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. A possible way of achieving this is by piggyback information on the beacon packets that are sent periodically by each vehicle in the network, as prescribed by the DSRC and ETSI standards. However, prescribed limitations on beacon size imply that only information about a very small number of surrounding vehicles can be piggybacked in a beacon packet. In most traffic situations, this number is well below the typical number of vehicles within transmission range, 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 designed different multi-hop forwarding strategies, and assessed their effectiveness in delivering fresh situational information to surrounding vehicles. Effectiveness is estimated in terms of both information age and probability of experiencing a potentially dangerous situational-awareness blackout. 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%, and 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 (LOS) conditions between vehicles. The fact that beaconing performs poorly in Non-Line-Of-Sight (NLOS) conditions jeopardizes the fulfillment of active safety applications' design goal of extending a driver's situation-awareness "beyond human eyes".

A possible way of improving beaconing performance in NLOS conditions is through multi-hop propagation of vehicle situational information. In principle, this information could be piggybacked in the periodic beacon messages, implying a minimal impact on radio channel congestion with potentially substantial benefits in terms of situation-awareness. The results presented in [10] confirm this intuition. However, the 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. More specifically, assume that, due to beacon size limitations, situational information about C vehicles can be piggybacked in the beacon, and that a certain vehicle – say, V – is aware of the status of N vehicles in its transmission range, with $N > C$. This paper is concerned with designing

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Manuscript received November 5, 2014; revised March 17, 2015, and August 21, 2015; accepted October 25, 2015. The associate editor coordinating the review of this paper and approving it for publication was F. Bai.

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Part of this work has been presented at IEEE Secon 2014 [1].

[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.

[2] Without security overhead.

and analyzing different situational information forwarding strategies, i.e., different possible ways for V to select C out of N situational information records to be piggybacked in the beacon. To our best knowledge, identifying the best forwarding strategy is an open problem which is addressed in this paper.

In this work, we developed and compared different situational information forwarding strategies, including a randomized strategy, network-coding based strategies, and an idealized strategy in which the complete situational information is piggybacked in the beacons which is used for reference purposes. The different strategies are evaluated by means of simulations whose multi-hop communication performance is corroborated by real-world measurements. The reference scenario for simulations is a multi-hop vehicle configuration in a linear arrangement, and the goal of the analysis is to 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 information age and the probability of experiencing a situational-awareness black-out of at least τ sec, where the value of τ in general should be defined based on the requirement of the active safety applications built on top of the beaconing mechanism. The results of the analysis clearly indicate that network-coding based strategies are the most effective in improving situational-awareness.

In the last part of the paper, we present a case study in which our results are applied to estimate the reliability of a forward collision warning active safety 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 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 of 10 Hz as dictated by standards [11], 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. To our best knowledge, our is the first work suggesting use of network coding to improve multi-hop beaconing performance. Finally, the effect of radio channel congestion was not considered in [10], while it is thoroughly investigated here.

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 consider 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.

The usage of a linear network topology, despite less general than more complex configurations, is not new in the literature [19], [23], especially when theoretical modeling and analysis are carried out. In our work, this choice let us develop a simulation scenario built on real world measurements collected through a properly designed experimental campaign (with a number of vehicles intrinsically limited by logistic and cost issues). Clearly, a multiple lane configuration would generate instead a two dimensional topology, which has an effect on the overall information exchange among vehicles. Nevertheless, since we are interested in the multi-hop propagation of beacons, the second dimension (given by the street width) is essentially negligible when compared to the first one, being much smaller than the transmission range. The presence of multiple lanes, unless a heavy traffic condition occurs, may thus be effectively represented by an augmented vehicle density in our model, while the increased channel congestion has been practically emulated in our experiments, as described in Section V.

In principle, vehicle speeds can be modeled to reproduce a realistic scenario, which would lead to time-varying inter-vehicle distances. However, it has 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 fixed points on a line with random inter-vehicle distances x smaller than the transmission range r. For the sake of definiteness and following [9], we fix $r = 160\ m$ and model x as an exponential random variable with average value $\tilde{x} = 30\ m$, to emulate a situation in which any two vehicles can directly communicate if up to 3 vehicles are positioned between them. Of course, the *probability* that such direct communication is successful quickly decreases with the number of obstructing vehicles, due to the negative effect of NLOS conditions on communication quality [9]. Modeling the decreasing communication quality as a function of NLOS conditions is fundamental to obtain accurate results. For this reason, we have performed a set of on-the-road-measurements to carefully estimate communication quality vs. NLOS conditions – see Section VI. Setting $r = 160\ m$ and $\tilde{x} = 30m$ 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 $T = 0.1\,s$ in accordance with [11]. The overall information exchange protocol works as follows.

Receive side: Each vehicle V constantly listens to the beaconing channel, in order to detect any incoming transmission. Every time a new beacon transmission is detected by V, the following actions are performed:

1) decoding of the incoming transmission is attempted;
2) the data field of the beacon are read and checked;
3) the vehicle lookup table is updated if newer information has been received.

The decoding success depends on the current channel conditions and interference, and can be modeled by defining a decoding probabiliy for each transmission. However, the results presented in [9] clearly indicate that it is *not* possible to accurately predict reception patterns of multiple, periodic beacons by simply looking at the probability of receiving a single beacon. This is because beacon reception events are not independent, but they display a strong temporal correlation. For this reason, in this paper the time-correlated decoding probability over each channel is described by a Markov-chain based beacon reception model that accounts for such temporal correlations. Our Markov-chain model, built on experimental measurements, can accurately reproduce the beacon reception patterns observed in real world conditions, and is detailed in Section VI.

