise, HELLO packets, which are usually about 20 Bytes long, carry information regarding i) the vehicle identifier, ii) its geographical position [2, 4] and ii) its speed [2]. The inter-beacon transmission interval B is usually *fixed* to a value between 1 s and 3 s, although it can also be *adapted* to the vehicle speed (as proposed in [7], on the basis of the observation that a node position changes more rapidly at higher speeds). In the following, we restrict our attention to fixed values of B and, to avoid synchronization and beacon collisions, we jitter the transmission of each beacon as in [4], so that the inter-beacon transmission is uniformly distributed in [$0.5B$, $1.5B$].

For what concerns the MAC protocol, nodes are equipped with carrier sense capabilities and adopt a Carrier Sense Multiple Access (CSMA) mechanism: in order to avoid collisions, they sense whether the channel is busy before starting a transmission. In case the channel is busy, then the message transmission is delayed, for an amount of time slots uniformly distributed between zero and the contention window size, until the medium is sensed idle.

We do not investigate the content of the warning message but we assume that the relaying vehicle piggybacks the beacon information on the warning message itself. Besides, alert packets carry: i) the position of the detected danger, ii) the time of the first warning transmission, iii) the original source identifier as well as iv) a randomly chosen packet identifier, assigned once by the original source. All nodes are required to cache this information on a received-alert table and, at every forwarding hop in the network, each node performs a table lookup. In this way, if a message with the same identifiers is found, then the node avoids to rebroadcast it: in this way, every node forwards a message related to the same danger at most once.

3.1 The HELP broadcast algorithm

The core of a broadcast distributed IWF is the forwarding decision locally implemented at every node in the security area: this section proposes a decision mechanism called HELLO-Estimated Location-based Procedure (HELP). The basic idea of HELP is that each node estimates the position of its neighbors by exploiting the information exchanged by IVC routing algorithms through the use of HELLO packets; the neighbors position is then used to decide whether a message should be forwarded or not. In order to describe the HELP algorithm, we adopt the following notation, sketched also in Figure 1. Let the road be represented by an x-axis in the direction of vehicles movement. The security area starts

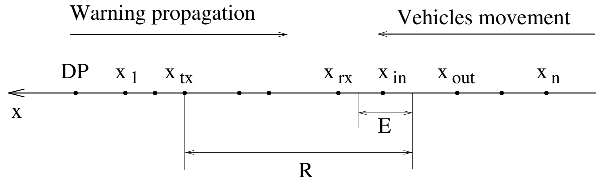

Figure 1. The warning propagation

in the Danger Point, DP, and comprises n vehicles positioned along the x-axis at $x_1 > x_2 > \cdots > x_n$. The warning message has to be propagated from DP in the opposite direction with respect to the vehicles movement, i.e., toward decreasing values of x and, hopefully, it should reach all nodes up to the n-th one.

We assume that the IVC routing layer maintains neighborhood state informations, called the neighbors set $\mathcal{S}$, recording for each neighbor i the touple $(i, \hat{t}_i, \hat{x}_i, \hat{v}_i)$ which stores the node identifier i, the time of the HELLO transmission $\hat{t}_i \leftarrow t_i$, the position $\hat{x}_i \leftarrow x_i$ and the speed $\hat{v}_i \leftarrow v_i$ of the node at the HELLO transmission time. Moreover, HELP maintains soft-state neighbor table entries based on their age using a timer T, which can be considered as an "age threshold": below the threshold T, HELP considers the routing-layer information to be up-to-date, whereas any member of the $\mathcal{S}$ set older than T is discarded.

