Evaluation of Integrated Routing/MAC Solutions for the Diffusion of Warning Messages in VANETs

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Abstract— **The efficiency of routing protocols in general mobile ad hoc networks may be highly affected by the specific Medium Access Control scheme the routing relies upon and by the mobility of the wireless nodes. In this work, we address the design of position based routing solutions for the support of safety oriented applications in Vehicular Ad hoc NETworks (VANETs) by focusing on the impact of the MAC layer on the performances of the routing strategies. Namely, we propose a simulation analysis in highway scenarios to assess the routing performance in the two cases where standard IEEE 802.11 technology and a dynamic TDMA scheme are adopted at layer 2 respectively. We discuss on the dimensioning of the routing parameters in both cases and we provide a comparative analysis of the two MAC/routing integrated solutions.**

Index Terms— **VANETs, geographical routing, Safety Applications**

I. Introduction

The constant increase in the number of cars traveling along the roads worldwide calls for effective means to improve road safety, transport efficiency, and passengers' comfort. To this end, the research community, the industries and the governments all over the world are investing much of their efforts and money in the development of integrated Intelligent Transportation Systems (ITS) based on wireless communication networks. The aim of ITS is to allow vehicles, equipment on the road, service centers and intelligent sensors to exchange information in a prompt and cost effective way [1] [2] [3].

The actual deployment of affective Vehicular Ad hoc NETworks (VANETs) poses extraordinary challenges to the wireless research community related to channel access [4], information routing [5], the control of highly variable network topologies [6], the design of flexible middleware solutions to effectively support the application layer [7].

The applications in the field of vehicular communications may be roughly divided into two main categories: safety and non-safety applications. Non-safety applications include information retrieval, entertainment services, tolling services, etc. On the other hand, safety applications are mainly devoted to traffic control and vehicle collision avoidance services.

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Roughly speaking, the road safety paradigm is moving from a passive one (air bags, ESP, etc.) to an active one, extensively employing networking functionalities. Sensors, radars, cameras, navigation systems, and microprocessors which are already commonly installed in vehicles can be easily integrated with wireless communication systems to support applications such as parking-assistance, lane-keeping, adaptive cruise-control, and many others. VANETs can efficiently warn and inform drivers via direct wireless vehicle to vehicle communications, eventually reducing reaction time and information availability limitation [8]. The core of safety applications is the VANET capability to distribute information on specific alarms or hazardous situations, like accidents, traffic jams, icy road surface etc. Such applications often resort to broadcast or multicast communications paradigms rather than to unicast ones. For example, a car noticing an accident may spread this information to all the following cars travelling in the same direction, so that they can slow down and eventually take another road. Similarly, an ambulance may communicate its route to the traffic light controllers in order to create a non-stop "all green" path to the destination. The simple examples above highlight the peculiarities of the road safety oriented communication service: first of all the communications are directed to a group of devices (vehicles, roadside network infrastructure, etc.); then, the composition of the group of intended receivers (vehicles) may depend on their position and direction, and finally, in many cases, a single transmission is not enough to target all the intended receivers due to the limited transmitter's range and the alarm message needs to be relayed by intermediate cars (multi-hop). To this end, position based routing [9] is commonly recognized to be one of the most promising solutions for VANETs [10] [5].

The performance of general position based routing solutions highly depends on the type of Medium Access Control (MAC) scheme the routing relies upon. To this extent, the parameters of the routing schemes should be optimized with respect to the specific characteristics of the MAC layer. The main purpose of the present work is to study the interaction between MAC layer and geographical routing. To this end, we consider a geographical routing scheme, named REACT (Routing for Emergency Applications in Car to car networks using Trajectories) [11] which belongs to the family of position based protocols and incorporates the trajectory based routing paradigm [12]. Roughly speaking, in REACT the packet diffusion is implemented through one hop broadcast transmissions which are forced to follow specific trajectories coded into the packets themselves.

In this paper, we compare through simulation the performance of REACT when varying the MAC solutions adopted at the lower layers. Namely, we test the cases where standard IEEE 802.11b [13] technology and a dynamic TDMA scheme, the ADHOC MAC [14], are adopted at layer 2. The performance analysis is carried out in a highway scenario, where vehicles move according to a realistic mobility model based on the concept of cellular automata [15].

The remainder of the paper is organized as follows. Section II overviews the basis of the REACT scheme, whereas Section III discusses on the integration of REACT with IEEE 802.11 Distributed Coordination Function (DCF) and ADHOC MAC. In Section IV we present the topological scenario and the realistic vehicles' mobility model adopted in the simulation analysis which is reported in Section V. In Section VI we review some of the recent works carried out in the field of the design and performance evaluation of position based routing solutions for VANETs . Finally, concluding remarks and comments are given in Section VII.

II. REACT BASICS

REACT algorithm is designed for the propagation of alert messages generated by emergency detection applications. Indeed, whenever the emergency detection application detects a danger along the road[1], it generates an alert packet and defines the trajectory and the intended destination of the packet[2].

REACT routing decisions are based on topological information, like vehicles' positions, directions and propagation trajectories, which can be easily available through GPS systems on vehicles.

REACT conceptually features two functionalities: the *Forwarding Decision Algorithm* (FDA) and the *Topology Discovery Algorithm* (TDA). The former determines the next forwarder on the basis of the geographical/topological information provided by the latter.

In the following, we describe the Forwarding Decision Algorithm (FDA) implemented in REACT for the selection of the next forwarder (Section II-A), the heuristic solutions introduced to cope with wireless network unreliability (Section II-B), while Section II-C describes the routing packet format.

[1]The design of emergency detection applications is out of the scope of the present paper.

[2]The destination is to be intended in the broader sense depending on the current vehicular scenario. It may be a a group of cars, a geographical area, or just a progression along the trajectory.