If the beacon has been decoded by V, its content is then extracted. Each beaconing packet has a size equal to $100\,B$ due to the standardization bodies' recommendations [11], [27]. 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). As depicted in the lower

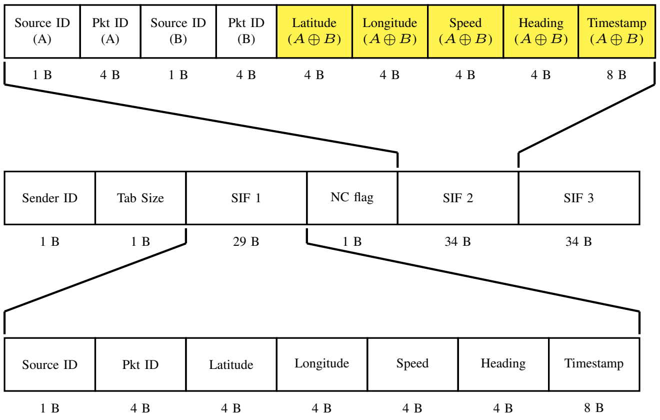

Figure 1. Beacon format. The yellow part highlights where the vehicle information to forward have been combined in SIF2 (similarly in SIF 3, if applies) when applying the *NC* strategy.

part of Figure 1, each SIF contains the following information about a given vehicle V_i of the network:

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

SIF 2 and SIF 3 are longer, since they can be used to send information about multiple beacons combined via Network Coding (NC), as explained in Section IV-B. However, when NC is not employed (which is indicated in the *NC flag* field), fields *Source ID (B)* and *Pkt ID (B)* of SIF 2 and SIF 3 can be left blank, whereas the remaining ones can be filled with the information of a single beacon, exactly as for SIF 1.

Every time a SIF is read, the information contained in it is used to update a neighbors lookup table at the receiving node. More specifically, we assume that V keeps a table with N entries, where the i–th entry contains the most recent situational information of node V_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 in vehicle V's table is updated only if: $i)$ a successfully received beacon contains a SIF referring to V_i; and $ii)$ the information contained in the SIF is newer than the one already stored the table. This latter property can be verified by checking either the packet ID or the packet timestamp contained in the SIF. Notice that, if advanced transmission techniques are employed, like Network Coding, it might turn useful to store not only the most recent information about a node V_i, but also older messages. In general, then, up to M data fields might be stored in the i-th table entry, with $M \geq 1$. In this case, whenever the most recent information about node V_i is received, it replaces the oldest one in the i-th table entry.

Transmit side: Each node transmits beacons periodically with period $T = 0.1$ sec. However, actual transmission times of the N nodes are assumed to be randomly scattered in time. More in details, for each node V_i, $i = 1, \ldots, N$, we randomly select a real value $t_0^i \in [0, 0.1]$, and define transmission times for node V_i as $t_0^i, t_0^i + T, t_0^i + 2T, \ldots$. Under moderate-to-low radio congestion levels, this model accurately resembles the dynamics of information propagation in a real world situation where transmissions are scattered within a time slot.

At the end of every period, a new packet broadcast is performed by vehicle V according to the following steps:

- V's current location and direction are measured via GPS;
- the C SIFs of the new beacon are properly filled with information about V (SIF 1) and other surrounding vehicles;
- the beacon is broadcast over the beaconing channel.

The information measured by V as per the first step includes its position and speed. They are inserted in the first SIF of the beacon, together with a timestamp and a unique sequence number. The remaining $C - 1$ SIFs are instead available to be filled with geographic information about surrounding vehicles. V can therefore choose from the updated lookup table the vehicles whose information is going to be inserted in the new beacon. In general, C is much lower than the number N of vehicles in the network. Henceforth, we need to define a *forwarding strategy* to choose $C - 1$ vehicles out of $N - 1$ possible vehicles whose information should be included in the beacon. This is actually the case with current beacon format, which allows piggybacking at most $C = 3 < N$ data fields in the beacon. The proposed forwarding strategies are listed and illustrated in Section IV.

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 *information age* at each vehicle. Let $\lambda_{i,j}(t)$ be the instantaneous information age at time t over the entire simulation, where $\lambda_{i,j}(t)$ is defined as the difference between t and the time at which the most recent information stored at node V_i regarding node V_j has been generated. In our simulations, we evaluated both the *distribution* of $\lambda_{i,j}(t)$, and its average value $\Lambda_{i,j}$.

Since we assume that the information age is measured at instants kT, with $k \in \mathbb{Z}^+$, it follows that the value of $\lambda_{i,i}(k)$, averaged over the possible realizations of t_0^i, is equal to $T/2$, $\forall i, k$.

Another metric of interest is the so-called *black-out time fraction* $\Gamma_{i,j}$ at node i regarding node j, defined as the fraction of time in which $\lambda_{i,j}(t) > \tau$, where τ is a threshold dictated by active safety application requirements. The rationale is that active safety applications typically impose strict requirements on situation awareness, which are often defined in terms of upper bounds to information age. In the following, we set $\tau = 1$ sec in accordance with the observation made in [9], [23] that a situation 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 information age and the black-out time fraction. Two classes of strategies are considered in the following: *Homogeneous* and *Heterogenous*. Strategies belonging to the former class are 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 our study, we develop a number of feasible forwarding strategies, and label each of them as either homogenous or heterogeneous. We recall that, in accordance with recommendations from standardization bodies [11], we fix $C = 3$, and that one of the data fields is always reserved for the transmitting node. 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 devised 9 strategies that can be applied to the considered scenario with no additional signal processing techniques required. However, we report here only the baseline random strategy and the ones with the best performance in the considered scenario. The remaining ones are listed in the Appendix.