With the help of Figure 1, let us assume that at time t node rx receives a warning message from node tx; the rebroadcasting decision process at rx is based on the following steps:

S1) the warning message coverage zone is *precisely* evaluated (by means of the transmission range R and of the *actual* transmitter position x_{tx}, which is piggybacked in the warning packet) as the zone from x_{tx} to $x_{tx} - R$;

S2) the position of the neighbors are *estimated* by using the information stored on node rx's neighbor set $\mathcal{S}_{rx}$ as $\tilde{x}_i = \hat{x}_i + (t - \hat{t}_i)\hat{v}_i, \forall i \in \mathcal{S}_{rx}$;

S3) the *closest preceeding* neighbor c is identified; c is the closest preceeding neighbor in the traveling direction or, equivalently, the closest neighbor in the warning propagation direction, thus $c = \arg\min_{i \in \mathcal{S}_i}(x_{rx} - \tilde{x}_i > 0)$;

S4) finally, the receiving node decides to rebroadcast the warning message when:

- c is *outside* the coverage range (i.e., as the case where $c = out$ in the Figure);
- c is *inside* the coverage range (i.e., $c = in$) but within a distance E from the coverage border.

The above two rules, separately described for the sake of clarity, can be expressed in a single threshold-based decision: thus, the warning message is forwarded iff, $\tilde{x}_c < x_{tx} - R + E$.

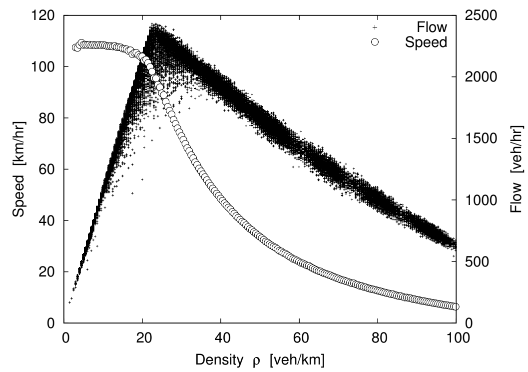

Figure 2. Vehicular fundamental diagram

The aim of the HELP algorithm is to exploit the position information in order to minimize the number of messages needed to inform vehicles traveling in the security area: intuitively, the number of unnecessary transmissions are minimized if only the last (faraway) node in the current message transmission range forwards the message. Observe that errors on the estimation of the neighbors position have negative impact on the performance of HELP. In particular, the *sign* of the error leads to opposite consequences: underestimating the distance of a neighbor raises the number of unnecessary relay nodes, whereas distance over-estimation reduces the number of informed vehicles. Therefore, the safety margin E is included in order to reduce the "missed forwarding" errors (i.e., nodes that erroneously decide to avoid to re-broadcast the warning) in the decision process, in order to account for i) over-estimation of the neighbor position and ii) possibly missing neighborhood information due to beacon collision.

4 Vehicular traffic models

During more that seven decades, several attempts have been undertaken in order to understand how the traffic flows: Cellular Automata (CA) models, to which we restrict our attention in the following, represent one of the core tools developed by the traffic research community. This microscopic modeling technique has been increasingly used in the last decade [8, 9], because it displays properties similar to the real traffic dynamics, as the good match with empirical traffic measurements testifies [10, 11].

In both the real and the simulated CA traffic two qualitatively different states can be identified, namely a "free-flow" and a "congested" regime, that correspond to rather different driving conditions, with increasing levels of correlation between vehicles. To enter in greater details, let us consider the typical measurement of the traffic, i.e., the so-called *fundamental diagram*, which is shown in Figure 2, along with the average vehicle speed as a function of the vehicular density. The fundamental diagram displays the traffic flow F, expressed in vehicles per hour, as a function of the density ρ, expressed in vehicles per kilometer. Each point on Figure 2 represents the system state sampled at the accident time over all simulations performed considering CA generated traffic.

The fundamental diagram clearly depicts the phase transition between the different traffic states: the typical transition is from the free-flow state, characterized by large velocity and small density, to a congested regime where the density is high whereas the average velocity of different vehicles is synchronized and considerably smaller. Reasonably indeed, there is no flow when there is no car on the road, $F = 0$, and there is also no flow when there is a dense jam $\rho = \rho_{max}$. In between, the flow reaches a maximum value F_{max} at some critical density $\rho_c \simeq 25$: below ρ_c, vehicles move nearly at maximum speed without interference from other vehicles; as the density increases above ρ_c the velocity decreases, flow and density are strongly correlated and the system eventually becomes *jammed* (i.e., small speeds, small flows and large densities).