A. The Forwarding Decision Algorithm (FDA)

Each vehicle, either generating an alarm message or appointed to forward it, runs the FDA in order to elect the next forwarder on the basis of: (i) the position of the current node i, (ii) the type of information reported in the alert packet, such as the type of message and the type of trajectory coded in the packet, and (iii) positional information regarding neighboring vehicles. Indeed, the TDA provides to each vehicle a list of the neighboring vehicles ($NEIGH\_LIST(i)$), whose fields are the position and direction of the motion. Details on how such information is distributed among the vehicles depend on the characteristics of the peculiar MAC layer and are discussed in Section III.

Besides the list of neighbors and the position of the current node i, the FDA takes in input: the position of the original message source (S), the trajectory (T), the target progression of the packet along the trajectory (Pr_{tg}), that is, the minimum distance the packet has to travel along the trajectory and the forwarding angle α, representing the maximum allowed deviation from the trajectory. Conceptually, the trajectory T represents the direction along which the safety information needs to be propagated.

Algorithm 1 FDA(i,S,α,Pr_{tg},T,NEIGH_LIST(i))

```
progression(i) = DistOnTrajectory(i,S,T)
MaxProgr = progression(i)
NextHop = i
if MaxProgr ≥ Pr_tg then
   return Null
else
   for all j ∈ NEIGH_LIST(i) do
   progression(j) = DistOnTrajectory(j,s,T)
   if (progression(j) ≥ MaxProgr AND AngleLimit(j,T,α)) then
      MaxProgr = progression(j)
      NextHop = j
   end if
   end for
end if
return NextHop
```

A pseudo code for the FDA is reported in Algorithm 1. First of all, the algorithm evaluates the length of the progression along the trajectory starting from the source of the packet S to the current forwarding node i, using the function $DistOnTrajectory(i, S, T)$. If this distance is greater than the target progression Pr_{tg}, the packet has already travelled enough and the selection of the next-hop is not necessary. Possible mechanisms to keep the information within this area can be implemented [16]. Otherwise, a next forwarder selection is needed. In this case, FDA evaluates the progression along the trajectory for all its valid neighbors in list $NEIGH\_LIST(i)$ and estimates their deviation from the trajectory using the function $AngleLimit(j, T, \alpha)$. This is used to eliminate from the decision those vehicles whose direction diverges

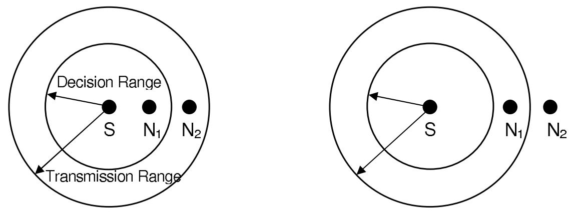

Figure 1. Transmission and decision range description.

from the trajectory. Finally, the node on the trajectory with the greater progression is appointed as the next-hop.

B. Forwarding Reliability

Packet transmissions can be impaired by connectivity holes and collisions due to interference and wireless link fluctuation. These events, in turn, can abruptly interrupt the forwarding process before the packet life time has expired or the target progression along the trajectory has been reached. To this end, the routing entity should implement mechanisms for increasing the reliability of the multi-hop communication.

We present hereafter three heuristics implemented by REACT, in order to augment the reliability of the safety information transfer.

B.1) Decision Range Limiting

The information stored in the $NEIGH\_LIST(i)$ can be out of date due to the high mobility of vehicles, and it may happen that a neighbor of vehicle i stored in $NEIGH\_LIST(i)$ in the meanwhile is no longer reachable by vehicle i itself.

In order to reduce the probability to select next-hops that are actually unreachable, REACT limits the decision range below the transmission range: i.e., the *decision range*, R_d, is defined as the maximum distance between a vehicle running the FDA and the potential next forwarder. Line 9 in the pseudo code is modified accordingly.

Consider, as an example the situation represented in Figure 1, where the node S can choose the next-hop between nodes N1 and N2. N2 is closer to the destination than N1, and, on the bases of the information in the neighbors's list, it appears to be the best choice. However, due to movements in opposite directions or to an high speed of node N2, it can happen that N2 is out of the transmission range of S at the transmission of the alarm packet. In this case, the best choice would be N1.

As a drawback, the network connectivity may result reduced: i.e., if the density of the vehicles is low, no nodes in the decision range could be available to forward the message, while one possible relay could be found in the transmission range.

B.2) Routing ACKs

REACT adopts broadcast transmissions to diffuse the alarms towards the intended destination zone. However, if the wrong forwarding node is selected or the next-hop does not receive the message due to collisions or errors on the wireless channel, the alert message propagation is discontinued before the destination is reached. In order to reduce the occurrence of such events an *implicit* ACKnowledgement (ACK) is introduced.

Source Position	Trajectory	Next Hop ID	Msg ID	Validity Time	Message
4 byte	Y byte	4 byte	1 byte	1 byte	X byte

Figure 2. Format of the packet used by REACT.

Indeed, the REACT entity stores the message it has forwarded and sets a waiting timer τ. If this timer expires without the packet rebroadcast has been performed by the selected next-hop, the last forwarding node re-runs the FDA to choose another next-hop and retransmits the packet.

B.3) Topology Holes Overcoming

If the density of vehicles along the trajectory is low, some gaps in the connectivity may appear and the current relay node may not be able to find a valid next-hop. In this case, the next-forwarder ID field is set as *invalid* but the packet is rebroadcasted in order to acknowledge the previous transmission.

Since no next-hop has been selected, the current transmission can not be implicitly acknowledged; thus, after a time τ, the FDA would be run again trying to find a valid next-hop. This procedure is reiterated until a valid forwarder is found or the message expiration time is reached.

