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Multihop Beaconing Forwarding Strategies in Congested IEEE 802.11p Vehicular Networks

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Abstract

Multi-hop propagation of situational information is a promising technique for improving beaconing performance and increasing the degree of situational awareness onboard vehicles. However, limitation on beacon size prescribed by standardization bodies implies that only information about 3-4 surrounding vehicles can be piggybacked in a beacon packet. In most traffic situations, the number of vehicles within transmission range is much larger than 3-4, implying that multi-hop forwarding strategies must be devised to select which neighboring vehicle's information to include in a transmitted beacon. In this paper, we investigate the effectiveness of different multi-hop forwarding strategies in delivering fresh situational information to surrounding vehicles. Effectiveness is estimated in terms of both average information age and probability of experiencing a situational-awareness blackout of at least 1 *sec*. Both metrics are estimated as a function of the hop distance from the transmitting vehicle, and in presence of different level of radio channel congestion. The investigation is based on extensive simulations

whose multi-hop communication performance is corroborated by real-world measurements. The results show that network-coding based strategies substantially improve forwarding performance as compared to a randomized strategy, reducing the average information age of up to 60%, the blackout probability of up to two orders of magnitude.

We also consider the effect of multi-hop propagation of situational information on the reliability of a forward collision warning application, and show that network-coding based propagation yields a factor three improvement of reliability with respect to a randomized forwarding strategy, and even higher improvements with respect to the case of no propagation.

Index Terms

Vehicular networks, IEEE 802.11p, beaconing, radio channel congestion, reliability.

I. INTRODUCTION

The beaconing[1] mechanism, according to which vehicles periodically transmit information about their status to surrounding vehicles, is at the heart of the important class of vehicular active safety applications. This explains the considerable attention that the research community has devoted to studying beaconing performance, initially by simulation/analysis [2]–[4] and, more, recently, also based on real-world measurements [5]–[10]. Measurement-based studies have revealed that beaconing performance is severely impacted by the radio environment, and especially by the absence of Line-Of-Sight conditions between vehicles. The fact that beaconing performs poorly in NLOS conditions jeopardizes the fulfillment of active safety applications' design goal of extending a driver's situation-awareness "beyond human eyes".

It has been recently observed [10] that multi-hop propagation of the situational information contained in beacons is very effective in improving beaconing NLOS performance. However, the

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[1]A message carrying the information concerning position and status of a vehicle is called Cooperative Awareness Message (CAM) according to the European ETSI-ITS standard, or Basic Safety Messages according to the American DSRC standards.

study of [10] is restricted to a three-vehicle scenario, implying that propagation of information is evaluated only up to the second hop of communication. Furthermore, due to the small scale of the considered scenario, the authors of [10] were able to piggyback the information about *all* surrounding vehicles in the beacons. In larger scale scenarios, piggybacking information about all surrounding vehicles in a beacon might not be possible, since beacon size cannot exceed a maximum length prescribed by standardization bodies [11]. For instance, if we consider a road with two-lane per direction, an average density of 20 cars per kilometer in each lane, and a typical transmission range of $200\ m$ [5], [9], we have about 16 cars within a vehicle's transmission range. Considering that about $30\ Bytes$ are needed to report a vehicle's situational information [11], we have that including information about all neighbors in a vehicle's beacon would require about $480\ Bytes$, which is well above the $100\ Bytes$ beacon size[2] recommended by DSRC [11]. Thus, an understanding of the benefits of multi-hop propagation of situational information beyond the second hop of communication and/or in medium-to-dense traffic scenarios is still mostly lacking to date.

When piggybacking complete situational information in beacon is not feasible, suitable strategies should be designed to optimally select the partial situational information to be propagated. The design of such strategies, and the evaluation of their effectiveness in propagating situational information across multiple hops of communication, is an open problem which is addressed in this paper.

More specifically, we consider a multi-hop vehicle configuration in a linear arrangement, and evaluate how quickly the quality of the situational information sent by the head vehicle degrades with hop distance, and in presence of different levels of radio channel congestion. Information quality is measured in terms of both the average information age and the probability of experiencing a situational-awareness black-out of at least $1\ sec$. In the paper, we propose different situational information forwarding strategies, including a randomized strategy, network-

[2]Without security overhead.

coding based strategies, and an idealized strategy in which the complete situational information is piggybacked in the beacons. The different strategies are evaluated by means of simulations whose multi-hop communication performance is corroborated by real-world measurements.

Furthermore, we present a case study in which our results are applied to estimate the reliability of a forward collision warning application. The case study clearly shows the effectiveness of multi-hop forwarding of situational information in improving safety conditions on the road, and promotes network-coding based solutions as the best performing forwarding strategy.

The rest of this paper is organized as follows. In Section II, we discuss related work. In Section III, we introduce the network model, while Section IV introduces the various multi-hop forwarding strategies considered in this study. The impact of radio channel congestion on the most representative forwarding strategies is then discussed in Section V. Section VI describes the simulation setup, while Section VII presents and discusses the simulation results. Section VIII presents a case study in which our results are used to estimate reliability of a forward collision warning application. Finally, Section IX draws some conclusions and describes possible directions for future work.

II. RELATED WORK

Since most applications for vehicular networks are based on beacons exchange among vehicles, the beaconing mechanism has been widely studied in the literature [12]–[20]. Although essential to improve the situational awareness, beaconing in dense networks can however increase the channel congestion beyond acceptable limits and consequently degrade the perfomance of the upper layer applications. Therefore, a number of techniques have been devised to reduce congestion, while maintaining the beaconing effectiveness. The impact of the node density, as well as the beacon frequency and duration, on the performance of an Adaptive Cruise Control application is analyzed in [12], whereas [13] illustrates the degradation of the probability of beacon reception in a large scale urban scenario. An analytcal derivation for the beacon delay

and the reception probability is shown in [14] for a scenario where the interval between two consecutive beacon transmissions is not determistic. In [15] the effect of the beacon frequency and transmit power, as well as of the Contention Window (CW) size, is studied, and a closed form expression for the optimal CW is derived in order to maximize the beacon throughput. A proper tuning of the Contention Window, depending on the vehicle density, is proposed also in [16], where the authors show the importance of adaptive MAC protocols in VANETs by means of an analytical model. The idea of modifying the beacon frequency taking into account both the estimated channel quality and the message prority is explored in [17], while the usage of multiple channels for beaconing, in order to lower the impact of congestion, has been suggested in [18]. The authors in [19] propose a statistical beaconing congestion control mechanism, which leverages the channel statistics and regulates the transmit power based on the measured channel busy time or vehicle density. The possibility of desynchronizing the beacon transmissions, in order to minimize the collision probability, is explored in [20].