1) Random selection (Random) – homogeneous: This is the baseline 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) – homogeneous: In this strategy, the transmitting node i selects the $C-1$ data fields to forward as the ones with the highest age $\lambda_{i,j}$, for $j \in \{1, 2, \ldots, N\}$, $j \neq i$. 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) Oldest with limit (OWL) – homogeneous: This strategy is similar to *OI*. However, motivated by the observation that too old information become 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 other hand, may cause the same problems of *OI*. 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).

B. Advanced strategies: Network Coding

We derived also 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 X and Y, which are superimposed via the bitwise XOR operation, getting $Z = X \oplus Y$. A receiving node which knows either X or Y can retrieve the other packet by applying again the bitwse XOR, since $X = Z \oplus Y$ and $Y = Z \oplus X$. 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 strategy, as well as the $NC-n$ reported in the Appendix, is designed specifically for $C = 3$, although extensions to more general cases may be readily derived.

1) NC plus Oldest with Limit (NC-OWL) – heterogeneous: This 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 2, 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

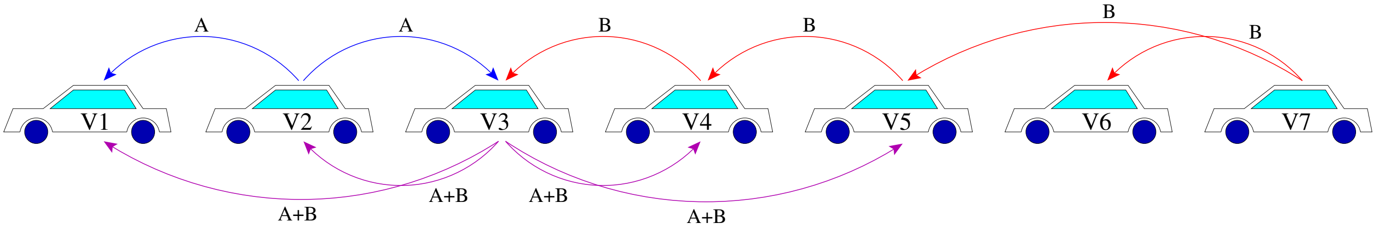

Figure 2. Example of Network Coding used in a linear vehicular network. Node $V3$ fills one of the data fields of its beacon with the combination of packets A, generated by $V2$, and B, generated by $V7$. In this way, up to 4 nodes can receive useful information: nodes $V1$ and $V2$ can obtain packet B, while nodes $V4$ and $V5$ can extract packet A.

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 *NC-OWL*. 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 table entries with a sufficiently low age. In this case the OWL strategy would leave the field empty, which is clearly undesirable. Therefore, we modify OWL by assuming that even packets whose age is greater than α can be forwarded, provided that all the data fields satisfying the age constraint have already been selected.

B. NC-OWL strategy in congested scenarios

The same improvement used for the *OWL* strategy is also applied to the *NC-OWL*. However, we have also to account for the following. First, since $C = 3$, 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 (satisfying 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 necessarily 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 data fields 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 data fields 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. 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.

In accordance with the above observations, we modify the *NC-OWL* strategy as follows. 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 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.

We recall that beacon reception patterns are highly influenced by LOS/NLOS conditions, and show a high degree of temporal correlation [9]. For this reason, we performed a set of real-world measurements with a vehicular network composed of 5 vehicles in a car-following configuration. This allowed us carefully estimating beaconing reception patterns up to the 4-th hop of communication, in presence of different radio congestion levels. Real-world measurements have then been used to tune the parameters of a Markov-chain based multi-hop communication model, which was specifically designed to account for the temporal correlations that govern the beacon reception pattern. The Markov-chain based model has then been included in the simulator that we have developed, and used to estimate propagation of situational information in a linear configuration of N vehicles.

A. Preliminary measurements: no congestion

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 4. 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 in principle necessary. 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 $CBT = 18\%$, 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 5. Notice that in this case we were able to measure link behavior up to the second hop.

C. Markov chain-based model

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 3 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.

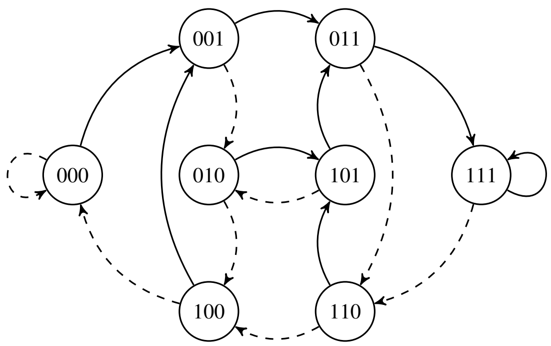

Figure 3. Representation of a Markov chain which $h = 3$: continuous lines represent successful beacon reception transitions; dotted lines represent beacon reception failure transitions.