C. REACT Packet Format

A prototype format of the routing packet adopted by REACT is sketched in Figure 2. The header part contains: the location of the original source of the message, the trajectory properly coded and the next forwarder ID, chosen by each forwarding node through the REACT algorithm. Moreover, the message includes the alert expiration time, based on the packet life time, that is set by the original source to limit the alert validity and the message life in the network, the message ID and the message payload which defines the type of alarm. Pr_{tg} defines the minimum progression along the trajectory (1 byte).

Trajectory coding and representation in the packet is out of the scope of this work. For the sake of simplicity we have presented the FDA considering a straight trajectory. In this case, T = 5 bytes can be used to code the trajectory (4 byte to define a second point of the single line trajectory and 1 more byte to define the minimum progression along the trajectory). Obviously, as in classical source routing protocols, the length of the header depends on the number of parameters of the trajectory to be coded in it. The FDA can be extended also to the case of piecewise trajectories or trajectory trees [17].

III. The Topology Discovery Algorithm

In the following, we describe how the TDA is implemented in case REACT runs on top of IEEE 802.11 DCF (Section III-A) and on the ADHOC MAC (Section III-B).

A. REACT over 802.11

In case REACT relies upon the IEEE 802.11 technology, the TDA can be implemented exploiting the broadcast transmission service offered by such technology for the diffusion of signalling packets, named beacons in the following, carrying the required topological information.

Sender ID	Sender Position	Sender Direction	SN
2 bytes	4 byte	4 bytes	2 byte

Figure 3. Format of the beacon signalling packets used to implement the TDA in IEEE 802.11.

The format of a beacon is reported in Figure 3. Each packet carries the sender ID, the sender position and direction and a time stamp to assess the validity of the beacon itself.

Beacons must be transmitted periodically by the vehicles in order to refresh the topological information required by the FDA. The optimum value of the Beacon Interval (BI) obviously depends on the vehicles' mobility and density. From one hand, a low beacon interval is favorable to have fresh topological information, nevertheless, from the other side the lower the beaconing interval the higher the traffic load which may lead to high collision rate.

Upon reception of a valid beacon, a vehicles stores the beacon's sender information in the $NEIGH\_LIST$ or updates the entry corresponding to the sender with the new data. Indeed, a validity timer γ is set for each entry of the neighbors' list and it is refreshed every time a new beacon is received by the specific vehicle. If no new information is received from the corresponding sender within γ seconds, the sender is removed from the list.

B. REACT over ADHOC MAC

ADHOC MAC [14] features a dynamic TDMA where each terminal, upon activation, acquires a Basic CHannel (BCH) which corresponds to a slot in a virtual frame (VF) and that is mainly used for MAC signaling. The very same BCH can be used also for broadcasting data to all the one-hop neighbors in a reliable way. ADHOC MAC adopts a distributed access algorithm for the acquisition of the BCH, which is named Reliable Reservation ALOHA (RR-ALOHA) [18]. The information needed for the RR-ALOHA correct operation is provided to all terminals by means of the BCHs. Each transmission on the BCH contains, besides data and header information, a control field named Frame Information (FI).

The FI is a vector with N entries specifying the status of each of the N slots preceding the current transmission, as observed by the transmitting terminal itself. The slot status can be either BUSY or FREE: it is BUSY if a packet has been correctly received from another terminal or transmitted by the terminal itself, otherwise it is FREE. In the case of a BUSY slot the identity of the transmitting terminal is reported. Consequently, the FIs report the information on the neighbors' activity of the sending terminal as perceived by the terminal itself in the previous VF.

Thus, a terminal receiving the FI from one of its neighbors gets aware of its neighbors'neighbors activity. Based on received FIs, each terminal marks a slot, say slot k, either as RESERVED, if slot $k-N$ is coded as BUSY in at least one of the FIs received in the slots from $k-N$ to $k-1$, or as AVAILABLE, otherwise. As in R-ALOHA, an AVAILABLE slot can be used for new access attempts.

Upon accessing an AVAILABLE slot, terminal j will recognize in the next VF its transmission either successful, if the slot is coded as "BUSY by terminal j" in all the received FIs, or failed, otherwise. More details on ADHOC MAC with a proof of correctness of the aforementioned access algorithm can be found in [14].

The BCHs provided by the ADHOC MAC carry periodical signaling information which can be used to spread out the topological information needed by REACT. To this end, the BCH's header needs to be enhanced and besides the usual FI other signaling fields should be added. Figure 4 shows the updated ADHOC MAC BCH format, including (i) the basic overhead (i.e. the FI), (ii) the transmitting vehicle's position (4 bytes for each coordinate) and (iii) the time-stamp (9 bytes), i.e., the time of position's survey. Another additional field, not directly related to REACT, is the protocol field, which is used to distinguish among different protocols of upper layers.

The performance of the integrated solution REACT/ADHOC MAC is mainly affected by the ADHOC MAC dimensioning parameters, i.e., the number of slots N in VF, the slot size S and the ADHOC MAC header dimension H. In order to have a fair evaluation of the impact of these parameters on the REACT protocol, we set the data rate $R=\frac{P}{T}$ [bits/s] of the channel provided to the alarm services, where P [bits] is the BCH payload dimension and T [s] is the VF duration. Under this assumption, the payload dimension P, the number of slots per VF, N, and the data rate R are related through the following:

$$P = R \times T = \frac{(P+H)N}{C}R, \qquad (1)$$

where C is the data rate of the physical channel depending on the specific technology used. Equation 1 can be expressed as:

$$P = \frac{(35N+144)\frac{NR}{C}}{1-\frac{NR}{C}}, \qquad (2)$$

where we have used the expressions of the ADHOC MAC header dimension $H = 35N + 144$.

Table I reports the VF duration T, the payload dimension and the header dimension with different numbers of slots per VF, when considering an alarm service with data rate R=44kb/s.