The idea of using network-level, multi-hop strategies to propagate the situational information contained in beacons is relatively recent. An adaptive strategy which exploits the propagation of beacons received from neighbors is detailed in [21] and in [22]; here, however, forwarding is requested only in potentially dangerous situations or when a beacon loss is detected. In [23], the authors investigate the effectiveness of two opposite strategies for delivering the situational information generated by a vehicle V to a target area: the single-hop strategy, in which V transmits at maximum power and directly reaches all nodes in the target area (up to possible transmission errors); and the multi-hop strategy, in which V uses a lower transmission power, and situational information is piggybacked in a vehicle's beacons. The simulation-based comparison reported in [23] indicates that the single-hop strategy performs significantly better than multi-hop forwarding, delivering fresher situational information to the target area with a lower beaconing load.

In our study, beacons are transmitted at fixed power, independently of whether they piggyback

situational information of other vehicles. Furthermore, a major difference between our approach and [23] is that in [23] the authors assume that a forwarding vehicle can anticipate the transmission of the own beacon to speed-up the propagation of the piggybacked information. This technique has two main drawbacks: it increases the beaconing frequency and, consequently, the beaconing load, which is likely already critical in medium-to-dense traffic conditions [3]; and it is not easily generalizable to scenarios in which information of more than one vehicle should be piggybacked in the beacons. For these reasons, in our study we assume that beacons are transmitted with a fixed frequency, independently of whether they piggyback situational information of other vehicles.

The conclusions of our study about the efficacy of multi-hop propagation of situational information are at odds with those of [23]. This is most likely due to the fact that the negative effect of NLOS conditions on beaconing reception rates, which has been recently observed in measurement-based studies [8], [9], is underestimated in the simulator used in [23]. On the contrary, the multi-hop communication model used in our simulations is designed to faithfully reproduce the beacon reception patterns observed in real-world scenarios, and it is fine tuned based on the results of a measurement campaign.

Another related study is [10], where the effectiveness of multi-hop information propagation in improving NLOS beaconing performance is demonstrated by means of real-world measurements. However, this study considers only a three-vehicle configuration in which complete situational information is piggybacked in the beacons. The analysis reported in this paper extends [10] by investigating the forwarding process beyond the second hop of communication, and by studying the performance of different strategies for including partial situational information in the beacons. Furthermore, given the inherently broadcast nature of the beaconing process, we introduce the usage of Network Coding [24], [25] to increase the information contained in each beacon packet. However, no congestion is considered in this study.

Beaconing performance in presence of radio channel congestion has been investigated based

on simulations/analysis in [2], [3], and on real-world measurements in [26]. However, none of these studies considers the effect of multi-hop propagation of beaconing information.

III. NETWORK MODEL

We focus on a linear vehicular network, where N vehicles (also called *nodes* in the following) are deployed in a line. The vehicles cannot overtake each other, and their IDs are sorted from 1 to N. In principle, their speeds can be modeled to reproduce a realistic scenario, which would lead to time-varying inter-vehicle distances. However, it has recently been shown in [9] that beacon reception patterns are only minimally influenced by inter-vehicle distance and relative speed, as long as they are within each other transmission range (estimated in about $160\,m$ in [9]). For these reasons, we model vehicles as stationary points on a line with arbitrary inter-vehicle distances smaller than the transmission range. Indeed, inter-vehicle distances (30 meters) are such that two vehicles are within each other transmission range even if up to 3 vehicles are positioned between them, so that, for instance, the first vehicle is – in principle – able to directly (one hop) communicate with the fifth vehicle. This assumption, aimed at replicating the scenario used in the measurements, allows comparing performance of single-hop and multi-hop information propagation strategies up to the 4-th communication hop, i.e. for each pair of vehicles $(i, i+j)$, where $1 \leq i \leq N-1$ and $1 \leq j \leq 4$ and $i+j \leq N$.

Vehicles exchange beacons containing information on their current position (and speed) every T seconds, where typically $T = 0.1\,s$. The beacon decoding probability, and the resulting beacon reception pattern, is modeled with a Markov-chain based model described in the following. The parameters of the model depends on the hop-distance between vehicles, and are tuned to faithfully reproduce the beacon reception patterns in presence of different levels of radio channel congestion, as observed in the real-world measurements we have performed.

Since each beaconing packet has a size equal to $100\,B$ due to the standardization bodies' recommendations [11], [27], only a limited amount of information can be contained in it.

Considering also the necessary overhead, up to C *data fields* are available in each beacon, meaning that, without specifically designed approaches, the information about at most C vehicles can be communicated. One of the data fields is always reserved to the location information of the transmitter itself, leaving $C - 1$ free slots for information forwarding. However, the choice of $C - 1$ vehicles out of $N - 1$ can be done in several different ways, leading to different *forwarding strategies*.

In a data field, reserved to node i (which may be different from the actual transmitter), the following information is contained:

- the geographic coordinates of vehicle i;
- the speed of vehicle i;
- a unique sequence number (packet ID), associated with the geographic information;
- the packet timestamp, indicating the instant when the geographic information were measured.

Every time a beacon is received, the information contained in each data field is used to update a neighbor lookup table at the receiving node. More specifically, we assume that each vehicle V keeps a table with N entries, where the i–th entry contains the most recent situational information of node i received by V. This information may be then inserted in a subsequent beacon sent by V, and be therefore forwarded to other vehicles. Observe that the content of the i–th entry is updated only if the information just received in a beacon is newer than the one already stored, which can be verified by checking either the packet ID or the packet timestamp. Secondly, in general it is not mandatory that only the last information received about node i is kept in the table. If there is enough memory, up to M packets may be stored in each table entry. In this case, whenever the $(M + 1)$–th information about node i is received, it replaces the oldest one already stored.

To simplify analysis, beacon transmission is modeled according to a synchronous model, in which transmissions from all vehicles are assumed to occur simultaneously, or, equivalently,

that the information in all the lookup tables is updated only at the end of each time slot. The time slot is assumed to be equal to the beaconing period, set to $0.1\ sec$ in this paper. Under moderate-to-low radio channel congestion levels, this model accurately resembles the dynamics of information propagation in a real world situation where transmissions are scattered within a time slot. This conjecture has been verified through a set of preliminary simulations, in which we have compared the results obtained with the synchronous model to those obtained with an asynchronous model where transmission times are randomly chosen within a time slot.

Performance metrics. The aim of the beaconing exchange process is to provide each vehicle with updated information on the positions of the surrounding ones. To achieve this, it is important that packets are delivered quickly, so as to maintain a low average *information age* at each vehicle. The average age of the information regarding node j stored at node i, which we call $\Lambda_{i,j}$, is computed by averaging the instantaneous information age $\lambda_{i,j}(t)$ at time t over the entire simulation. In the synchronous model, this metric is discretized. The information age $\lambda_{i,j}(k)$ at time slot k is the difference between k and the time slot in which the current information about node j stored at node i has been generated. Since we assume that information is generated by all nodes at the beginning of the time slot, whereas the information age is measured at the end of the time slot, it follows that $\lambda_{i,i}(k) = 1$, $\forall i, k$.

Similarly, we also derive the *black-out time fraction* $\Gamma_{i,j}$ at node i regarding node j, as the fraction of time slots in which $\lambda_{i,j} > \gamma$, where γ is a predefined threshold. The value of γ is set to $1\ sec$ (equivalent to 10 time slots), following the observation made in [9], [23] that a situationally awareness blackout of $1\ sec$ severely impacts road safety.