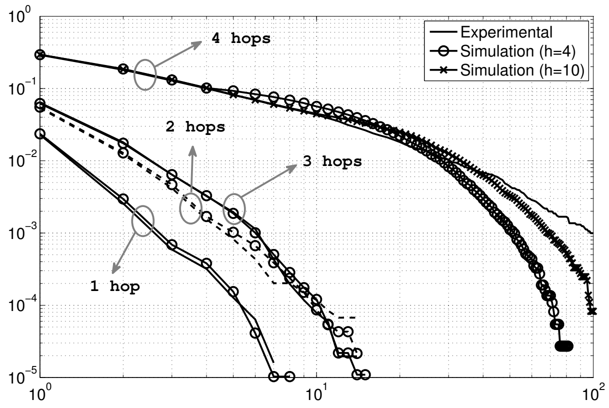

Figure 4. PIR time probability distribution: comparing measured PIR with the one derived with the Markov-based model. The curves refer to the complementary cumulative density function (ccdf) of the distribution.

Given Π and the success (conversely the failure) on each channel, we can simulate an arbitrary number of beacon transmissions (in our case 100,000). By doing the same for all the channels, we can determine the beacon propagation on a N vehicles queue.

Figure 4 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 5, 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. SIMULATION RESULTS

In our simulations, obtained through a MATLAB simulator designed for this purpose, we studied a network composed of $N = 16$ vehicles, placed at random distances from each other, and moving at constant speed. The distances are modeled as exponential random variable with average value $d_i = 30\,m$. We averaged the results over 100 topologies for each set of parameters. As explained above, 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 1. In case of *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 the upper part of Figure 1. Suppose SIF 3 does not contain combined packets: in this case the corresponding *Source ID (B)* and *Pkt ID (B)* are simply not filled in.

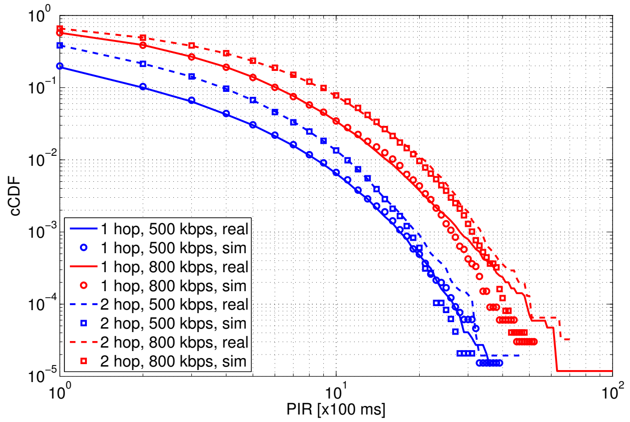

Figure 5. PIR probability distribution (measurements and through Markov model) in congested scenarios. We report the PIR cCDF for the scenarios with CBT values of 18% and 29%, and for both 1-hop and 2-hops links.

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 network-coding strategy (*NC-OWL*), and the idealized *Full Information* strategy. Furthermore, we report the results obtained without multi hop forwarding, 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* is not able to outperform the baseline random selection in delivering information to farther nodes. However, lowering the value of α can improve its performance, making it closer to the randomized strategy, especially at distant nodes. The *NC-OWL*, on the contrary, outperforms every other strategy for both valus of α, and 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

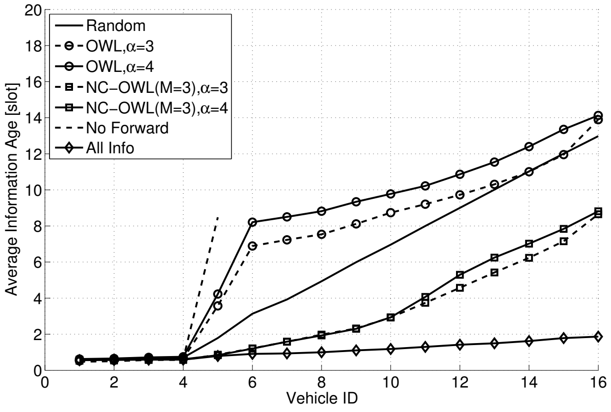

Figure 6. Non congested scenario: average information age $\Lambda_{i,1}$, i.e. the age of information generated by node 1, measured for all the nodes in the network.

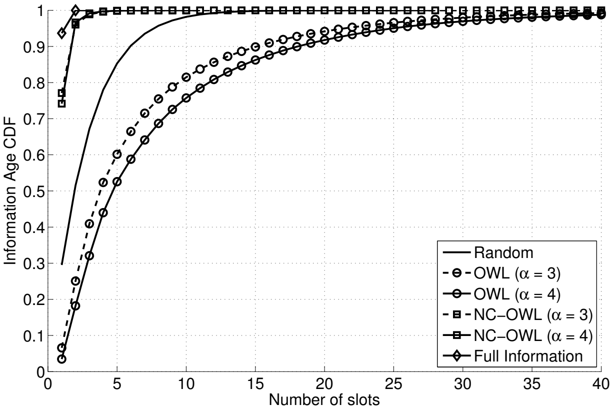

Figure 7. Distribution of information age (from all the sources) at vehicle 6.

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.

In terms of average information age, therefore, 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.

The distribution of information age at different vehicles is reported in Figure 7–9. As seen from the figures, *NC-OWL* consistently provides the better performance. It is interesting to note that, while *NC-OWL* with $\alpha = 3$ consistently outperforms *NC-OWL* with $\alpha = 4$ at vehicles 6 and 12, at the furthest vehicle 16 the situation is different, with the largest setting of α providing better performance for relatively high information ages.