Through the ADHOC MAC header, vehicles gather topological information on neighboring nodes (positions and identifier) every VF, thus ADHOC MAC accomplishes the functionality of providing implicit beaconing of topological information. In this way, the node adds the sender to its neighbors' list if it is not already there or updates the nodes position and the time of this information (time-stamp), keeping the previous information of that node in order to be able to estimate the neighbor's direction. A validity timer γ is set for each entry of the neighbors' list. If no information is received from the corresponding sender within γ seconds, the sender is removed from the list.

TABLE I.
NUMBER OF SLOTS CONSIDERED FOR AN ALARM RATE $R = 44\ kb/s$.

N	P [bits]	H [bits]	T [ms]
15	330	669	7.50
20	664	844	15.08
25	1246	1019	28.31
30	2318	1194	52.68
35	4584	1369	104.18
40	11323	1544	257.34

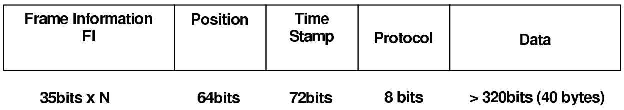

Figure 4. The new ADHOC MAC packet format.

REACT can exploit such information in the decision process of the next forwarder. Alert messages can be transmitted by the designated forwarders in their own BCHs and the corresponding acknowledgement/unacknowledgement is provided in the following frame: in fact, if the BUSY bit in the FI of the selected next-hop forwarder is equal to one, the next-hop forwarder has actually received the message and may rebroadcast it. If the BUSY bit is not set, the transmission toward the intended relay has failed (due to collision or vehicles' movement) and a new next-hop relay should be selected. In this last case, the next transmission attempt is performed in the next VF, thus the value of transmission timeout, as defined in Section II, is $\tau = T$, having called T the time duration of a VF.

IV. HIGHWAY SCENARIO

The simulation scenario considered in this paper represents a highway with a crossing bridge and an exit lane. Figure 5 shows the considered topology (i.e., the highway on the horizontal axis and the bridge on the vertical axis). An alert packet is transmitted at a given source point and should travel the target progression Pr_{tg} along the trajectory as soon as possible. Table II summarizes the scenario parameters.

In each lane, vehicles move accordingly to a realistic traffic mobility model that abstracts the real drivers behavior. In the following we restrict our attention to Cellular Automata (CA) models which have been increasingly used in the last decade [15] [19] due to the good match

TABLE II.
SCENARIO PARAMETERS.

Parameter	Value
Highway length	$10km$
Bridge position	$4km$ on highway
Vehs' density on the bridge	$20vehs/km$
Vehs' density on the highway	$5, 15, 25, 35, 45vehs/km$
Vehs' speed on the bridge	$18.75m/s$ $(67.5km/h)$
Vehs' speed on the highway	$31.25m/s$ $(112.5km/h)$
Bridge length	$3km$
Sender	$9.5km$ on highway
Exit position	$8.5km$ on highway
Bandwidth, C	$2Mbps$
Radio communication range	$250m$

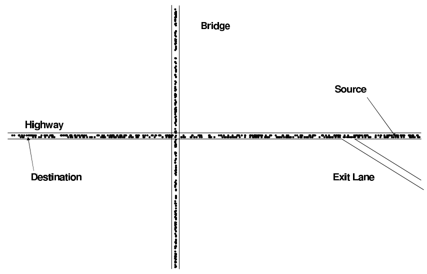

Figure 5. Scenario description.

exhibited with empirical traffic measurements [20]. In these models, each *vehicle* k is individually resolved by the couple (x_k, v_k) describing the spatial location and the speed of the k-th vehicle along a one-dimensional road with wrap-around boundary conditions. The model then consists of a set of rules or equations to update these quantities over time, depending on the states of other vehicles around. CA models are discrete in both space and time: space is typically coarse-grained to the length that a car occupies in a jam, and time step 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 time step. As previously mentioned, many different models exist: we selected the Nagel and Schreckenberg automaton [15]. The set of update rules, performed in parallel for each vehicle, is as follows:

1. Car-follow : $v_k \leftarrow \min\{v_k + 1, d(k-1, k), v_{max}\}$
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 what 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. In our evaluations we assume a P_d value equal to 0.16. Note that, due to the parallel update, an implicit reaction time of the order of the time step 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.

V. PERFORMANCE EVALUATION

The performance of REACT over ADHOC MAC and IEEE 802.11b is tested hereafter using $ns2$ simulator [21] in the topological scenario described in Section IV. The performance statistics gathered from the simulation analysis are:

- the Delivery Failure Probability, i.e., the probability for a packet not to cover the target progression,
- the conditional delivery delay, i.e., the delivery delay of those packets which are actually delivered,

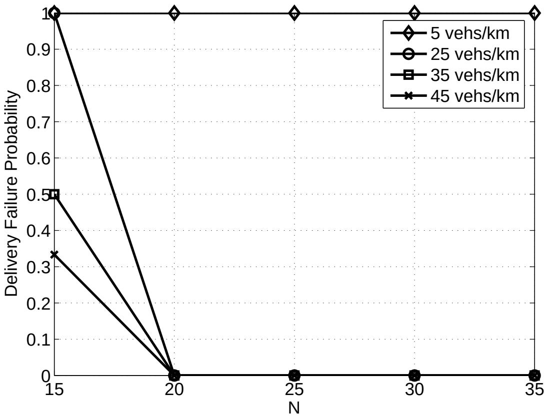

Figure 6. Delivery Failure Probability versus the number of slots N in the ADHOC MAC virtual frame.

- the packet collision probability.

Results reported in the following are obtained with a confidence level of 99% and a confidence interval of 2%.

TABLE III.
SIMULATION PARAMETERS.