IV. FORWARDING STRATEGIES

The choice of the nodes whose information is to be forwarded in a beacon is of key importance, in order to reduce both the average information age and the black-out time fraction. A *Homogeneous* strategy is applied in the same manner by all the nodes in the network. Conversely,

a *Heterogeneous* strategy allows nodes in different positions to perform different actions.

In the following, we list a number of forwarding strategies, either Homogeneous or Heterogeneous. Some of them are defined by additional parameters, which will be explained. In this study, and in accordance with recommendations from standardization bodies [11], we fix $C = 3$, meaning that 3 data fields are available in each beacon – one of which is reserved for reporting the information of the transmitting vehicle. The strategies are presented without considering the possible impact of radio channel congestion on forwarding. The effect of radio channel congestion on the most representative forwarding strategies is discussed in Section V.

A. Basic strategies

We collect here 9 strategies that can be applied to the considered scenario with no additional signal processing techniques required.

1) Random selection (Random): This is the baseline strategy. With this homogeneous strategy, the $C - 1$ data fields of each beacon are filled with the information of $C - 1$ nodes randomly selected from the $N - 1$ belonging to the analyzed network.

2) Oldest Information (OI): When this homogenous strategy is applied, the transmitting node i selects the $C-1$ data fields to forward as the ones with the highest age $\lambda_{i,j}$, for $j \in \{1, 2, \ldots, N\}$. The idea behind this strategy is to speed-up the forwarding of information generated by likely far nodes, thus preventing it to become too old and, therefore, useless. On the other hand, this strategy may be stuck if no information is received for a long time from some nodes, leading to repeated transmissions of stale information.

3) Newest Information (NI): Opposite to the previous one, this homogenous strategy aims at delivering the newest (and most useful) information. Each node i selects the $C - 1$ data fields with the lowest values of $\lambda_{i,j}$. Although this helps in promptly delivering information from surrounding nodes, this strategy is unable to forward information over long paths, since the traveling information becomes soon older than the one from the local nodes, and is stopped.

4) Farthest Information (FI): This homogeneous strategy chooses the information to be forwarded based on the distance of the information source. More specifically, node i chooses the data fields of the $C-1$ nodes which were farthest from it when they transmitted the information currently stored in the i's lookup table. The strategy is meant to enlarge the awareness radius of the nodes in the network. However (especially in a network with fixed positions, as the one considered in this study), each node would probably transmit always the information from the same nodes, and its behaviour is likely to be similar to that of the *OI* strategy.

5) Closest Information (CI): Similarly to the previous one, this strategy aims at forwarding the information about the closest nodes. Consequently, its behavior is likely very similar to that of the *NI* strategy, and is likely unfit to forward information to far nodes.

6) Local oldest - global oldest (LOGO): The idea behind this homogeneous strategy is to balance the traffic from far nodes and from neighbors. In the system model described above, the neighbors of a node i are those with IDs $i-2$, $i-1$, $i+1$, $i+2$, up to $i\pm4$. In selecting the $C-1$ nodes whose information is to be forwarded, half of them are chosen among the neighbors. More precisely, the $(C-1)/2$ neighbors with the oldest information age are selected. The remaining ones are instead chosen following the *OI* strategy. The *LOGO* strategy tries to balance the amount of resources used to forward information from far nodes and those used to update the local awareness.

7) Oldest with limit (OWL): This strategy is similar to *OI*. However, motivated by the observation that a too old information becomes useless, the selection of the nodes whose information is forwarded is still based on the information age, but with an age limit α. The $C-1$ selected vehicles at node i are those with the largest $\lambda_{i,j}$, subject to the constraint $\lambda_{i,j} \leq \alpha$. The value of α plays a key role. High values of α make it possible to forward information over long paths but, on the contrary, may cause the same problems of *OI* (a node which cannot receive information from a vehicle j continues to transmit its old information about j). Low values of α are useful to ensure a prompt forwarding of the information, but far nodes may be unreachable,

due to the excessively high amount of hops necessary. This tradeoff corresponds to the choice between having a very good awareness of only the local situation or having some knowledge also about far nodes (but with slightly less reliable local information).

8) LOGO with limit (LOGOL): This strategy works exactly as *LOGO*. However, when selecting the $(C-1)/2$ oldest information about non neighboring nodes, only those with an age not older than α are considered, as in the *OWL* strategy. In general, a slightly higher value of α can be adopted with this strategy than with *OWL*, since part of the resources are in any case reserved for local transmission. However, if the network is large, dedicating half of the resources to four neighbors may be excessive.

9) OWL with neighbors selection probability (OWL-np): With *LOGO* and *LOGOL*, half of the resources are dedicated to neighboring nodes. A way to add flexibility could be to change the fraction of data fields reserved to the neighbors. If, however, C is quite low, as is in our scenario, this is not possible. An alternative is to set a probability p. With this strategy, every time node i transmits, it behaves as with the *OWL* strategy with probability $1-p$. In the remaining cases, it uses all the data fields to forward information about its neighbors. The value of p may be the same for all nodes; however, in general, the nodes in the middle of the network are less likely to transmit information about the neighbors, with the simple *OWL* strategy, since they often receive old information from the vehicles in both the head and the tail regions. Therefore, different probability values p_i should be used. In the resulting heterogenous strategy, the nodes in the center are likely to have higher values of p_i.

B. Advanced strategies: Network Coding

We present here some strategies which are based on the concept of Network Coding. Briefly, the idea behind these schemes is to transmit information about more than C nodes, without the need for an increased beacon size.

When Network Coding is used, different data packets can be superimposed through linear

combination. In principle, a node which receives enough linearly independent combined packets can retrieve the whole set of original data packets. In our case, we limit the combination to only two packets A and B, which are superimposed via the bitwise XOR operation, getting $C = A \oplus B$. A receiving node which knows either A or B can retrieve the other packet by applying again the bitwse XOR, since $A = C \oplus B$ and $B = C \oplus A$. However, a receiver which does not know any of the two packets cannot obtain any information.

A forwarding strategy based on Network Coding may use a single data field of the beacon to transmit the information about two nodes, rather than one. In doing this, three points should be observed:

- the choice of the nodes whose information is coded is important, since the other vehicles can decode it only if they already know at least one packet;

- a small overhead is necessary, to inform about the IDs (and the source nodes) of the combined packets, so as to let the receiving node use the correct packet to decode the received data. However, in the following we show that a few bytes are sufficient for this purpose, and that this small overhead does not impact beacon size limitations.

- the memory size M introduced above, which can be equal to 1 in all the previously described strategies, plays a key role when Network Coding is adopted. In order to decode an incoming packet, it is necessary to combine it with a packet already received, which in turns requires to be kept in memory for a while. A tradeoff between memory size and Network Coding effectiveness could be investigated.

The following strategies are currently designed specifically for $C = 3$, although extensions to more general cases may be derived as well.