Figure 10 reports the fraction of time vehicles experience a situation-awareness black-out. According to this metric, *OWL* performs now much better than *Random* strategy at farther nodes. The effect of an increased α is pronounced, but *NC-*

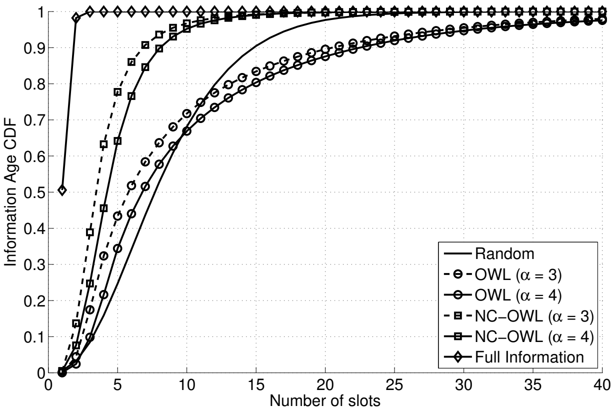

Figure 8. Distribution of information age (from all the sources) at vehicle 12.

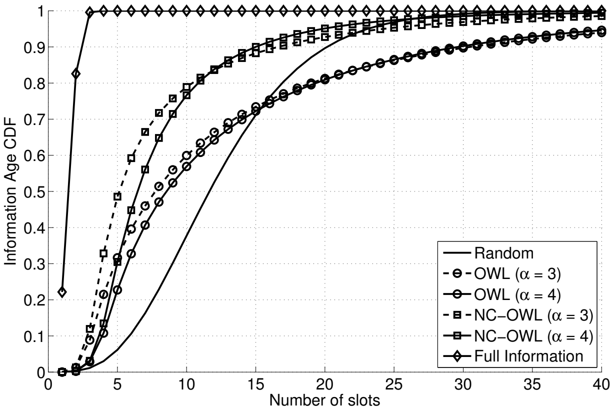

Figure 9. Distribution of information age (from all the sources) at vehicle 16.

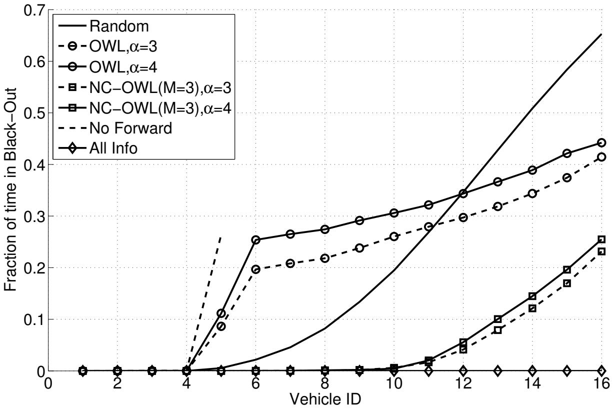

Figure 10. Non congested scenario: black-out time fraction $\Gamma_{i,1}$ for the nodes in the network.

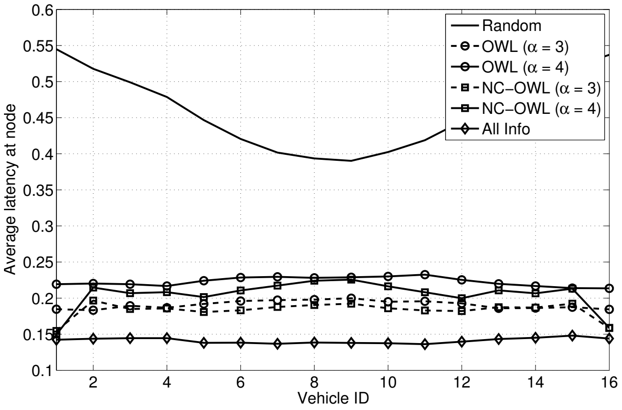

Figure 11. Average latency of forwarded packets at the various vehicles of the network, for different forwarding strategies.

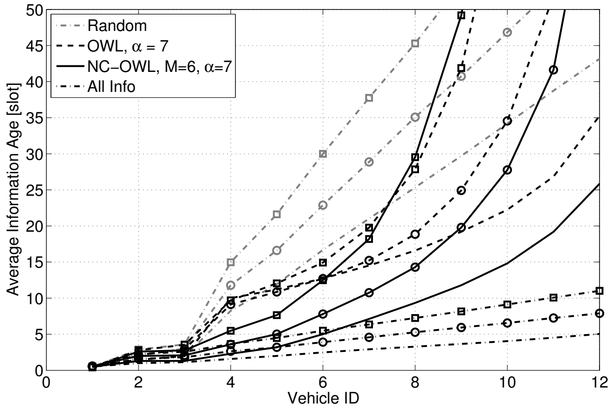

Figure 12. Congested scenario: average information age $\Lambda_{i,1}$ measured for all the nodes in the network, for various values of the CBR application rate R. No markers are for $CBT = 18\%$, round markers are for $CBT = 24\%$, and square markers are for $CBT = 29\%$.

OWL still grants much better performance, with black-out probability which is below 0.1 up to node 13. Notice that *NC-OWL* performance is very close to that of the idealized *Full Information* strategy up to the 10-th hop of communication, which is a very notable results since situational information is likely to become scarcely relevant at large hop distances. Notice also that all multi-hop strategies perform much better than the single-hop strategy.