In microscopic modeling each *vehicle* is individually resolved: a vector of state variables (x_k, v_k) describes the spatial location and the speed of the k-th vehicle along a one-dimensional road with periodic boundary conditions. Though the latter assumption may seem in contrast with real highways, it is nevertheless justified, since it has been shown for a large class of models that different boundary conditions select steady state behaviors rather than change their microscopic structure. A *model* then consists of a set of rules or equations to update these quantities over time, depending on the states of other vehicles around. Let us assume that vehicles move to the left, that is, referring to Figure 1 toward increasing values of x. CA models are discrete in both space and time, which is an advantage for computer simulation: space is typically coarse-grained to the length that a car occupies in a jam, and timestep is usually about one-second long. Among the different CA models we selected the Nagel and Schreckenberg (NaSch) automaton [8], whose set of update rules, performed in parallel over all vehicles, is as follows:

$$\begin{array}{ll} \text{1. Car-follow :} & v_k \leftarrow \min\{v_k + v_u, d(n_{k-1}, n_k), v_{max}\} \\ \text{2. Noise :} & v_k \leftarrow \max\{v_k - v_u, 0\} \quad \text{w.p.} \quad P_d \\ \text{3. Motion :} & x_k \leftarrow x_k + v_k \end{array}$$

The first rule describes deterministic car-following behavior: drivers try to accelerate by one speed unit (v_u) except when the gap from the vehicle ahead is too small or when the maximum speed v_{max} is reached. The second

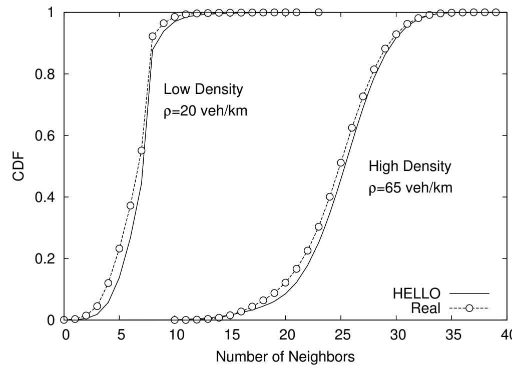

Figure 3. CDF of the number of neighbors and of the number of received HELLO messages

rule introduces random noise: with probability P_d, a vehicle ends up being slower than calculated deterministically; this parameter simultaneously models effects of i) speed fluctuations at free driving, ii) over-reactions at braking and car-following, and iii) randomness during acceleration periods. By tuning the parameter of the NaSch model, the free-flow branch of empirical fundamental diagrams [10] is in agreement with empirical findings and, for the practical purpose of this work, also the congested moving vehicles are described at the microscopic level with a sufficient degree of realism.

5 Numerical results

Using a discrete event simulator that accurately describes the system behavior, we evaluate the performance of the warning-propagation strategy described in Section 3. Indeed, though vehicle dynamics have a rather coarse timescale, the simulator features a μs time-granularity, which is apt to describe networking dynamics. We assume that on-board IVC devices transmit on an error-free wireless medium at a 2 Mbps rate, with transmission range $R = 200$ m equal for all vehicles. In the CSMA, the contention window is set to 31 time-slots and the time-slot is $20\,\mu$s long. Warning message size is 1000 Bytes, whereas HELLO packet size is 20 Bytes; we consider different beaconing intervals B, among values usually used by routing algorithms. Movements of vehicles, as well as distances, are one-dimensional along the direction of the highway, and we consider a 2 km long security area.

The NaSch traffic model is calibrated as follows: the security area is divided into cells of 7.5 m and vehicles position and speed are updated in timesteps of 0.12 s; the maximum speed is set to $v_{\max} = 0.5$ cells/step, corresponding to 112 km/hr, and the speed change unit is $v_u = 0.1$ cells/step; the decay probability is set to $P_d = 0.16$.