1) NC of neighbors (NC-n): This heterogeneous strategy aims at compressing the information about the neighboring nodes. The two available slots in the beacon sent by node i (the first one is still reserved to the data from the transmitting vehicle itself) are used as follows: in the former, the information about node $i + 1$ and node $i - 2$ are combined together, while in the latter the
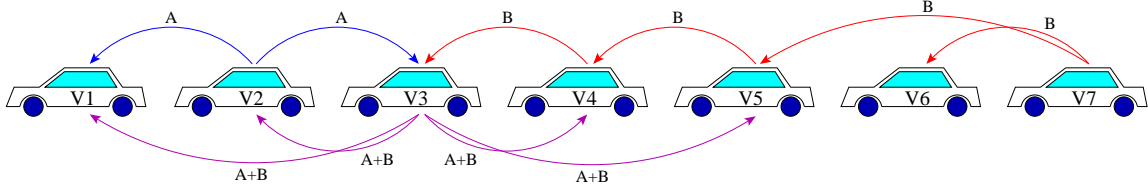
Fig. 1. Example of Network Coding used in a linear vehicular network. Node $V3$ fills one of the data fields of its beacon with the combination of packets A, generated by $V2$, and B, generated by $V7$. In this way, up to 4 nodes can receive useful information: nodes $V1$ and $V2$ can obtain packet B, while nodes $V4$ and $V5$ can extract packet A.

same is done with the information about node $i-1$ and node $i+2$. Note that the combination is always between information sent by nodes which are in opposite directions. This is necessary to increase the probability that in both directions a node which already has only one of the two combined packets is found. This strategy is very effective to handle the local traffic, since information is constantly updated about all the neighbors. However, no forwarding is possible beyond 4 hops. The nodes in the first and last positions of the network, having less neighbors, can combine less packets, and have to use their data fields to trasmit uncoded information.

2) NC plus Oldest with Limit (NC-OWL): This heterogeneous strategy combines the idea of *OWL* with Network Coding. A node i starts by looking at the oldest information (within the usual limit α) it has stored from nodes with ID $j > i$. Subsequently, it combines this information with the one of either node $i-1$ or $i-2$ (a random choice, or the information with higher age), and put the result in the second data field. For the last data field, the oldest information coming from nodes with ID $j < i$ (and within limit α) is found and combined with the information coming from either $i+1$ or $i+2$. With this approach, the resources are equally shared between local traffic and forwarding information from far nodes. The choice of the information to be coded is again aimed at maximizing the probability that the coded packet can be decoded in both directions. As *OWL*, the value of α can be tuned to increase either the reliability of information from close nodes or the capability of forwarding beacons over long paths. An example of this strategy is also reported in Figure 1, which depicts how one of the data fields of node $V3$ is

filled via Network Coding.

C. Reference strategies

For reference purposes, we consider also the two following strategies.

1) Full information: This is an idealized homogeneous strategy in which C is set to be equal to N, i.e., the beacon has enough room to piggyback information about all network nodes. This strategy is not compliant with beacon size recommendations from standardization bodies [11], yet we keep it as it provides the best possible information quality that is achievable with multi-hop information forwarding.

2) Single-hop: In this case, no multi-hop forwarding of beaconing information is performed: C is set to 1, and the beacon reports only the information of the transmitting vehicle. This strategy is useful to assess the benefits of multi-hop vs. single-hop propagation of situational information.

V. THE IMPACT OF RADIO CHANNEL CONGESTION

So far, we haven't considered the possible impact of radio channel congestion on the beaconing forwarding strategy. Relatively higher channel congestion leads to relatively worse channel conditions [26] which, in turn, can deeply affect the information propagation speed, being the longest links usually unavailable. In addition, forwarding strategies based on Network Coding may become less effective, since decoding a superimposed packet requires the correct reception of previous beacons.

In general, the beaconing forwarding strategies listed in Section IV can be also applied in the congested scenarios. Nevertheless, the more frequent losses due to the worse channel conditions reveal some peculiar behaviors which result in degraded performances. This is the case of the *OWL* strategy, as well as of the *OWL-NC*. In the following, we point out what is the weak point of these strategies in a congested scenario, and how they can be tackled.

A. OWL strategy in congested scenarios

The OWL strategy aims at forwarding the oldest information kept in the lookup table, whose age is no greater than a limit α. While in a non congested scenario the rate of information updates is quite high, due to both better channel conditions and longer transmission range, this does not hold when congestion is non-negligible. It follows that, if the time constraint α is tight, it is possible that there are not enough beacons with a sufficiently low age. The basic OWL strategy simply leaves the field empty, which is not the optimal behavior. Therefore, we modified the strategy by assuming that even packets whose age is greater than α can be forwarded, provided that all the beacons matching the age constraint have been already selected.

B. NC-OWL strategy in congested scenarios

The same improvement used for the *OWL* strategy is also applied to the *NC-OWL*. However, here two other aspects have to be considered. As a first point, for the case $C = 3$, we have to ensure that each information to be transmitted is chosen only once. This always happens in the non congested scenario, where the oldest information (matching the age limit) in each direction is very likely to be about a far vehicle, due to the longer transmission range. However, this is not true in a congested scenario, especially when α is low. Frequent packet losses may result in the oldest information being about a neighboring vehicle. The same information may also be chosen to be combined with the oldest information coming from a vehicle in the opposite direction. If this happens, 3 beacons rather than 4 are actually combined, with a clear performance degradation. It follows that an additional check is necessary when *NC-OWL* is adopted in a congested scenario to ensure that 4 different beacons are combined and forwarded.

A second observation is about the age of the beacons to be forwarded. We assume that a vehicle keeps the M most recent beacons from each other vehicle, which are used for decoding superimposed packets. However, when channel conditions are bad, it may happen that even the age of the last beacon x received by a neighboring vehicle V_i is higher than M. In this case, to

combine x in a superimposed packet $x \oplus y$, as required by *NC-OWL*, may be detrimental. In fact, vehicle V_i is no longer able to decode this packet, having already deleted x from its lookup table (a new beacon is generated every time slot). In addition, x is a relatively old information, thus potentially already outdated for other neighboring vehicles. Results obtained through simulations show that in this case it is therefore better to avoid NC, and to transmit only y.

We hence apply also the following modification to the *NC-OWL* strategy: when the oldest information from vehicles in a given direction has to be combined with the one about a neighbor in the opposite direction, only the former is instead forwarded if the latter has an age greater than M.

Observe that such a situation almost never occurs in the non congested scenario, whereas its frequency increases with the congestion level. This new version of the *NC-OWL* then introduces a certain degree of adaptivity to the channel conditions.

VI. SIMULATION SETUP

A large-scale assessment of multi-hop beaconing performance based on measurements is challenging due to cost and logistic issues. For this reason, we have adopted an evaluation methodology based on simulations, but with the remarkable feature that the multi-hop communication model used in simulations is based on the outcome of a real-world measurement campaign. More specifically, we performed preliminary measurements with a real vehicular network composed of 5 vehicles in a car-following configuration to estimate beaconing reception patterns up to the 4-th hop of communication. Then, we have designed a Markov-chain based multi-hop communication model whose parameters are tuned to mimic the beacon reception patterns observed in the measurements. Finally, we have used the Markov-chain based model in a linear configuration of N vehicles to estimate how quickly the quality of situational information degrades with hop distance.

