Avoiding broadcast storms in inter-vehicular warning delivery services

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***Abstract*— This paper proposes a simple and efficient distributed broadcast algorithm for warning delivery services to be used in inter-vehicular ad hoc networks. The performance achieved by the proposed algorithm is compared against those of a simple probabilistic flooding scheme. Investigations are lead under two different kinds of vehicular traffic: i) the popular and commonly used Poisson-based mobility model, and ii) a microscopic traffic model. Our findings are twofold. First, we show by extensive simulation that the proposed solution is very effective; second, we show that vehicular traffic dynamics have an important impact on the network performance, especially under low density conditions.**

I. Introduction

It is often envisioned that tomorrow networks will be so deeply rooted in the surrounding environment that hardly any activity will be undertaken without interacting with some wireless technology. Inter-vehicle networking, being no exception, seems particularly promising: indeed, while entertainment services on board of vehicles are appealing for improving traveling comfort, services aiming at increasing road safety are even more interesting. The enormous human and social costs of road deaths and injuries is pushing governments and companies to invest on the deployment of new applications for road safety, based on wireless technologies for inter-vehicle communications [1]. In this context, warning delivery service consists 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 broadcasted to vehicles that follow by adopting ad hoc networking capabilities.

Even if wireless technology is now mature enough to allow the deployment of such services, inter-vehicular ad hoc networking poses a number of new challenges. The novelty with respect to other ad hoc networks has been recently discussed in [2], which highlights that i) rapid changes in the network topology are difficult to predict and manage; ii) the network is prone to frequent fragmentation, leading to high variability of the connectivity; iii) the redundancy should be limited. The case of warning delivery service is particularly critical due to the need for very short delay and high reliability in the information delivery. In this paper we propose *distance-aware delayed-flooding (*d^2*-flooding)*, a broadcast algorithm that aims at meeting these requirements while avoiding to use an excessive amount of bandwidth, so that the contemporary deployment of other services is also possible.

The effectiveness of a broadcast algorithm is strongly dependent on the network topology and connectivity, which in their turn depend on the mobility model. Thus, when developing a broadcast algorithm, realistic and accurate mobility models should be used, especially for scenarios with high vehicles mobility, such as for highway traffic. However, despite their common use, mobility models traditionally considered by the networking community are not suitable for vehicle movement patterns; neither are models used in the studies of cellular systems, which focus on aggregate statistics, such as road and cell capacity. Indeed, the analysis of inter-vehicle ad hoc networks requires a detailed description of the traffic dynamics at a *microscopic* level, i.e., by considering the individual vehicle movements and the correlation between the behavior of neighboring vehicles. Thus, in the paper, in order to evaluate the performance of the proposed broadcast algorithm, we use both a simple Poisson-based mobility model, as those commonly used, and a more realistic model, based on cellular automata research. Indeed, it is our belief that while Poisson-based models remain a core tool, e.g., for analytical frameworks, it is also extremely important to assess the achievable network performance level under more realistic scenarios.

Summarizing, the main contributions of this paper are the following.

- We propose *distance-aware delayed-flooding* (d^2-flooding), a broadcast algorithm that is suitable for the warning delivery service in inter-vehicular ad hoc networks.
- While evaluating the algorithm performance, we use both a Poisson-based mobility model and a more realistic traffic model, so that we can evaluate to what extend the traditional model is accurate.

The reminder of the paper is organized as follows. Section II describes the warning delivery service and the networking assumptions, while Section III focuses on the vehicular traffic models; simulation results are reported in Section IV, and Section V summarizes our findings.

II. Warning Delivery Service

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.

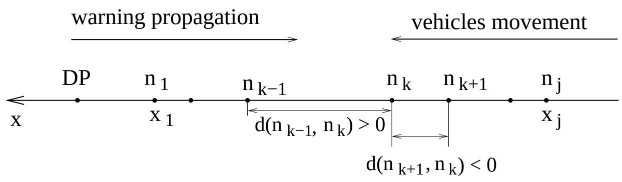

Fig. 1. Schematic representation of the warning propagation

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 close to the detected danger and called *safety area*.

The warning delivery task is accomplished by forwarding the warning message over the safety area, exploiting multi-hop ad hoc communications. In order to extend the message lifetime within the zone of relevance, subsequent broadcast cycles can periodically be triggered either by any of the vehicles involved in the accident or by stationary road-side units [3], which may store messages from passing vehicles and relay these messages to other vehicles later in time. In the following, since our focus is on the effectiveness of the broadcast mechanism, we limit the analysis to the performance achieved within a single cycle.