Performance is expressed in terms of the probability

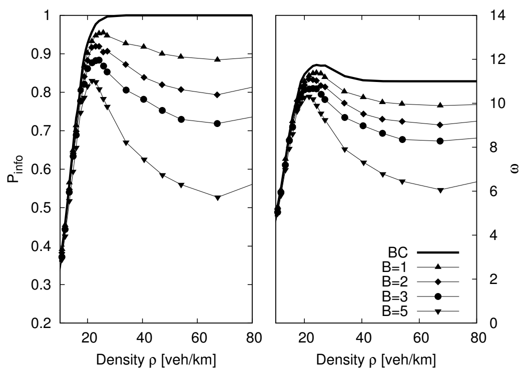

Figure 4. Average probability of informing all nodes and average number ω of transmitted warning versus the vehicle density ρ for different values of the beaconing interval B

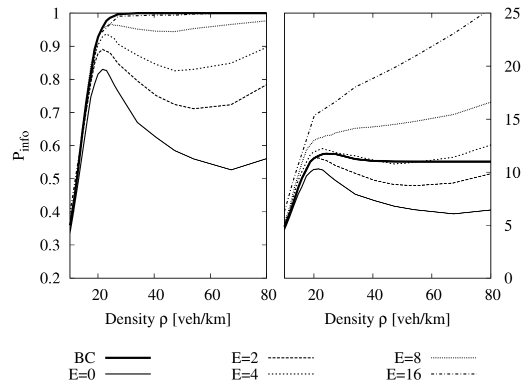

Figure 5. Average probability of informing all nodes and average number ω of transmitted warning versus the vehicle density ρ for different error margins E, when B=5 s

P_{info} of informing all vehicles in the security area, and of the number ω of warning messages exchanged in the security area. We compare results obtained by the proposed algorithm with the Best Case (BC in the Figures), derived with a centralized approach based on the knowledge of all nodes exact position: the BC selects the smallest set of rebroadcasting nodes such that all connected nodes are advised, thus maximizing the number of informed nodes while minimizing the number of exchanged messages. Note that we do not directly investigate the beacon messages overhead, since we assume that they have to be independently transmitted by the implemented routing strategy.

Figure 3 reports the cumulative distribution function (CDF) of the number of vehicles in the transmission range at the time of the IWF decision and the CDF of the number of received HELLO messages in the last beaconing interval (i.e., the estimate of the number of neighbors through the beaconing procedure) when $B = 1$ s. The plot shows that, at both low (20 veh/km) and high (65 veh/km) densities, the number of received beacons corresponds quite well to the actual number of neighbors. This underlines how the use of a jittered beacon transmission keeps collisions of HELLO messages negligible. As a consequence, in every beaconing interval B, nodes gather a complete information of their neighborhood. Therefore, we select the age threshold to be $T = B$, thus considering valid only the information received during the last beaconing cycle.

Figure 4 depicts the performance of the HELP algorithm as a function of the density ρ and for different values of the beaconing interval B. Besides the values $1, 2$ and 3 s, usually used by routing algorithms, we also consider a larger interval of 5 s: the latter will allow us to assess the impact of the information age on the achievable performance. Initially, we do not consider any error margin on the position estimate, thus we set $E = 0$ m. The left plot of Figure 4 reports the average probability of informing all vehicles in the security area, achieved by HELP as well as by the best case BC, reported as a reference. It is interesting to notice that when vehicles are in free-flow ($\rho < 25$ veh/km), HELP performance is very close to the best case –which is mainly driven by the network connectivity– for any of the considered B: indeed, since the road is uncongested, vehicles unlikely modify their speed in 5 seconds or less and the HELP position estimate results very accurate. On the contrary, when traffic is jammed, vehicles speed may rapidly change and the accuracy of the position estimate is possibly significantly threatened as B increases. In order to explain the significant performance gap at high densities between $B = 1$ s and the optimum performance, let consider what happens in the worst case, where a vehicle may advertise the maximum speed at the beaconing time and then gradually come to a complete stop: in this case, it is easy to gather that the position over-estimation error exceeds 20 meters.