Parameter	Value
Decision range, R_d	$50, 100, 125, 150, 175, 200, 225, 250m$
Forwarding angle, α	$60deg$
Target Progression, Pr_{tg}	$8.5Km$
Packet Lifetime	$10s$
Validity Timer γ	$3s$

The parameters values that ADHOC MAC and 802.11b share are summarized in Table III. In our reference scenario, the IEEE 802.11b Distributed Coordination Function (DCF) is implemented at the MAC layer. The DCF parameters are set to the standard values and broadcast transmissions are used for the alarm packets.

In the following results a single alarm packet is generated and relayed according to REACT rules until either the target progression has been matched or the packet lifetime has expired.

A. Parameters Dimensioning

As a first step, we investigate the impact of the parameters to be specifically set using ADHOC MAC or 802.11b. In order to have a fair evaluation we set the dimension of the alarm packet to the common value of $P = 256$ bytes.

In this scenario, we investigate the impact of the number of N slots per frame on the performance of the routing protocol, in case ADHOC MAC is used. The results are reported in Figures 6 and 7 which show respectively the delivery failure probability and the conditional delivery delay versus the number of slots in ADHOC MAC virtual frame. The curves have been obtained setting the decision range $R_d = 200$ m and the one in Figure 6 limits the range of N to those value ensuring the actual packet delivery for the values of vehicles' density considered, that is, $N \geq 20$. The results reported by the two figures show that the optimum value of N comes from a trade off between two distinct effects: if from one hand a low number of slots speeds up the delivery time since shorter

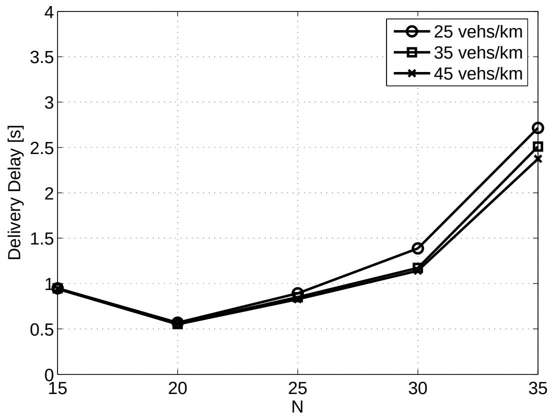

Figure 7. Delivery Delay versus the number of slots N in the ADHOC MAC virtual frame.

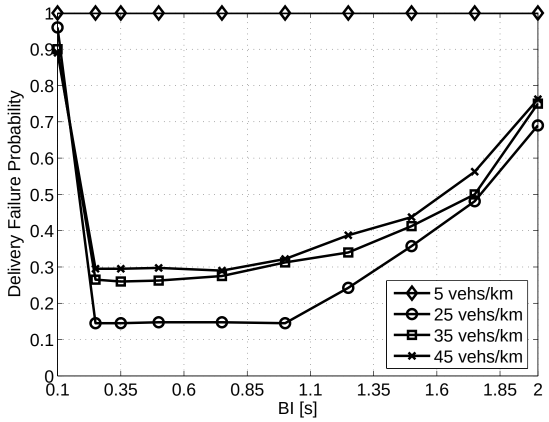

Figure 8. Delivery Failure Probability versus the beacon interval BI in IEEE 802.11b.

frames are used, on the other hand a low number of slots increases the collision probability and probability of failure in acquiring a BCH. Thus, all the results presented in the following are obtained using, for each vehicles' density, the lower number of N ensuring null delivery failure probability, i.e., $N =$20.

On the other side, when 802.11 supports REACT, the parameter to be optimized is the beacon interval (BI). Figure 8 reports the delivery failure probability versus the beacon interval for different vehicles' densities. From the figure, the delivery failure probability never goes to zero for any values of the beacon interval. However, it has a minimum which comes from a trade off choice between the need of having fresh topological information (frequent beacons) and the one of limiting congestion due too frequent beacons. As for ADHOC MAC, all the results presented in the following are obtained using the optimized BI value for each value of vehicles' density, i.e., $BI =$0.2s.

B. Performance Comparison

As mentioned in the previous section, the performance of the routing scheme depends also on the value of the decision range, R_d. Figures 9 and 10 show the delivery failure probability, versus the decision range when adopting ADHOC MAC and standard IEEE 802.11

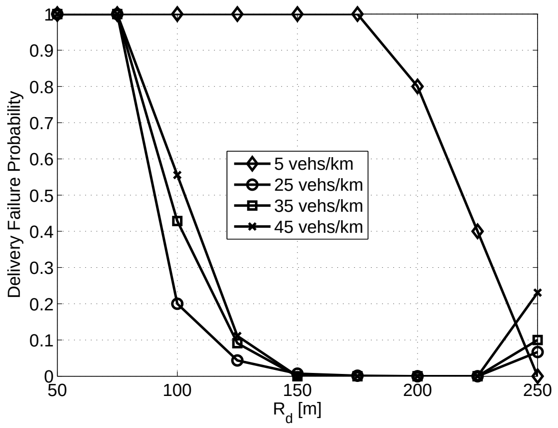

Figure 9. ADHOC MAC: Delivery failure probability versus the decision range value for different vehicles' density.

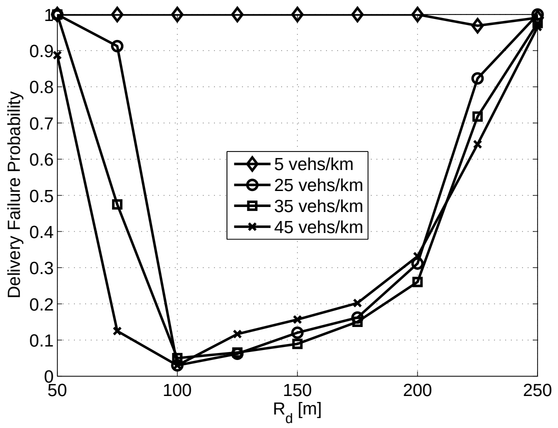

Figure 10. 802.11b: Delivery failure probability versus the decision range value for different vehicles' density.

respectively.