Figure 11 reports the average latency of forwarded packets, as a function of the vehicle position. Differently from information age, latency is a metric measured at the transmitter side of the communication, and it is defined as the difference between the time at which a certain data field is piggybacked in a beacon and transmitted, and the time at which the data field was received. Results clearly show the effectiveness of the proposed forwarding strategies: average latency of both *OWL* and *NC-OWL* strategies are significantly lower than that of *Random*, independently of the vehicle position. Most importantly, with *OWL* and *NC-OWL* latency values are rather uniform and independent of vehicle position, while in case of *Random* latency values are significantly lower for central vehicles vs. border vehicles. Notice also that the average information latency of the proposed *OWL* and *NC-OWL* strategies is only about 100 $msec$ larger than the of the idealistic, optimal *Full Information* strategy.

B. Radio channel congestion

We now present the results in presence of radio channel congestion. In Figure 12, we report the average information age from vehicle 1 achieved through the same strategies analyzed in the non congested scenarios. Clearly, as the radio channel congestion increases, it becomes more difficult to obtain fresh information from distant vehicles, resulting in a higher delay. All the strategies, 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 to vehicle 9 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 data field to be combined via Network Coding, as shown later.

In Figure 13 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 role of parameter α is here 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. In other words, increasing α allows to reach farther vehicles, but at the cost of a higher information age at the neighbors. However, this is true only for *OWL*: setting $\alpha = 7$ 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.

As shown in Figure 14, performance is different if *NC-OWL* is improved as explained in Section V. In this case, for low values of α *NC-OWL* 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 optimal policy up to vehicle 5, while at vehicle 7 the

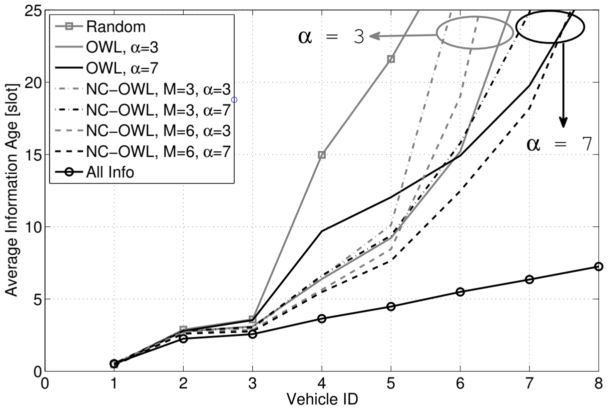

Figure 13. Congested scenario: average information age $\Lambda_{i,1}$, when $CBT = 29\%$, for different policies. Here *NC-OWL* is applied without modifications, as in the non congested scenario.

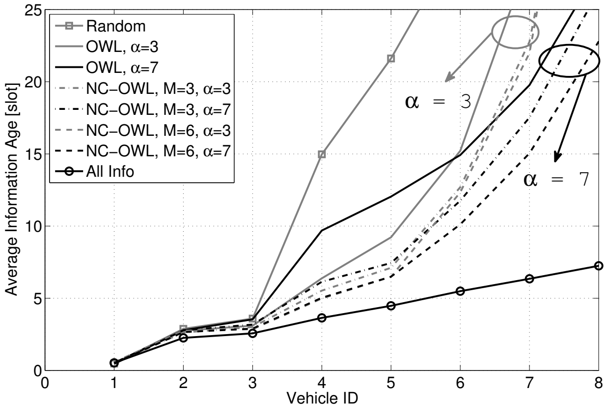

Figure 14. Congested scenario: average information age $\Lambda_{i,1}$, when $CBT = 29\%$, for different policies. Here *NC-OWL* is modified as explained in Section V.

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 15 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 16 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.

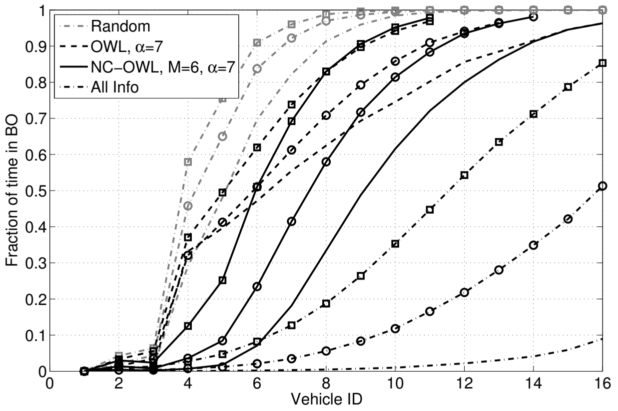

Figure 15. Congested scenario: black-out time fraction $\Gamma_{i,1}$, for all the nodes in the network, for different values of the CBR application rate R. No markers are for $CBT = 18\%$, round markers are for $CBT = 24\%$ and square markers are for $CBT = 29\%$. Here *NC-OWL* is applied without modifications, as in the non congested scenario.

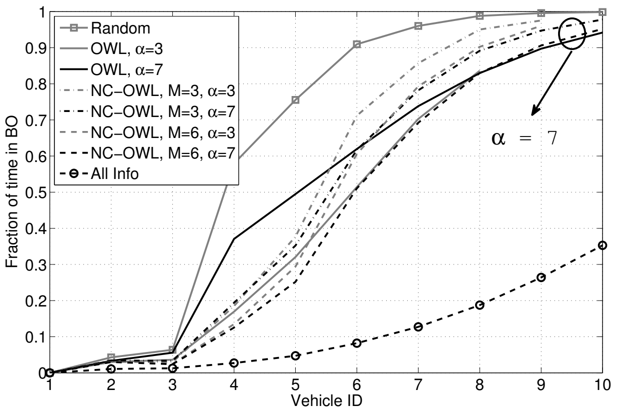

Figure 16. Congested scenario: black-out time fraction $\Gamma_{i,1}$, when $CBT = 29\%$, for different policies. Here *NC-OWL* is applied without modifications, as in the non congested scenario.