Also, we do not investigate the content of the warning message but we assume that all vehicles are equipped with the Global Positioning System (GPS), and that the following information is reported: i) the position of the detected danger, ii) the time of the first warning transmission and iii) the position of the relay vehicle. Besides, alert packets carry iv) the original source identifier as well as a v) randomly chosen packet identifier, assigned once by the original source. All nodes[1] are required to cache these information on a received-alert table and, at every forwarding hop in the network, each node performs a table lookup. If a message with the same identifiers is found, then the node avoids to re-broadcast it: in this way, every node forwards a message related to the same danger at most once.

With the help of Figure 1, we introduce the notation used in the following. Let the road be represented by an x-axis in the direction of the vehicle movement. The safety area starts in the *danger point*, DP, and comprises j vehicles. Let $n_1, \cdots, n_j$ indicate the j vehicles in the safety area, and $x_1, \cdots, x_j$ their positions along the x-axis, with $DP > x_1 > x_2 > \cdots > x_j$. The warning should be propagated from DP in the opposite direction with respect to the vehicle movements, i.e., toward decreasing values of x and, hopefully, it should reach all nodes up to n_j. Let the distance between node n_i and node n_k be denoted by $d(n_i, n_k) = x_i - x_k$, where, clearly, the distance is positive if node n_i is closer to DP than node n_k.

The assumption that $x_i < x_j$ for $i > j$ bares additional discussion. Indeed, it could be argued that roads are actually quite convoluted and, in fact, the geographical distance $d(n_i, n_{i+2})$ can be smaller than $d(n_i, n_{i+1})$ for some i. However, we point out that, being vehicles equipped with a positioning system, they are also likely equipped with a navigation system as well. Therefore, a digital map will be available to the receiver node: the position advertised by transmitters in the alert packets can be re-mapped to a "linearized" road portion, and thus the actual road-distance, rather than the air-distance, could be easily considered. A number of additional justifications of this assumption can be raised. First, such road winding can be expected to occupy a relatively small highway portion compared to the roughly straight one. Second, the study of a linear road stretch is a preliminary but necessary step, in order for more realistic and complex geographical scenarios to be taken into account.

Finally, we point out that although alert packets usually refer to a single traffic direction, they are nevertheless received by both directions of the traffic flow. For the sake of simplicity, in the following we consider the road in the broadcast propagation direction, only. This basically is equivalent to assuming that vehicles traveling in the opposite direction can discriminate, via the GPS, that the alert message is not pertinent to the safety of lanes they are traveling along. The knowledge of the position of the danger point and of the relaying node, allows vehicles to evaluate the pertinence of the alert, simply by testing whether the direction of the broadcast message propagation is the opposite, as expected and depicted in Figure 1, with respect to their traveling direction[2]. To summarize, in the following we assume that nodes avoid to re-broadcast the alert when the danger is not related to the direction of the traffic flow they belong to.

A. The d²-flooding Broadcast Algorithm

The core of a broadcast distributed warning propagation algorithm is the forwarding decision implemented at a node. In this paper we propose a scheme called *distance-aware delayed-flooding* (d²-flooding), that is based on two main ideas: i) the forwarding decision depends on the distance from the closest neighboring relay node, and ii) a short waiting time is introduced before the message transmission. The rationale behind the idea of letting the decision depend on the distance is the following: when a node hears the message for the first time and its distance from the transmitting node is small, then the additional coverage that can be achieved by re-broadcasting the message is also small[3]; thus, the decision to forward the message should be taken with low probability. The role of the waiting time is to allow nodes to listen for new copies of the alert message: this yields to a better estimate of the closest relay distance, which is then used to tune the forwarding decision process.

[1]Since vehicles can be considered as nodes of the dynamic network, we will use the terms node and vehicle interchangeably.

[2]We acknowledge that this simple approach may be compromised by traffic intersection, motorway overpasses and highway junctions: however, we point out that more complex schemes involving digital maps could be devised to handle these scenarios; thus, we believe that also in this case, considering a linear highway stretch does not compromise the validity of the analysis.

[3]This assumption is particularly relevant if vehicles have the same transmission range and in *unidirectional* propagation, like the highway scenario we consider.