The right plot of Figure 4 reports the amount of traffic generated in the security area in terms of the number w of transmitted warnings; notice that w also corresponds to the number of *relay* nodes, since every vehicle forwards the message at most once. First, it can be observed that HELP always transmits less warnings messages with respect to the best case: this implies that nodes implementing HELP rarely forward the warning message unnecessarily, whereas, more often, they fail to relay a warning message due to an overestimation of the neighbor distance.

However, these errors can be easily avoided by considering an error margin E on the position estimate, whose benefits are presented in Figure 5. We choose E in [0,16] m and we consider the worst among the previous analyzed cases, namely B=5 s. The left-hand side plot shows the ratio of informed nodes for different values of E, as a function of the density ρ: as expected, when a safety error margin is

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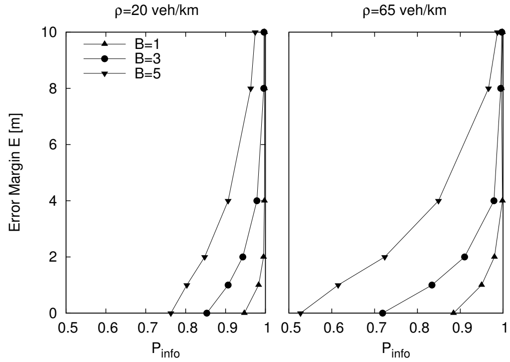

Figure 6. Required minimum error margin E [m] as a function of the target probability to inform all nodes in the security area

adopted, the probability P_{info} of informing all nodes in the security area increases with E, eventually reaching the best case performance. At the same time though, the number ω of transmitted warnings may significantly increase beyond the best case reference, as it can be gathered from the $E \geq 8$ m curves of the right-hand side plot. The latter observation suggests that, for any given beaconing interval B, an *adaptive* error margin (e.g., depending on vehicles densities, speeds and other traffic parameters) may be required in order to jointly increase as much as possible the number of informed vehicles while keeping the number of exchanged messages close to the optimum. Notice also that, although the number of messages required to broadcast the warning increases with E, the increase is quite small and probably convenient, if the beaconing *overhead* that decreases with B is also considered. In other words, the use of an error margin $E = 16$ when $B = 5$, which yields to the optimum P_{info} under any traffic conditions, may cost as much as 10 more messages per-alert, but allows to economize as much as 4 beacons per-vehicle per-second with respect to $B = 1$.

Finally, we provide in Figure 6 the means to properly tune, given the beaconing interval B, the error margin E as a function of the target desired value of P_{info}. Indeed, the plot depicts different curves, one for each beaconing interval, representing the minimum error margin E (on the y-axis) necessary to achieve the desired ratio P_{info} of informed nodes (on the x-axis) under different traffic conditions. Specifically, we consider both the transition phase between free-flow and congested state (on the left-hand side), as well as high congested traffic conditions (on the right-hand side); conversely, the free-flow state is not reported, as HELP performance tightly follows the optimum. Figure 6 confirms that a larger error margin is required in order to obtain a satisfactory level of performance under i) an increasing beaconing interval as well as ii) an increasing traffic congestion, further quantifying the actual error margin that can be used in real implementations. This can be also instrumental to the design of adaptive beaconing intervals [7], aimed at reducing the number of transmitted messages in jammed traffic conditions: our results suggest that, in order to maintain the same ratio of informed nodes across different beaconing intervals, also the error margin E has to be adapted accordingly.

6 Conclusions

In this paper we proposed a distributed broadcast algorithm for information and warning functions in inter-vehicular networks. The forward decision is based on the neighborhood location information, achieved through the beaconing service usually adopted by position-based routing algorithms: given the position and speed of the neighbors at the beacon transmission time, every node decides whether to forward the warning message or not, by estimating the neighbors position at the time of the decision. The algorithm performance is evaluated in realistic traffic conditions and are promising in the considered scenarios: by tuning the error margin and the beaconing interval, we showed that it is possible to achieve a target performance (i.e., the desired ratio of informed vehicles) with different costs (i.e., in terms of the number of exchanged broadcast messages and of the beaconing overhead).

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