When applying the modifications illustrated in Section V, the black-out probability offered by *NC-OWL* drops dramatically: for instance, at vehicle 5 the value appears to decrease of about 33% in Figure 17. 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.

VIII. CASE STUDY: FORWARD COLLISION WARNING

In this section, we present a case study in which the previous results 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.

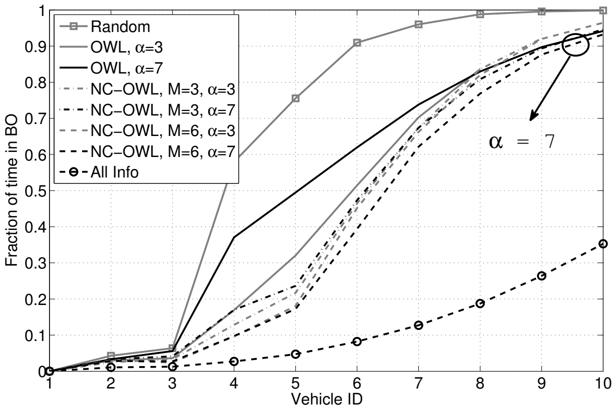

Figure 17. Congested scenario: black-out time fraction $\Gamma_{i,1}$, when $CBT = 29\%$, for different policies. Here *NC-OWL* is modified as explained in Section V.

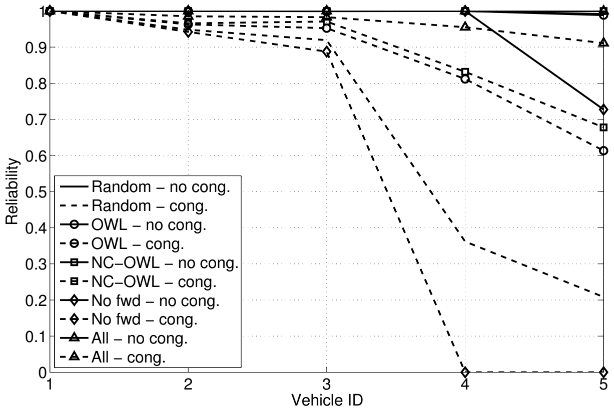

Figure 18. Reliability: Awareness time fraction $\Omega_{1,j}$, with different forwarding strategies. For each strategy, we report the results obtained without congestion, and with the highest congestion level ($CBT = 29\%$).

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 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 18 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 devised 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. Such a simple solution could potentially increase by a factor of 3 the reliability of a safety application with respect to the randomized strategy. 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.

APPENDIX

We report here a list of the other developed forwarding strategies. They were not included in the results since, in our specific scenario, they are outperformed by *OWL* and

NC-OWL. All these strategies can be implemented without additional signal processing, except the last one, which is based on Network Coding.

1) Newest Information (NI) – homogeneous: Opposite to the previous one, this 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.

2) Farthest Information (FI) – homogeneous: This 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 behavior is likely to be similar to that of the *OI* strategy.

3) Closest Information (CI) – homogeneous: 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.

4) Local oldest - global oldest (LOGO) – homogeneous: 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 $i \pm 4$. 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.

5) LOGO with limit (LOGOL) – homogeneous: 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.

6) OWL with neighbors selection probability (OWL-np) – heterogeneous: 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 strategy, the nodes in the center are likely to have higher values of p_i.

7) NC of neighbors (NC-n) – heterogeneous: This strategy aims at compressing the information about the neighboring nodes. The two available slots in the beacon sent by node i 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 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.

REFERENCES

[1] F. Librino, M.E. Renda, P. Santi, "Evaluating multi-hop beaconing forwarding strategies for IEEE 802.11p vehicular networks", *Proc. IEEE VNC*, pp. 31–38, 2013.

[2] D. Jiang, Q. Chen, L. Delgrossi, "Optimal Data Rate Selection for Vehicle Safety Communications", *Proc. ACM VANET*, pp. 30–38, 2008.

[3] M. Torrent-Moreno, D. Jiang, H. Hartenstein, "Broadcast Reception Rates and Effects of Priority Access in 802.11-based Vehicular Ad Hoc Networks", *Proc. ACM VANET*, 2004.

[4] G. Resta, P. Santi, J. Simon, "Analysis of Multi-Hop Emergency Message Propagation in Vehicular Ad Hoc Networks", *Proc. ACM MobiHoc*, pp. 140-149, 2007.

[5] F. Bai, D.D. Stancil, H. Krishnan, "Toward Understanding Characteristics of Dedicated Short Range Communications (DSRC) From a Perspective of Vehicular Network Engineers", *Proc. ACM Mobicom*, pp. 329–340, 2010.

[6] K. Hong, D. Xing, V. Rai, J. Kenney, "Characterization of DSRC Performance as a Function of Transmit Power", *Proc. ACM VANET*, pp. 63–68, 2009.

[7] J. Gozalves, M. Sepulcre, R. Bauza, "IEEE 802.11p Vehicle to Infrastructure Communications in Urban Environments", *IEEE Communications Magazine*, Vol. 50, n. 5, pp. 176–183, 2012.