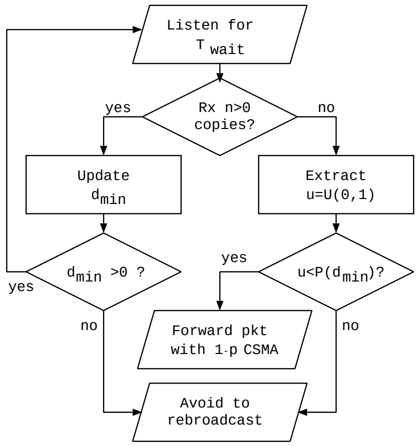

Fig. 2. Flow-chart of the d²-flooding algorithm

The d²-flooding scheme, whose flow-chart is presented in Figure 2, works as follows. As soon as a node r has received for the first time a warning message from node t_0, the node sets the variable d_{min} to the distance $d(t_0, r)$ and starts sensing the channel for a time T_{wait} during which the node checks if other copies of the same message are received. The waiting time T_{wait} is set proportional to the warning transmission time T_{tx} by a factor f plus a random amount of time-slots uniformly distributed in $[0, CW]$:

$$T_{wait} = fT_{tx} + U[0, CW]T_{slot} \quad (1)$$

where T_{slot} is the time-slot duration. Notice that T_{wait} is composed by a fixed and a variable component. The role of the fixed component fT_{tx} is to ensure that *every* node will gather sufficient information of the system status. Since we verified by simulation that the performance results are not significantly affected by any $f > 1$ value of (1), in the following we consider $f = 2$. The role of the variable component $U[0, CW]T_{slot}$ is twofold: first, it avoids the synchronization of retransmissions from nodes that decided to rebroadcast the alert. Second, and most important, it allows the *unordered* retransmission of nodes belonging to the same transmission range.

Assume that, after time T_{wait}, node r has collected m copies of the message from m nodes $t_1, t_2, \cdots, t_m$. If at least one node is further away from the DP, i.e., it exists a node t_i such that $d(t_i, r) < 0$, then r can safely avoid to forward the message: indeed, the message has already covered an area which is outside the transmission range of r and a re-broadcast from r would be useless. Otherwise, if all the transmitting nodes are closer to DP than r, i.e., if $\forall i,\ d(t_i, r) \geq 0$, then r computes the minimum estimated distance $d_{min} \leftarrow \min_i\{d_{min}, d(t_i, r)\}$ and enters a new waiting phase.

Conversely, when during the sensing period no copies of the message are received, the alert is then forwarded with a probability $P(d_{min})$, increasing with the minimum estimated distance d_{min} from the relaying hosts. Thus, in the case where the node decides to rebroadcast, the alert message is delivered to the MAC layer, which adopts a 1-persistent Carrier Sense Multiple Access (CSMA) mechanism. Among the several function families that can be used to set the probability $P(d_{min})$, we choose:

$$P(d_{min}) = 1 - (1 - d_{min}/R)^k, \quad k > 1 \quad (2)$$

Note that in the support $d_{min} \in [0, R]$, the curves are monotonically increasing in both d_{min} and k, and that the function degenerates into d_{min}/R when $k = 1$. The impact of k in (2) will be thoroughly discussed in Section IV.

The work closest to ours can be found in [4] and [5]. The idea of letting the decision process depend on the distance was already present in [4], but the decision process was threshold-based rather than *probabilistic*. Moreover, though many broadcast protocols, such as [5], introduce a waiting time, this is usually randomly chosen from a uniform distribution between $U[0, T_{max}]$; instead, our approach actually *increases* the lowest waiting time to $fT_{tx} > 0$, in order to ensure that every node will gather sufficient information of the system status; however, as we will show in Section IV-B, delaying the decision does not negatively affects the timeliness of the broadcast propagation.

For comparison purposes, in what follows we also consider the very simple α-*flooding* strategy ruling that, upon reception of a new message, a node chooses to forward the message with probability α. In both the considered strategies, the d²-flooding and the α-flooding, forwarding happens only *within* the safety area: vehicles outside this area, instead, never relay the warning, so that the medium remains available for other possible communication services.

III. Vehicular Traffic Models

Inter-vehicular networking performance are usually evaluated using the so-called Poisson-Arrival Location Model, i.e., models in which vehicles arrive according to a Poisson process and move independently from each other. For example, [6] considers vehicular speeds conforming to a truncated Gaussian distribution, using different speed averages to model different levels of congestion – and similar approaches are still adopted by other very recent work [7]. Moreover, all these models, that we will indicate as No-Brake No-Accelerator (NBNA), consider that vehicles travel on the safety area at a constant speed.