The first observation coming from the figures is that, in the case ADHOC MAC is used, the delivery is always successful for vehicles' density above 5 vehs/km when considering the decision range values between 150 m and 250 m. This suggests that the main factor determining the efficiency of the routing is the network connectivity, rather than packet collisions (which increases with the vehicles' density) or non-consistent choices of the next forwarders (which increases with the decision range).

Furthermore, we can observe that the delivery failure probability decreases when increasing the decision range until 225 m for a fixed vehicles' density value, since greater decision range values increase network connectivity, i.e., the probability of finding a proper next-hop. On the other side, if the connectivity is assured (i.e., densities bigger than 10 vehs/km), the delivery failure probability increases when increasing the vehicles' density; in fact, in this case many vehicles do not acquire a BCH, thus, with small decision ranges, the probability of missing the next forwarder increases. If we further increase the decision range (up than 225 m) misleading choices on the next hop and collisions appear thus increasing the failure probability.

When the IEEE 802.11 is considered (Figure 10), there is no value of decision range for which the delivery failure probability is null. Even when the network is fully connected, the collisions among the beacons lead to routing failure due to inconsistent topological information. This is well portrayed by Figure 11 which captures the packet collision probability versus the decision range for different vehicles' density in the cases the ADHOC MAC and the IEEE 802.11 are adopted. The curve referring to IEEE 802.11 accounts for alarm to beacon, beacon to beacon and alarm to alarm collisions, whereas in ADHOC MAC the only possible collisions are among alarm packets. As clear from the figure, ADHOC MAC is very effective in avoiding collisions in all the decision ranges considered, thus the performance of the routing is mainly affected by the network topology only. On the other side, the collision probability characterizing IEEE 802.11 is never null and much higher, thus affecting the routing reliability in those cases where the network is potentially connected.

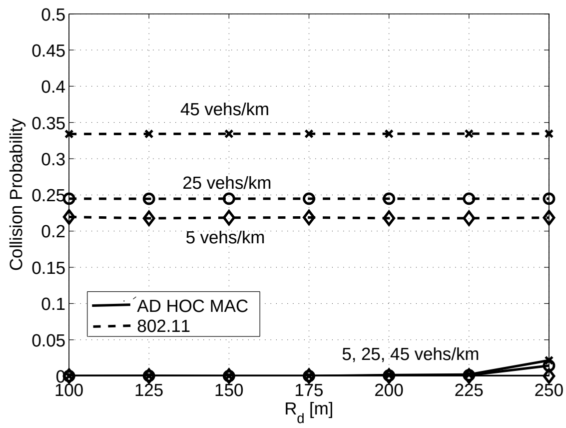

Figure 11. The packet collision probability versus the decision range value for different vehicles' density

An important performance parameter for safety application is the reliability in terms of degree of diffusion of the information. To this end, Figure 12 presents the delivery failure probability versus the target progression along the trajectory. This figure shows that ADHOC MAC provides null delivery failure probability at high vehicles' density for any target progression value considered, since the

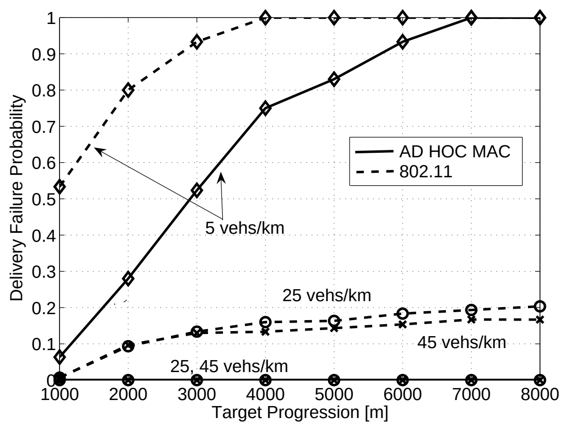

Figure 12. Delivery failure probability versus the distance between source and destination for different vehicles' density.

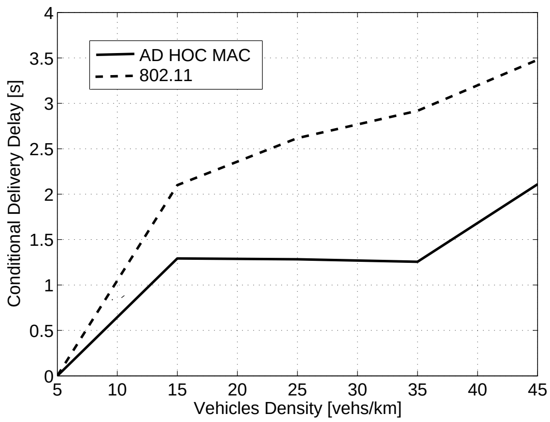

Figure 13. The packet delivery delay versus the decision range value for different vehicles' density.

network is fully connected and collisions are limited. Conversely, at the density of 5 vehs/km, an increasing distance to be covered raises the delivery failure probability since on longer portions of the road gaps in the connectivity are more likely to appear. On the other side, as expectable from the discussion on the previous figures, in case IEEE 802.11 is used, the delivery failure probability is not null even at high vehicles' density values.

Besides the geographical diffusion degree, it is also interesting to give some insights on the delivery delay. Figure 13 reports the delivery delay with a target progression $Pr_{tg} = 8000$ m conditioned to actual delivery versus the vehicles' density when adopting optimum configuration (R_d, N, and BI) for ADHOC MAC and IEEE 802.11. ADHOC MAC provides lower delivery delay values for all the tested vehicles density values. To wrap up the results of Figures 12 and 13, IEEE 802.11 does not guarantee the actual delivery of an alarm packet and, even in the cases it does, the measured delivery delay is higher than the one provided by ADHOC MAC. Similar results not reported here for the sake of brevity have been obtained with other values of the target progression along the trajectory.