A. Preliminary measurements: no congestion

Preliminary on-the-road measurements were performed in order to get the input data for our simulations, and to validate our simulation model and its results. The measurements setup was quite similar to that described in [10], using five beaconing vehicles instead of three. For vehicular communications we used IEEE 802.11p compliant NEC LinkBird-MX units. Each one was deployed on a single vehicle, together with an omnidirectional WiMo antenna ($108\,mm$ long, $5\,dBi$ gain) installed at the centre of the roofs (as recommended in [8], [28]), a laptop, and a GPS receiver. Channel 180 at $5.9\,Ghz$ (the control channel, recommended for safety applications) was selected for radio communication among vehicles. The transmission power was fixed to $20\,dBm$, with a $3\,Mbps$ PHY layer data rate and a $10\,Mhz$ channel bandwidth. Note that using a fixed transmission power guarantees high overall situational awareness, but could also imply scalability issues due to the possible channel congestion with dense vehicular scenarios. As part of the future work, we plan to investigate the tradeoff between transmission power and the increasing situational awareness achieved onboard vehicles.

We performed a $160\,km$ long trip, from Pisa to Florence (along a freeway, with speed limit of $90\,km/h$ and two lanes per direction) and from Florence to Lucca (along a highway, with speed limit of $130\,km/h$ and two/three lanes per direction). Note that since we performed the experiments mostly over 2-lane roads, the 5 vehicles were allowed to change lane, when possible; this implies that a line of sight (LOS) was often available also between non adjacent vehicles. The beaconing application running on each vehicle triggers the transmission of a new beacon every $100\,ms$, and records beacons received from other vehicles, as well as those it transmitted. For further details see [10].

With the collected data we were able to compute the Packet Inter-arrival Time (PIR), defined as the interval between two subsequent successful beaconing receptions, and derive the PIR probability of being (or not) into a blackout. Notice that the PIR metric has been observed to more

faithfully represent situational-awareness than the packet delivery rate [9], [29]. The resulting PIR time distributions at different hop distances from the transmitter are shown in Figure 3. Notice that there is no multi-hop piggybacking of situational information in the measurement experiments, hence the curve k-hop refers to the metric measured on beacons sent by vehicle V, and received by a vehicle k hops away from V. From the figures, the degradation of situational information quality with hop distance is evident: the probability of observing a blackout (i.e., the probability that the PIR time is $\geq 1\ sec$) is negligible at 1 hop, about 10^{-4} at 2 and 3 hops, and about 10^{-1} at 4 hops.

B. Preliminary measurements: radio channel congestion

In order to reproduce scenarios with different levels of radio channel congestion, a high number of vehicles would be necessary in principle. However, this is not practical in real-world experiments, due to logistic as well as cost reasons. Therefore, we instead opted to *emulate* the background traffic by running a Constant Bit Rate (CBR) application on two of the five deployed vehicles, with different rates. The congestion level is measured in terms of Channel Busy Time (CBT). We tested three levels of congestion, namely 18%, 24% and 29%, corresponding to a rate of $500\ kbps$, $650\ kbps$ and $800\ kbps$ for the CBR application. For each level, we performed an experiment, driving a platoon of five vehicles along the same $160\ km$ long route used for the measurements in a non congested scenario. The interferer vehicles, running the CBR application, were placed at the head and at the tail of the platoon; in addition, these two vehicles were taller than the beaconing ones, with the aim of obtaining a more uniform traffic floor. The obtained PIR time distributions are reported in Figure 4. Notice that in this case we were able to measure link behavior up to the second hop.
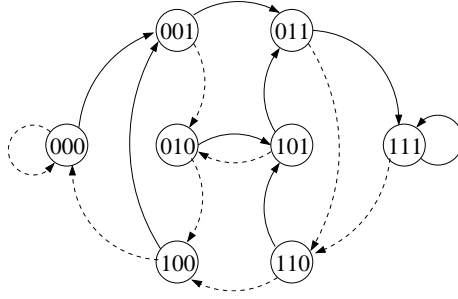
Fig. 2. Representation of a Markov chain which $h = 3$: continuous lines represent successful beacon reception transitions; dotted lines represent beacon reception failure transitions.

C. Markov Model-based simulations

As observed in [9], black-out events *(i)* severely impair onboard situation-awareness, and *(ii) are not* temporally independent, since they are typically caused by bad channel conditions, which usually show strong temporal correlation. Since we want to predict the average black-out frequency observed on each vehicular link, to be as accurate as possible we use a Markov Chain-based Model that keeps memory of the past states.

To model beaconing packet reception on a given channel, we can define a Markov process $\mathcal{P}_h$ of order h as follows. Given the measured PIR values, we derive the binary sequence $\mathcal{S}$ of 1 (received packets) and 0 (lost packets) on that channel. By scanning $\mathcal{S}$ we save each occurrence s_h of h-long binary strings and the probability p_{s_h} of having 1 (success) or 0 (failure) immediately afterwards. Thus, each state S_i of the Markov chain is represented by the s_h string, and the above defined probabilities define the state transition matrix Π corresponding to the channel. As an example, in Figure 2 a 3-order Markov chain is represented, where a continuous line represents a transition given a new correctly received beacon, while a dotted line represents a transitions occurring after a beacon transmission failure.

Given Π and the success (conversely the failure) on each channel, we can simulate an arbitrary number of time slots (in our case 100,000). By doing the same for all the channels, we can determine the beacon propagation on a N vehicles queue.
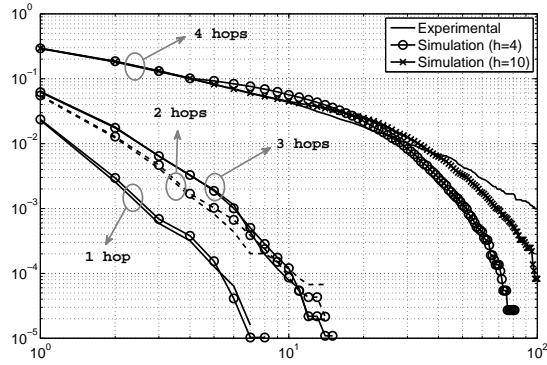
Fig. 3. PIR time probability distribution: comparing measured PIR with the one derived with the Markov-based model. The curves refer to the complementary cumulative density function (ccdf) of the distribution.

Figure 3 compares the binary sequences returned by the simulator, using $h = 4$ and $h = 10$, with the PIR distribution obtained during our measurement campaign. We observe that lower values of h do not properly approximate the channel, and this could be even worse if the channel conditions are not so good. For this reason we decided to use $h = 10$ in our simulations, leading to a good prediction of the PIR distribution up to the 4-th hop of communication.

In Figure 4, we plot the measured and the simulated PIR time cCDF for the congested scenarios with CBT values of 18% and 29%, respectively. Since the channel conditions here are bad, we chose $h = 10$ in the Markov model, which appears to properly emulate che real curves for both the 1-hop and the 2-hop links.