However, vehicular traffic modeling is now older than seven decades [8], and several attempts have been undertaken in order to understand how the traffic flows. Many models currently in use display properties similar to the real traffic dynamics; this is the case of Cellular Automata (CA) models to which we will restrict our attention in the following. Already introduced in the 1950s [9], this microscopic modeling technique has been increasingly used in the last decade [10], [11], [13], [12], also because of the good match exhibited by such models with empirical traffic measurements [14], [15], [16]. Indeed, in both the real and the simulated traffic two qualitatively different states, namely a “free-flow” regime and a “congested” one, can be identified. These regimes correspond to rather different driving conditions, with increasing levels of correlation between vehicles: the free-flow state is characterized by large velocity, small density, and vehicles moving almost independently from each other, while in the congested state the density is high whereas the average velocity of different vehicles is synchronized and considerably smaller.

Nevertheless, to the best of our knowledge, the only communication-oriented work that makes use of CA models is [17], where networking model is limited to a connectivity-graph. Alternatively, communication-oriented studies that attempted to take realistic traffic dynamics into account [18], rely on the use of commercial highway traffic simulators such as CORSIM[19].

A. Cellular Automata Models

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 wrap-around boundary conditions. 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. A side effect of this convention is that space can be measured in "cells", time in "steps" and usually these units are assumed implicitly and left out of the equations: e.g., a speed $v = 5$ means that the vehicle travels five cells per timestep.

As previously mentioned, many different models exist: we selected the Nagel and Schreckenberg (NaSch) automaton [10], which is a minimal model, in the sense that any simplification leads to a loss of realism. The set of update rules, performed in parallel for each vehicle, is as follows:

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

The first rule describes deterministic car-following behavior: drivers try to accelerate by one speed unit except when the gap from the vehicle ahead is too small or when the maximum speed v_{max} is reached. The second 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. Due to the parallel update, an implicit reaction time of the order of the timestep is introduced; however, rather than representing the actual driver's reaction time, which would be much shorter, the reaction time is a measure of the time elapsed between the stimulus and the action of the vehicle. It is worth mentioning that several modified rules exist, such as velocity-dependent randomization [11] (where the decay probability P_d depends on the driving speed) or increased interaction-horizon [12] (where vehicles stochastically accelerate provided that their distance is above a safety threshold).

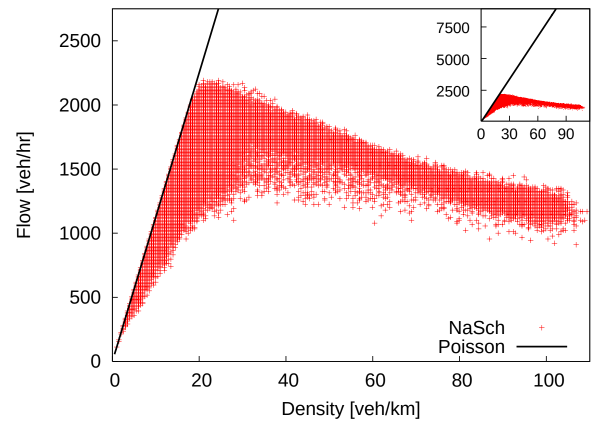

Fig. 3. Fundamental Diagram of NaSch versus Poisson-based Traffic

B. Fundamental Diagram

The typical measurement of traffic flow, the so-called *fundamental diagram*, displays the traffic flow F expressed in vehicles per hour as a function of the density ρ in vehicles per kilometer. The fundamental diagram well represents the phase transitions between the free-flow and congested traffic states: the typical transition is from the free-flow regime to a regime where throughput is virtually undiminished but densities are much higher, meaning much lower velocities, since in general $\rho = F/\overline{v}$. 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 ρ_c: below ρ_c, vehicle moves nearly at maximum speed without interference from other vehicles; as 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).

Figure 3 contrasts the fundamental diagram of a simple NBNA (Poisson-based) model with the traffic generated by the NaSch automaton: each point of the diagram represents the system state sampled at the accident time over all simulations performed. By tuning the parameters of the NaSch model, the free-flow branch of empirical fundamental diagrams [14], [15] can be reproduced quite well: both the slope as well as the maximum are in agreement with empirical findings. Thus, the NaSch model describes the moving vehicles at the microscopic level with a sufficient degree of realism, especially in comparison with Poisson-based approaches. Indeed, it is evident that while the free-flow branches of both NBNA and NaSch traffic are similar, NBNA cannot represent the congested state, as the inset of Figure 3 clearly shows: infact, the lack of a collective driving strategy yields to high unrealistic values for Poisson-based traffic flow.