[8] T. Mangel, M. Michl, O. Klemp, H. Hartenstein, "Real-World Measurements of Non-Line-Of-Sight Reception Quality for 5.9Ghz IEEE 802.11p at Intersections", *Proc. Nets4Cars*, pp. 189–202, 2011.

[9] F. Martelli, M.E. Renda, G. Resta, P. Santi, "A Measurement-based Study of Beaconing Performance in IEEE 802.11p Vehicular Networks", *Proc. IEEE Infocom*, 2012.

[10] M.E. Renda, G. Resta, P. Santi, F. Martelli, A. Franchini, "Understanding Vehicle-to-Vehicle IEEE 802.11p Beaconing Performance in Real-World Highway Scenarios", *Tech. Rep. IIT-16-2013*, Istituto di Informatica e Telematica del CNR, 2013.

[11] "Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems – 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications", *ASTM E2213-03*, 2010.

[12] M. van Eenennaam, W.K. Wolterink, G. Karagiannis, G. Heijenk, "Exploring the solution space of beaconing in VANETs", *Proc. IEEE VNC*, pp. 1–8, 2009.

[13] H. Noori, B. B. Olyaei, "A novel study on beaconing for VANET-based vehicle to vehicle communication: Probability of beacon delivery in realistic large-scale urban area using 802.11p", *Proc. IEEE SaCoNeT*, pp. 1–6, 2013.

[14] A. Vinel, D. Staehle, A. Turlikov, "Study of Beaconing for Car-to-Car Communication in Vehicular Ad-Hoc Networks", *Proc. IEEE ICC*, pp. 1–5, 2009.

[15] H.-H. Nguyen, A. Bhawiyuga, H.-Y. Jeong, "A Comprehensive Analysis of Beacon Dissemination in Vehicular Networks", *Proc. IEEE VTC Spring*, pp. 1–5, 2012.

[16] R. Stanica, E. Chaput, A.-L. Beylot, "Why VANET Beaconing Is More Than Simple Broadcast", *Proc. IEEE VTC Fall*, pp. 1–5, 2011.

[17] C. Sommer, O.K. Tonguz, F. Dressler, "Adaptive beaconing for delay-sensitive and congestion-aware traffic information systems", *Proc. IEEE VNC*, pp. 1–8, 2010.

[18] F. Klingler, F. Dressler, J. Cao, C. Sommer, "Use both lanes: Multi-channel beaconing for message dissemination in vehicular networks", *Proc. Wireless On-demand Network Systems and Services (WONS)*, 2013.

[19] E. Egea-Lopez, J.J. Alcaraz, J. Vales-Alonso, A. Festag, J. Garcia-Haro, "Statistical Beaconing Congestion Control for Vehicular Networks", *IEEE Trans. Veh. Comm.*, Vol. 62, n. 9, pp. 4162–4181, 2013.

[20] T. Settawatcharawanit, S. Choochaisri, C. Intanagonwiwat, K. Rojviboonchai, "V-DESYNC: Desynchronization for Beacon Broadcasting on Vehicular Networks", *Proc. IEEE VTC Spring*, pp. 1–5, 2012.

[21] R. Lasowski, C. Linnhoff-Popien, "Beaconing as a service: a novel service-oriented beaconing strategy for vehicular ad hoc networks", *IEEE Communications Magazine*, Vol. 50, n. 10, pp. 98–105, 2012.

[22] R. Schmidt, R. Lasowski, T. Leinmüller, C. Linnhoff-Popien, G. Schafer, "An approach for selective beacon forwarding to improve cooperative awareness", *Proc. IEEE VNC*, pp. 182–188, 2010.

[23] J. Mittag, F. Thomas, J. Harri, H. Hartenstein, "A Comparison of Single- and Multi-Hop Beaconing in VANETs", *Proc. ACM VANET*, pp. 69–78, 2009.

[24] R. Ahlswede, N. Cai, S.-Y.R. Li, R.W. Yeung, "Network information flow", *IEEE Trans. Inform. Theory*, Vol. 46, n. 4, pp. 1204–1216, 2000.

[25] J. Le ; J.C.S. Lui, D.-M. Chiu, "On the Performance Bounds of Practical Wireless Network Coding", *IEEE Trans. Mobile Comput.*, Vol. 9, n. 8, pp. 1134–1146, 2010.

[26] F. Librino, M.E. Renda, P. Santi, "Measurement-based Modeling of Packet Inter-Reception Times in Presence of Radio Channel Congestion", *Proc. IEEE Secon*, pp. 432–444, 2014.

[27] VSC Consortium, "Vehicle Safety Communications Project Task 3 – Final Report: Identify Intelligent Vehicle Safety Applications Enables by DSRC, *DOT HS 809 859*, 2005.

[28] S. Kaul, K. Ramachandran, P. Shankar, S. Oh, M. Gruteser, I. Seskar, T. Nadeem, "Effect of Antenna Placement and Diversity on Vehicular Network Communications", *Proc. IEEE Secon*, pp. 112–121, 2007.

[29] T. ElBatt, S.K. Goel, G. Holland, H. Krishnan, J. Parikh, "Cooperative Collision Warning Using Dedicated Short Range Wireless Communications", *Proc. ACM VANET*, pp. 1–9, 2006.

[30] M. Sepulcre, J. Gozalvez, "Experimental Evaluation of Cooperative Active Safety Applications based on V2V Communitcations", *Proc. ACM VANET*, pp. 13–20, 2012.

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