VII. RESULTS

In our simulations we studied a network composed of $N = 16$ vehicles, placed at distance $d_i = 30\,m$ from each other, and moving at constant speed. The size of the beacon is $100\,B$, leading to $C = 3$. For the Network Coding-based strategies we assume the memory size $M = 3$. The format of the beacon message is reported in Figure 5. Besides the sender vehicle ID (1B), and the number of vehicles (Tab Size, 1B), the beacon also contains the situational information fields (*SIF*) of C beaconing vehicles, including the sender's one (SIF 1). In case of *NC* strategy,
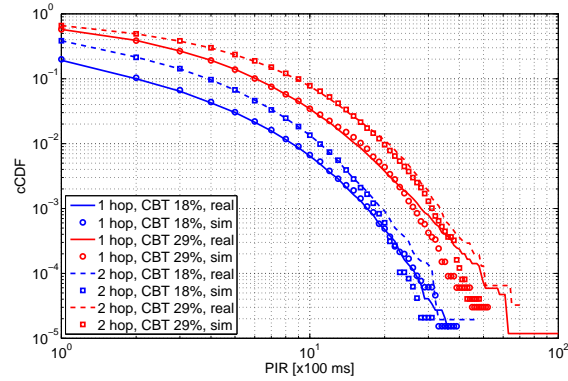
Fig. 4. PIR probability distribution (measurements and through Markov model) in congested scenarios. We report the PIR cCDF for the scenarios with CBT values of 18% and 29%, and for both 1-hop and 2-hops links.
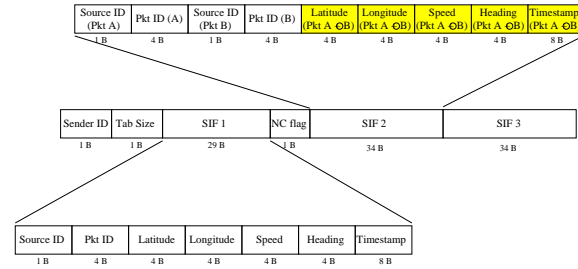

Fig. 5. Beacon format. The yellow part highlights where the vehicle information to forward have been combined in SIF2 (similarly in SIF 3, if applies) when applying the *NC* strategy.

an *NC* flag (1B) tells if SIF 2, SIF 3 or both contain combined packets, and, if so, the SIF 2 and/or 3 are opportunely changed, as pictured in Figure 5. Suppose SIF 3 does not contain combined packets: in this case the correspondent *Source ID (Pkt B)* and *Pkt ID (B)* are simply not filled in.

Although we have simulated all the forwarding strategies mentioned in Section IV, we report in the plots only the curves referring to the most representative strategies, namely: the randomized strategy, the best basic strategy (*OWL*), the best network-coding strategy (*NC-OWL*), and the idealized *Full Information* strategy. Even if the latter is quite an unrealistic strategy, we report it here because it is supposed to perform the best, in terms of information "penetration" and

propagation, so to understand how good the selection strategies we propose here are. Furthermore we report the results obtained without multi hop strategies, only relying on the single-hop propagation of the beacons.

A. No congestion

We start reporting the results obtained in the case of no congestion on the radio channel. Figure 6 reports the average information age at the various nodes of the information from node 1, namely $\Lambda_{i,1}$ as a function of i: the strategy *OWL* outperforms the baseline random selection in delivering information to far nodes. However, this comes at the cost of a higher information age at closer nodes, where *Random* gives better results. The *NC-OWL* performs even better up to 12 nodes, outperforming every other strategy when $\alpha = 4$; in this case, in fact, it is perfectly bounded by the *Random* strategy on one side and the *Full Information* on the other, being the best selection strategy analyzed so far. Single-hop propagation performs well up to hop 3, but at hop distance 4 the quality of received information degrades and becomes far worse than that achieved with multi-hop propagation. Notice that the single-hop curve stops at hop distance 4, due to the fact that the communication model, derived from measurements, assume that a direct communication between vehicle can occur only up to hop distance 4.

The role of parameter α is perfectly highlighted: increasing α may lower the information age at far nodes, but on the contrary worsens the performance at closer nodes, since more resources are used for older information. Notice also that $\alpha = 4$ is the minimum value which guarantees the delivery of information from node 1 to node 10. In any case, the usage of Network Coding yields the best performance, with performance close to that of the idealistic *Full Information* strategy, and a halved average information age with respect to the randomized strategy.

In Figure 7 similar results are depicted for the fraction of time vehicles experience a situation-awareness black-out. In this case *OWL* performs better than *Random* strategy at farther nodes. The effect of an increased α is more pronounced, but *NC-OWL* still grants much higher performance,
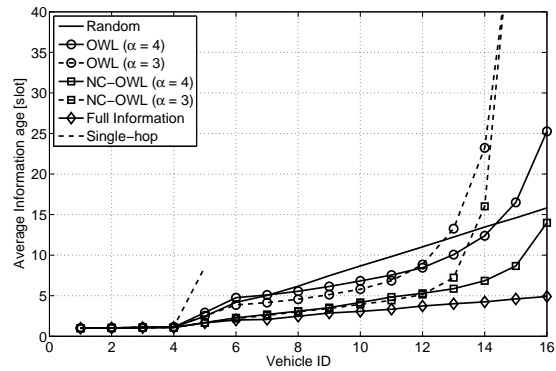
Fig. 6. Average information age $\Lambda_{i,1}$, i.e. the age of information departed from node 1, measured for all the nodes in the network.
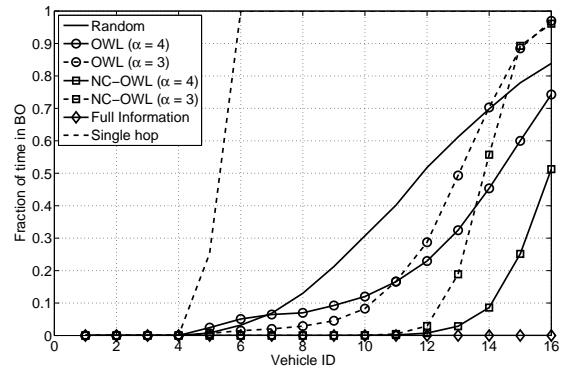

Fig. 7. Black-out time fraction $\Gamma_{i,1}$ for the nodes in the network.

with black-out probability which is below 0.1 up to node 14. Notice that *NC-OWL* performance is very close to that of the idealized *Full Information* strategy up to the 12-th hop of communication, which is a very notable results since situational information is likely to become un-relevant at large hop distances. Notice also that all multi-hop strategies perform much better than the single-hop strategy.
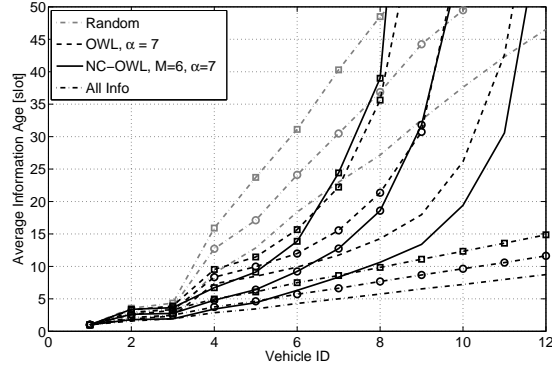
Fig. 8. Average information age $\Lambda_{i,1}$, i.e. the age of information departed from node 1, measured for all the nodes in the network, for various values of the CBR application rate R. No markers are for $CBT = 18\%$, round markers are for $CBT = 24\%$ and square markers are for $CBT = 29\%$.