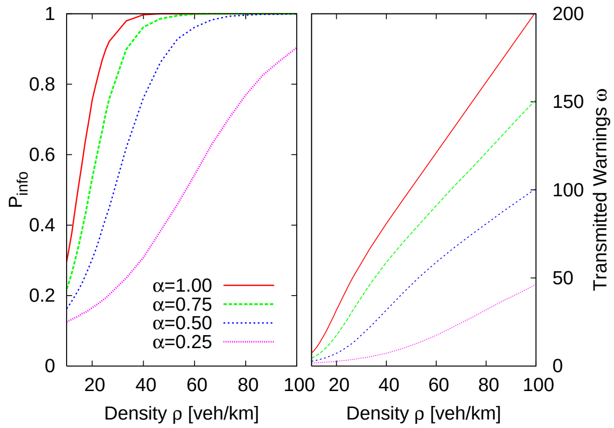

Fig. 4. Average probability of informing all nodes (left) and average number ω of warning transmitted in the safety area (right) versus vehicle density ρ for different values of the forwarding probability α

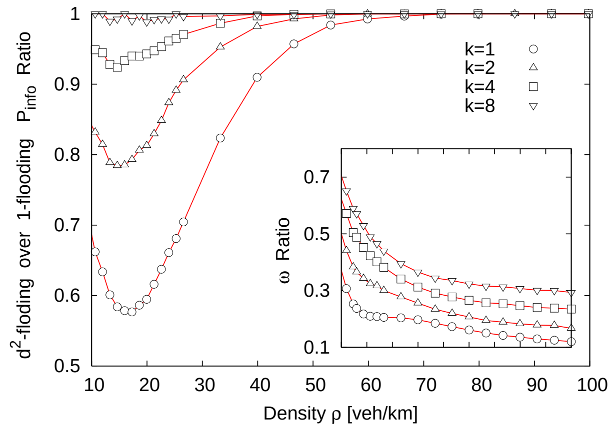

Fig. 5. Ratio of informed nodes of d²-flooding over 1-flooding algorithms (outset) and ratio of the average number of transmitted warnings (inset)

IV. Numerical Results

In this Section we evaluate the performance of the warning-propagation strategies described in Section II, using a discrete event simulator that accurately describes the system behavior. Indeed, though vehicle dynamics have a rather coarse time-scale, the simulator features a μs time-granularity, which is apt to describe networking dynamics. Movements of vehicles, as well as distances, are one-dimensional along the direction of the highway, and we consider a 2 km long safety area; vehicles transmit 1000 Bytes long warning messages at a 2 Mbps rate, with transmission range $R = 200$ m equal for all vehicles, on an error-free wireless medium. In the CSMA, CW is set to 31 and T_{slot} is 20 μs long.

Performance is expressed in terms of the probability P_{info} of informing all vehicles in the safety area, and of the number ω of warning messages exchanged in the safety area.

As previously stated, we consider two distinct traffic models. The first one is a NBNA model where vehicles arrive at average rate λ according to a Poisson process, and move at a constant speed while crossing the safety area; the speed of a vehicle is uniformly chosen in [80,120] km/hr. The second is the NaSch automaton described in Section III-A and calibrated as follows: the safety area is divided into cells of 7.5 m, representing the average length a vehicle occupies in a jam, and vehicles position and speed are updated in steps of 1.2 s; the maximum speed is set to 5 cells/step, corresponding to 112 km/hr, and the noise has probability $P_d = 0.16$.

Since, as shown early on Section III-B, NBNA and NaSch kinds of traffic have rather different flow supports, networking performance are compared for the same value of density ρ, expressed in vehicles per kilometer.

A. Poisson Arrivals

First, we analyze the alert service considering Poisson arrivals: Figure 4 depicts the performance of the α-flooding algorithm, which will be used as reference for the evaluation of d²-flooding, for different values of α as a function of the density ρ. The left-hand side plot reports the average probability of informing all vehicles in the safety area: as expected, the probability increases for larger α; however, while at high node densities almost every vehicle receives the warning message even for small values of α, the value of α has a massive impact when the node density is low. Furthermore, when $\alpha = 1$, every vehicle forwards the received message and the percentage of informed nodes approaches that of *connected* nodes: indeed, most of the times the collision cannot prevent a vehicle to be informed, since at least one of the several copies is correctly received.