C. Performance with Fixed Relay Points

As clear from the results presented in the previous sections, routing reliability and efficiency highly depends on the network topology, and in particular on the connectivity degree. Indeed, we have shown that delivery failure probability is close to 1 for low vehicles densities (5[vehs/km]).

A possible solution to overcome these connectivity holes, is to resort to fixed roadside infrastructure featuring Fixed relay Points (FPs) which artificially increase the density of vehicles. Thus, it is worth studying the trade-off between the infrastructure installation cost (number of FPs to be installed), and the routing performance improvement.

To this end, we performed simulations in the aforementioned highway scenario where n FPs are uniformly distributed along the road, with a radio communication range of 200m (see Figure 14).

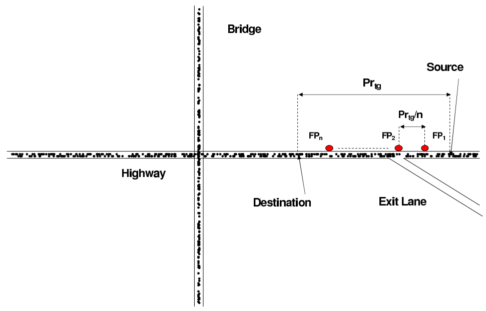

Figure 14. Scenario description with infrastructure.

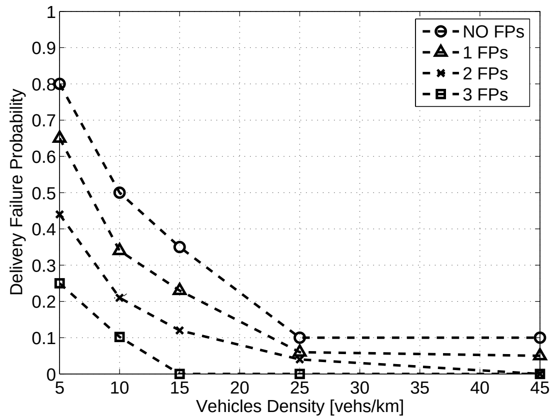

Figure 15. The delivery failure probability versus the vehicles' density for different FPs in the 802.11 case.

Figures 15 and 16 show the delivery failure probability versus the vehicles' density for different values of n, when assuming a $Pr_{tg} = 2000m$. In both cases (REACT+802.11 and REACT+ADHOC MAC), we have a significant improvement in terms of delivery probability. However, we note that 3 FPs are still not enough to guarantee the 100% of delivery for the value of density 5vehs/km.

D. Impact of Message Redundancy

Alarm signalling applications can lead to high network overhead in terms of redundant messages transmitted throughout the network [22]. In fact, it is very likely that multiple vehicles detect the same dangerous situation, which may possibly lead to the diffusion of multiple and redundant copies of the same piece of information throughout the network. If from one hand redundancy

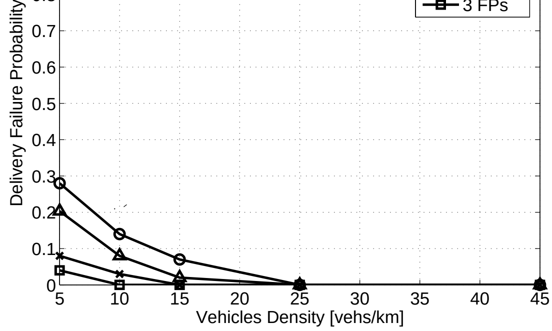

Figure 16. The delivery failure probability versus the vehicles' density for different FPs in the ADHOC MAC case.

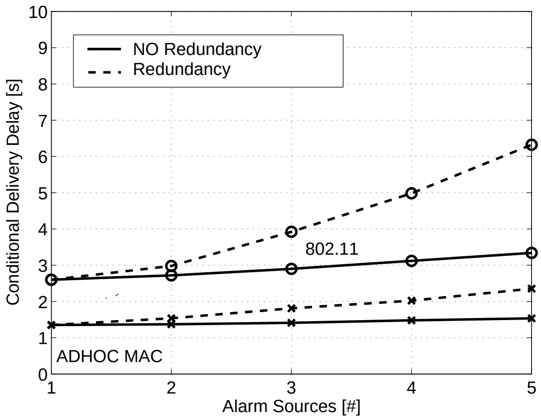

Figure 17. The delivery delay versus the number of sources when the intermediate nodes group or not the information.

may be beneficial for the actual information delivery, from the other hand it artificially increases the load in the network, leading to more frequent collisions. To this end, information redundancy may be limited either by introducing some type of coordination among the "danger-detecting" vehicles, or by letting the intermediate forwarding nodes filter redundant information. Hereafter, we want to qualitatively characterize the impact of redundant transmissions on the performance of the overall routing strategy.

Figure 17 shows the conditional delivery delay versus the number of multiple sources detecting the danger for both integrated solutions. We have considered the scenario in Figure 5 with Pr_{tg}=8000m and density equal to 25 vehs/km. Two cases are compared in the figure: the case where intermediate nodes forward every packet they receive, and the case where intermediate nodes do not forward messages referring to the same alarm they have already received. As clear from the figure, when intermediate nodes do not filter redundant information, the average delivery delay increases due to increased congestion level in the network. On the other hand, if packet filtering is adopted, the delivery delay remains almost constant when varying the number of detecting sources.

VI. Related Work and Contributions

The general problem of routing in ad hoc networks has been extensively researched in the literature. On the one hand, proactive protocols like DSDV [23] and OLSR [24], which maintain routing information about the available paths even if these paths are not currently used, are not suited in the vehicular scenario, characterized by the high variability of the network topology. On the other hand, reactive routing protocols (AODV [25], DSR [26], TORA [27]), that build up on the fly a route to a specific destination without maintaining constant path information, have drawbacks if applied for the support of vehicular safety applications: i.e., they often require a route discovery phase before packet transmission which may cause high message delivery delays at the application layer.