B. Radio channel congestion

As to the scenarios where congestion is present, we first plot in Figure 8 the average information age from vehicle 1 achieved through the same policies analyzed in the non congested scenarios. Clearly, as the radio channel congestion increases, it becomes more difficult to obtain fresh information from far vehicles, resulting in a higher delay. All the policies, including the idealized *Full Information*, have worse performance than in the scenario with no congestion. We observe that while both *OWL* and *NC-OWL* grant a much lower information age for closer vehicles, they are not able to propagate the information beyond a given threshold. This threshold, for $\alpha = 7$, drops from vehicle 12 to vehicle 8 when the CBT ratio grows from 18% to 29%. We also notice that while *NC-OWL* outperforms *OWL* when congestion is low, a reversed situation occurs for a CBT ratio equal to 29%. This is due to a bad choice of the beacons to be combined via Network Coding, as shown later.

In Figure 9 we focus on the most congested scenario (CBT ratio equal to 29%), to analyze more in depth the effect of the parameters α and M. First of all, the effect of α is consistent with what illustrated in the non congested scenario. Increasing α allows to reach farther vehicles, but
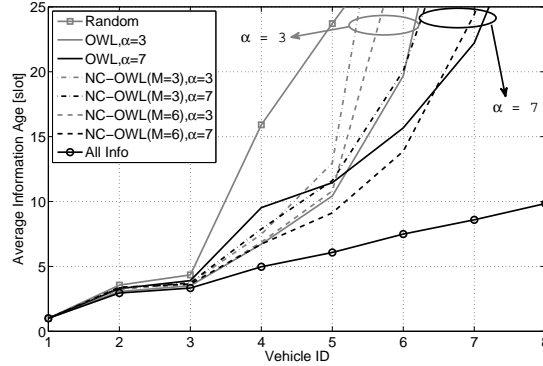
Fig. 9. Average information age $\Lambda_{i,1}$, when $CBT = 29\%$, for different policies. Here *NC-OWL* is applied without modifications, as in the non congested scenario.

at the cost of a higher information age at the neighbors. However, this is true only for *OWL*: putting $\alpha = 7$ instead of $\alpha = 3$ makes it possible to send beacons up to vehicle 8, but the average information age at vehicle 4 is more that 40% higher. *NC-OWL* does not suffer from the same problem, since the superposition of beacons coming from neighbors always keeps the average information age quite low for close vehicles. On the other side, however, the frequent packet losses severely reduce the impact of Network Coding, resulting in a lower performance. Increasing the memory parameter M can help (when α is also high, since otherwise old packets are almost never forwarded) but even when $M = 6$, the simple *OWL* performs better on long distances.

Performance is different if *OWL-NC* is improved as explained in Section V. In this case, for low values of α *OWL-NC* obtains the same performance as *OWL*. When $\alpha = 7$, the improvement is even more pronounced: there is a wider set of beacons which can be forwarded, but the superposition is done only when it is likely to be useful. In general, this modification is particularly effective when M is low, since it avoids most of the detrimental superpositions of already deleted information. We can hence observe that now even $M = 3$ is enough to obtain better performance than *OWL*. With $M = 6$, the new curve is quite close to the one of the
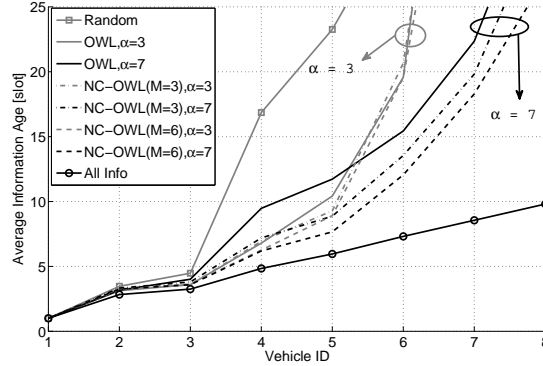
Fig. 10. Average information age $\Lambda_{i,1}$, when $CBT = 29\%$, for different policies. Here *NC-OWL* is modified as explained in Section V.

optimal policy up to vehicle 5, while at vehicle 7 the average information age has been reduced by approximately 25%, becoming much lower than that offered by *OWL*.

Similar considerations are valid for the black-out time fraction $\Gamma_{i,1}$, which is plotted in Figure 11 for three different channel congestion levels. We notice that the presence of background traffic severely hampers the inter-vehicle communications, thus strongly increasing the black-out probability even with the idealized *All Information* policy. Both *OWL* and *NC-OWL* are much more effective than the *Random* forwarding, with the latter always being better than the former on short distances. We also observe that *OWL* outperforms *NC-OWL* when congestion is high, on long distances, confirming what illustrated with the average information age.

Looking more in details at the scenario with higher congestion (CBT ratio 29%), we first notice in Figure 12 that the *NC-OWL* policy, without modifications, performs quite worse than the simpler *OWL* when α is equal to 3. In this case, again, channel losses lead to the superposition of quite old packets from neighboring vehicles, which have been already deleted at other nodes, leading to a waste of capacity. Increasing α can improve the situation, but only on short distances, where *OWL* instead performs bad, for the reasons explained above.

When applying the modifications illustrated in Section V, the black-out probability offered by
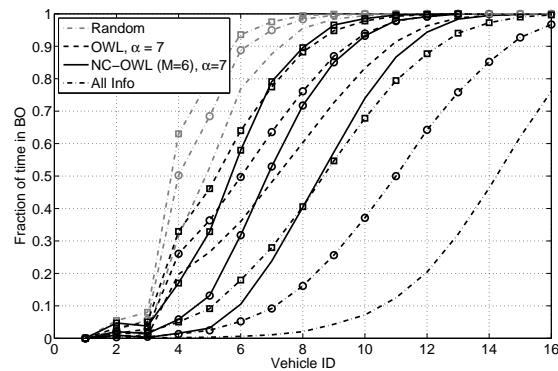
Fig. 11. Black-out time fraction $\Gamma_{i,1}$, for all the nodes in the network, for different values of the CBR application rate R. No markers are for $CBT = 18\%$, round markers are for $CBT = 24\%$ and square markers are for $CBT = 29\%$. Here *NC-OWL* is applied without modifications, as in the non congested scenario.
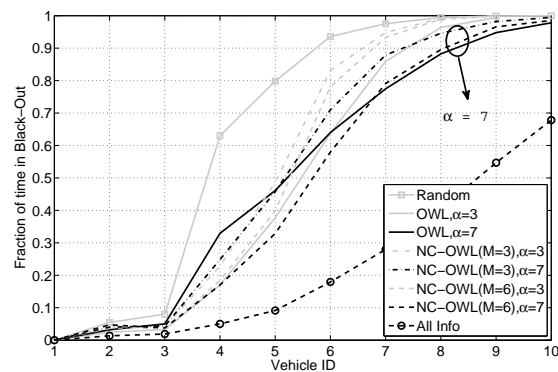

Fig. 12. Black-out time fraction $\Gamma_{i,1}$, when $CBT = 29\%$, for different policies. Here *NC-OWL* is applied without modifications, as in the non congested scenario.