In the right-hand side plot we study the amount w of traffic generated in the safety area: not surprisingly, if on the one hand, duplicate warnings offer robustness in case of errors due to the wireless channel, on the other hand, they often lead to an unnecessary waste of radio resources. Note that the number of transmitted warnings corresponds to the number of *relay* nodes: indeed, every vehicle forwards the message at most once. It is interesting to observe the dependence of the number of transmitted messages on α and ρ: it can be gathered that as α increases, the relay nodes density increases as well, which in turns enlarges the network connectivity for the broadcast service, thereby raising the amount of generated traffic. Therefore, it is desirable for any warning delivery algorithm to i) achieve the same number of informed nodes of 1-flooding, which can thus be assumed as a *target*, while ii) reducing as much as possible the number of transmitted warnings.

Figure 5 compares the number of informed nodes and the number of transmitted messages achieved by d²-flooding with those achieved by 1-flooding. The outer plot presents, for different values of the k parameter in (2), the ratio of the percentage of vehicles informed by the d²-flooding algorithm normalized over the 1-flooding one, that is our reference algorithm. As previously noticed, at high densities almost any vehicle is informed and d²-flooding reaches the performance of 1-flooding independently from k. Conversely, the effect of k is more relevant at lower density: a negative peak appears, for any $k < 8$, which is symptomatic of a delicate equilibrium between forwarding decisions and connectivity. In other words,

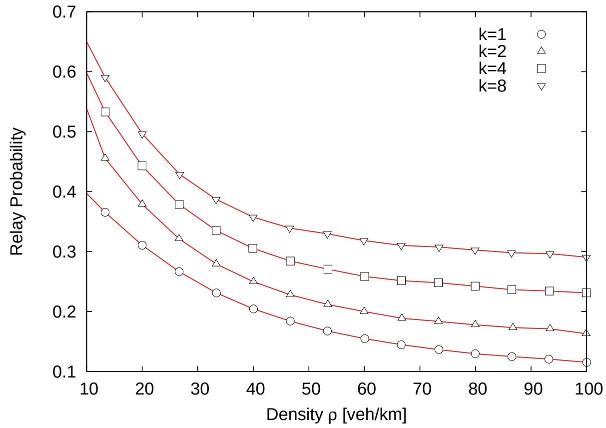

Fig. 6. Average flooding probability adopted by d²-flooding for different densities ρ and for different values of parameter k

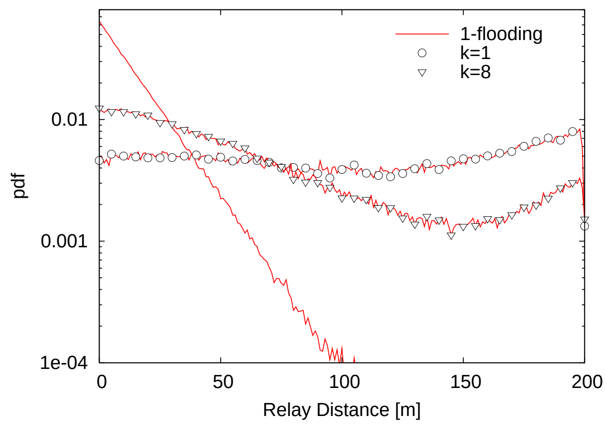

Fig. 7. Probability distribution function of the inter-relays distance, for different broadcast algorithms, at ρ=80 veh/km

at high densities all the vehicles are informed irrespectively of the rebroadcast decision; at low densities, though the protocol tuning has an important impact, the network connectivity massively limits the achievable performance. Besides, we point out that the performance increase for very low density is only apparent: infact, for such low densities the very existence of a network is questionable. Nevertheless, as expected, as k increases the forwarding probability increases, and so does the amount of informed nodes: when $k = 4$ at least 92% of the target is reached, while d²-flooding informs as many nodes as 1-flooding when $k = 8$.

The great advantage of the d²-flooding scheme is the reduction of the generated traffic, as testified by the inset of Figure 5, depicting the ratio between the number of warnings transmitted by d²-flooding and by 1-flooding. Though the number of relay nodes increases with k, for any k and for any density ρ the number of forwarded messages is significantly lower for d²-flooding than for the 1-flooding algorithm. Infact, considering $k = 8$, the d²-flooding traffic amount is at most 70% of the 1-flooding one; moreover, as desired, the higher the density, the higher the gain, since at most one third of the traffic generated by 1-flooding is needed to achieve the target P_{info} when $\rho \geq 50$ veh/km.