In general, the most of these protocols have been designed for general purposes ad hoc networks, while vehicular networks and applications have many peculiarities which should be taken into account. These characteristics are, for example:

- the topology of the nodes which is typically a string (queues, cars in a lane), thus the intended receivers of a given transmission are often positioned along trajectories or trajectory trees.
- the clustering of cars (e.g. cars in a traffic jam, cars in a lane that drive more or less the same speed, etc.).
- the high mobility of the nodes (between 20 and 130 km/h).
- the high percentage of traffic that is usually broadcast or multicast (in particular for accident warning messages).
- the possibility of having low cost localization techniques on board (Global Positioning System, GPS).
- the possibility of accessing an infrastructure network (GSM, GPRS, EDGE, UMTS, WLAN).
- the fact that energy consumption is no longer an issue.

In this context, position based routing [9] [28] [29] [10] seems to be the most promising solution for VANETs [5]. According to the position based paradigm, each node determines its own position, through the use of GPS or other positioning services, and the positions of neighboring nodes. A destination's position is then defined and the routing decision at each node is locally performed on the basis of the destination's position, the position of the current routing node and eventually the positions of the neighboring ones.

Different from reactive and proactive protocols, position based routing does require neither the establishment nor the maintenance of routes and furthermore can easily support the definition of groups of destinations based on their geographical positions (geoacasting), which may be extremely helpful in the vehicular scenarios.

Besides position based routing, also Trajectory Based Routing (TBR) [30] [12] paradigm can fit very well the VANET context. The TBR is a particular type of source routing where packets are routed not along paths (sequences of nodes) both along physical trajectories. Such routing paradigm can be well suited for those situations where either physical trajectories are more stable than paths (i.e. sensors networks[3]), or the packet diffusion is forced to follow specific trajectories due to topological constraints, like roads and streets in VANET. Within these frameworks, reference [31] proposes a geocast algorithm for the support of virtual warning sign, whose target is to distribute the information within a defined geocast zone. The proposed scheme adopts a unicast routing to reach the destination area according to which each forwarding node chooses as next forwarder the neighbor which is closets to the final destination. The aforementioned mechanism has some contact points with REACT:

[3]Sensors networks topology may vary due to sensors activity periods.

both need topological information on the neighboring nodes and both implement a greedy algorithm for the choice of the next forwarder. However, one substantial difference exists: REACT is more tailored for applications requiring a directional broadcast rather than a real geocast support at the network layer. In fact, REACT resorts to broadcast transmissions only and tries to follow a specific trajectory rather than the shortest feasible path to the destination. Reference [16] follows up the aforementioned work by focusing on different techniques to store the geocast information within the final destination area, so that it is periodically broadcasted to new come nodes. Within the same field, Yang *et al.* [22] focus on the design of position based solutions for the support of cooperative collision warning among vehicles, with the specific target of developing distributed congestion control algorithms to limit the impact of multiple collision warning messages on the overall system performances. Collision warning services are addressed also in reference [32], which presents a directional broadcasting protocol using geographical information. Different form REACT, the proposed mechanism implements a receiver oriented next forwarder choice. Each receiving node sets up a timer on the basis of its own position and its distance to the destination, according to the qualitative criteria that nodes in better positions will have shorter timers. Upon timer expiration, the receiving node forwards the packet and all the nodes overhearing this transmission simply abort their own. The proposed solution has two main drawbacks: multiple unwanted transmissions of the same packet can happen if nodes do not overhear packet transmission and no recovery procedure is implemented. Conversely, in our solution the transmitter chooses the next forwarder and recovery procedures are implemented to cope with temporary forwarding failures (lack of connectivity).

All the works referenced above and the most of the works carried out in the past evaluate the performance of the several proposed routing/forwarding schemes in the case IEEE 802.11-oriented technology is used at layer 2, whether the basic form, IEEE 802.11b [33] [4], or enhancements, DSRC [34] [35]. To the best of our knowledge, very few works study the interaction of position based routing with dynamic TDMA MAC schemes and none of them provides a comparative analysis of integrated MAC/Routing solutions. To this extent, the novel contributions of the present work can be summarized in the following points:

- integration of position based routing with dynamic TDMA scheme,
- dimensioning guidelines for the integration of position based routing solutions both with standard IEEE 802.11 technology and with dynamic TDMA based one,
- qualitative analysis of the two integrated solutions in a realistic highway mobility scenario.

VII. Conclusions

In this paper we have addressed the issue of designing routing solutions to support safety applications in vehicular networks. To this end, we have focused on a directional broadcast solution which leverages the position based routing paradigm and the trajectory based one, and bases the routing/forwarding decision heuristic on both classical geographical information (neighboring vehicles' positions and directions, current vehicle's position, destination's position, etc. . .) and information on physical trajectories which should be followed by the flow of alarm packets. The necessary topological information to be spread to support the routing/forwarding decision can be achieved either with a "ad hoc" signaling protocol based on periodical beacon exchange among nodes, or adopting specific MAC schemes able to distribute such information at layer 2. To this end, we have compared through simulation the performance of the routing scheme in a realistic highway mobility scenario when implemented respectively on top of standard IEEE 802.11 technology and on top of a dynamic TDMA based MAC scheme, the ADHOC MAC.

The results we gathered outline that the performance of position based routing based on standard IEEE 802.11 technology can be greatly impaired by the overhead traffic used for recovering topological information which each transmitter bases its routing decision on. To this end, we are planning of extending the same analysis carried out in this paper to the case where the routing/forwarding decision is moved from the transmitter to the receiver, in which case the signalling overhead can potentially be reduced.

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