NC-OWL drops dramatically: for instance, at vehicle 5 the value appears to decrease of about 33% in Figure 13. In this case, even a low dimension of the lookup table ($M = 3$) is enough to achieve good performance, although $M = 6$ is needed to keep the black-out probability around 0.2 up to vehicle 5.
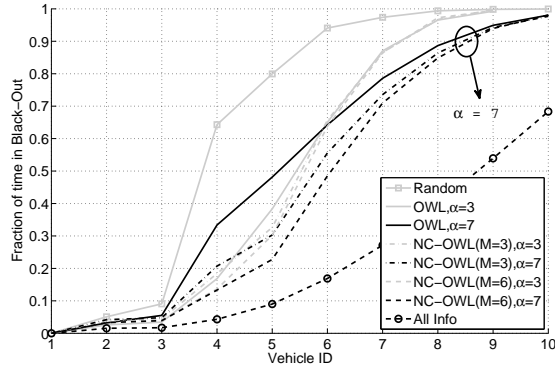
Fig. 13. Black-out time fraction $\Gamma_{i,1}$, when $CBT = 29\%$, for different policies. Here *NC-OWL* is modified as explained in Section V.

VIII. CASE STUDY: FORWARD COLLISION WARNING

Up to now we have focused our attention on two performance metrics, namely, the PIR time and blackout frequency in VANET communications, but how these parameters could be used to actually improve safety on the road? To gain a better understanding of this, we present a case study in which the results presented in the previous section are used to estimate the *reliability* of an active safety application, in presence of different levels of radio channel congestion and forwarding strategies. As defined in [30], the reliability of a safety application is the percentage of time during which the application requirement is satisfied. Note that, in case of vehicular networks, several factors could impact the reliability of a safety application, such as the speed of the vehicles, and the distance between the vehicles. The specific active safety application considered is forward collision warning.

A forward collision warning (FCW) application warns the driver when a rear-end collision danger is detected, so to reduce the risk of an accident. In this application, a vehicle needs to constantly monitor the status of forward vehicles. Considering two vehicles A (back) and B (front), a rear-end collision would be avoided if the PIR time measured at A referring to the beacons sent by B is kept below a certain threshold. Upper bounding the PIR time ensures that
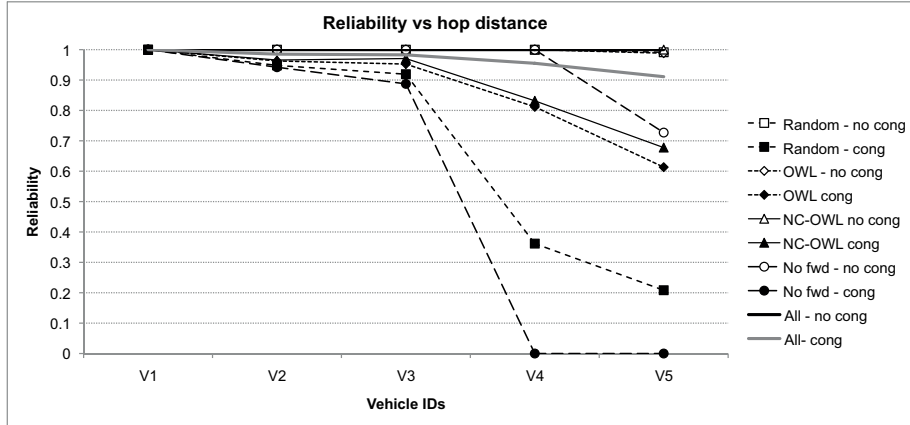
Reliability vs hop distance

Fig. 14. Reliability: Awareness time fraction $\Omega_{1,j}$, with different forwarding strategies. For each strategy, we report the results obtained without congestion, and with the highest congestion level ($CBT = 29\%$).

A constantly keeps a relatively "fresh" information about the status of vehicle B, allowing for a prompt detection of potentially dangerous conditions onboard vehicle A. The upper bound on the PIR time is set by the FCW application, and depends on parameters such as speed and distance between vehicles. For instance, in [30] it is estimated that, in case of vehicle speed around 80 km/h and distance between vehicles of about 60 m, the PIR time upper bound should be set to 1 sec, which is exactly the value used to define black-out events in our analysis. Given this, we can use the *black-out time fraction* $\Gamma_{i,j}$ between two vehicles i and j to estimate the reliability of the FCW as $\Omega_{i,j} = 1 - \Gamma_{i,j}$, representing what we call the *"awareness" time fraction*.

Here we analyze the $\Omega_{1,j}, j = 2, \ldots, 5$, i.e., up to the 5-th hop of communication. This choice is motivated by the fact that the distance between vehicle $i = 1$ and vehicle j is assumed to be in the order of 60 m, hence having at most 3 vehicles in between i and j seems a reasonable choice.

Figure 14 reports the reliability obtained with different forwarding strategies and hop distance from the front vehicle. For each strategy, the figure reports two curves: one referring to a non-congested radio channel (empty markers, mostly collapsed in a single upper curve), and

one referring to the congested radio channel with $CBT = 29\%$ (black markers). Three main observations can be made by analyzing the results:

1) *the effect of radio channel congestion on reliability is substantial*: while without congestion the FCW application has nearly maximal reliability independently of the forwarding strategy, in presence of congestion reliability drops considerably – up to 80% with random forwarding, and to nearly 100% without forwarding.

2) *multi-hop forwarding of situational information is a very effective method for improving reliability*: while reliability in presence of congestion is nearly 0 in case of no forwarding, it is increased of as much as 70% in case of forwarding.

3) *network-coding based forwarding is the best performing strategy*, increasing reliability of as much as three times as compared to the randomized forwarding strategy.

IX. CONCLUSIONS

In this paper, we have considered different strategies for multi-hop forwarding of situational information in IEEE 802.11p vehicular networks. The results reported in the study clearly indicate that piggybacking information about few neighboring vehicles, if adequately selected, is sufficient to substantially improve beaconing performance in NLOS scenarios, and to improve reliability of active safety applications. The most effective strategy is based on a simple network-coding approach, that can be readily implemented and made compliant to IEEE 802.11p beaconing format. Thus, a major contribution of this study is showing that the poor NLOS beaconing performance observed in recent measurement-based studies can be improved and made adequate to the need of active safety applications by means of a simple and readily implementable network-level solution.

For future work, we plan to investigate other dimensions along which situational awareness and communication channel use can be traded off, such as transmission power control and other congestion control techniques.

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