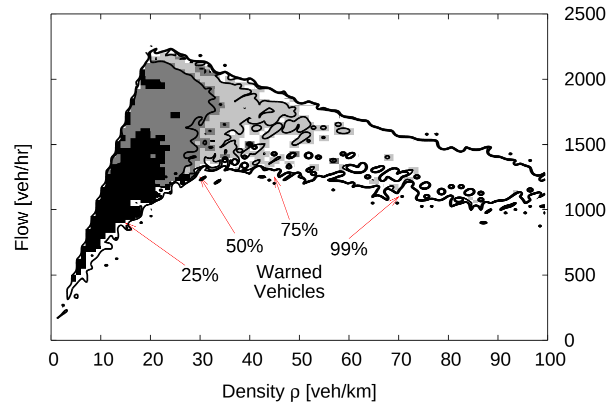

Fig. 8. Performance of 0.75-flooding in Presence of NaSch Traffic: a Fundamental Diagram Perspective

In order to better understand the d²-flooding behavior, we now take into account different metrics, starting from the analysis of the average relay probability, i.e., the probability that a node rebroadcasts the alert. Observing Figure 6, we note that, as desired, the relay probability decreases as the density increases: on the one hand, this allows a satisfactory degree of coverage of the safety area, particularly at low density; on the other hand, it contributes to significantly reduce the number of duplicate packets at higher densities. To explain this behavior, one should take into account the distance between two consecutive relay vehicles, whose probability distribution function (pdf) is plotted in Figure 7 for both 1-flooding and d²-flooding with $k = \{1, 8\}$. We report the pdf at high density (ρ=80 veh/km) where, despite the proximity of vehicles, the use of faraway relays reduces the network utilization, allowing at the same time good performance in terms of informed vehicles. When 1-flooding is used, the relay distance, which follows a negative exponential distribution, is in most of the cases shorter that 50 m and reaches 100 m with very low probabilities. Conversely, d²-flooding naturally allows the selection of maximum-distance relays (i.e., one transmission range away) with non-negligible probability for both values of k. Besides, we point out that the higher inter-relay distance contributes to both i) limit the number of exchanged messages and ii) bound the delay of the alert message

B. Realistic Traffic

In this section, we present the performance achieved by the two algorithms when the NaSch mobility model is adopted. First of all, we present in Figure 8 a natural extension of the vehicular-traffic fundamental diagram to the networking problem of broadcast information: in this plot, using the contour plot and different colors, we represent the percentage of informed vehicles in the safety area as a function of the flow and density achieved under the realistic highway traffic. Also in this case, when the traffic is congested (i.e., at high density) most of the vehicles are informed, whereas in free-flow (i.e., at low density), possibly half of fast-moving drivers

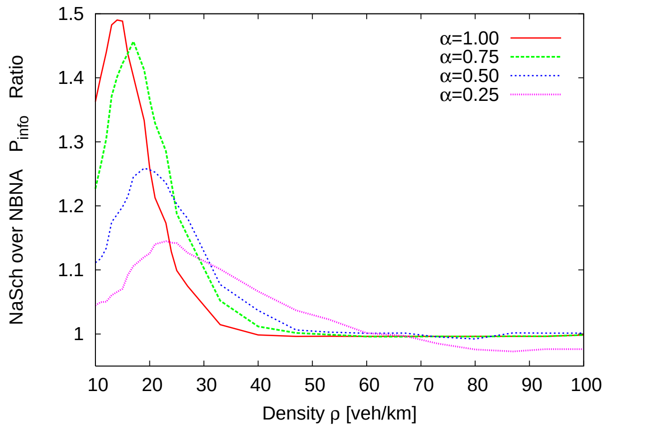

Fig. 9. Ratio between percentage of informed nodes with NaSch mobility model and with NBNA model, with α-flooding algorithm

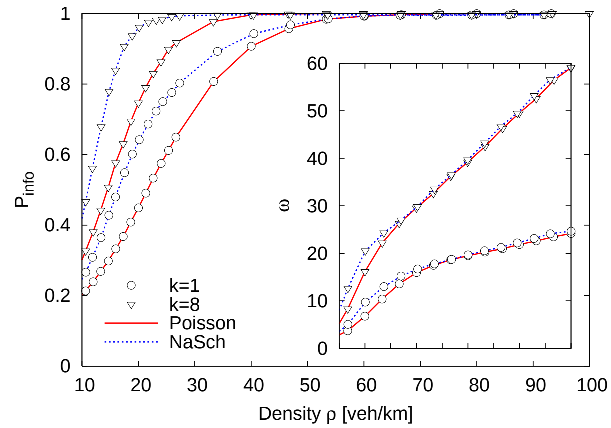

Fig. 10. Probability of informing all nodes (outset) and number of transmitted warning (inset) with d²-flooding, for both NBNA as well NaSch model

are unaware of approaching a danger.

In Figure 9 the number of informed NaSch-moving nodes is compared to the number of NBNA-moving nodes, in the α-flooding broadcast case for different values of α. It is interesting to evaluate the impact of the vehicular traffic model on the broadcast performance. For densities above 40 veh/km, the performance of the algorithm is largely unaffected by the traffic models. That is, despite the intrinsic difference of the traffic dynamics (indeed, under the NBNA model vehicles are in an artificial free-flow phase, while they are definitely in congested conditions under the realistic NaSch traffic model), the high vehicles density yields to very similar communication performance. However, this should not be surprising in reason of the previous results, which showed that several configurations of either algorithms achieved nearly the same networking performance at high traffic densities. Conversely, at lower densities, where the connectivity deeply affects the algorithm performance, the effects of different traffic models are more pronounced. Interestingly, the use of a realistic traffic model increases the connectivity, yielding to better performance of the α-flooding algorithm in terms of the number of informed vehicles. The reasons of this behavior are rooted on the properties exhibited by the *time-headway*, i.e. the time elapsed between two consecutive passing cars as measured by a standing observer. More in detail, for a given average value of the inter-vehicular distance, the *dispersion* of these values around the average plays a critical role: indeed, the time-headways distribution of both real traffic and NaSch model is known to have a peak around 0.7 s, which is caused by "platoons", i.e., groups of vehicles moving with nearly the same speed but with very small headways. This peak arises from the speed correlation among vehicles and, being clearly absent in the NBNA models with exponential inter-arrivals and constant speeds, is a probable cause of the observed performance difference.

In Figure 10 the performance of d²-flooding with realistic traffic is compared to the performance achieved under Poisson arrivals; the outer plot reports the percentage of informed nodes as a function of the density ρ for $k \in \{1, 8\}$. These results confirm the trend observed in Figure 9: Poisson-based traffic may lead to a significant *under-estimation* of the achievable performance. When designing warning delivery services, this under-estimation may lead to two effects. On the one hand, it leads to conservative estimate, and ultimately to a higher safety degree than expected. On the other hand, in the case of road-side relays (i.e., the use of stationary devices placed in highways aiming at increasing the communication performance), the performance under-estimation may lead to over-estimating the number of needed devices. Besides, it is interesting to notice that the number of transmitted warnings, reported in the inset of Figure 10 is very similar under both traffic models: the generated amount of traffic differs only for a few warning messages per kilometer at very low densities, when the generated traffic is so low to be trifling. Finally, Figure 11 shows the time necessary for the message to cover the *whole* safety area, evaluated thus when only *all* nodes are informed: both the average as well the tenth and the ninety percentiles of the distribution are reported. The plot clearly shows that d²-flooding keeps the alert propagation delay close to that of 1-flooding, and that, furthermore, the actual delay is always very close to the average in both cases.

V. Conclusions

In this paper we proposed a broadcast algorithm for the warning delivery service in inter-vehicular networks. The forward decision rule locally implemented at a node is based on the estimation of the distance from the closest neighboring relay node and on the use of a short delay, that, besides allowing the distance estimation, also avoids synchronization between transmissions.

Performance is evaluated in a wide number of scenarios considering two kinds of vehicular traffic: a very simple Poisson model in which vehicles move independently, and a more realistic model deriving from a detailed description of the vehicle movement. Two main conclusions can be drawn from the numerical results. First, the proposed algorithm is very effective. Second, Poisson-based mobility models lead to accurate results only when vehicle density is high; on the

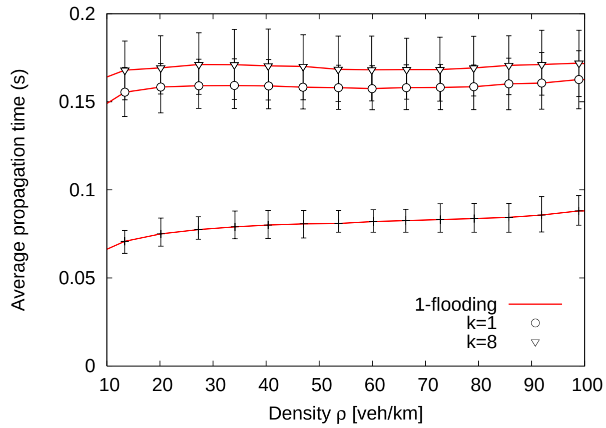

Fig. 11. Average time necessary to inform all vehicles in the safety area

contrary, under uncongested road conditions, Poisson models are inaccurate but conservative.

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