Evaluating Multi-Hop Beaconing Forwarding Strategies for IEEE 802.11p Vehicular Networks

Federico Librino, **M. Elena Renda**, **Paolo Santi**
Istituto di Informatica e Telematica del CNR, Pisa–ITALY,
E–mail: {`federico.librino, elena.renda, paolo.santi`}`@iit.cnr.it`

***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. 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 two orders of magnitude, and providing a performance similar to that of an idealized strategy in which complete situational information is included in the beacon.**

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 [5], [12], [13] and, more, recently, also based on real-world measurements [1], [4], [6], [8], [9], [11]. 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 [11] that multi-hop propagation of the situational information contained in beacons is very effective in improving beaconing NLOS performance. However, the study of [11] 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 [11] 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 [2]. 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 $200\ m$ [1], [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 [2], 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 [2]. 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. Information quality is measured in terms of both the average information age and the probability of experiencing a situational-awareness

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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, respectively.

[2] Without security overhead.

black-out of at least 1 sec. In the paper, we propose 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. The different strategies are evaluated by means of simulations whose multi-hop communication performance is corroborated by real-world measurements.

The results of our study clearly promote network-coding as an effective technique for propagating situational information in vehicular networks: the performance provided by our proposed network-coding based approach is very close to that of the idealized strategy up to the 12-th hop of communication, and it is orders of magnitude better than that provided by the randomized strategy.

II. RELATED WORK

The idea of using network-level, multi-hop strategies to propagate the situational information contained in beacons is relatively recent. In [10], 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 [10] 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 [10] is that in [10] 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 [13]; and it 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 [10]. 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 [10]. 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 [11], 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 [11] 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.

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 $0 \leq i \leq 10$ and $1 \leq j \leq 4$ and $i + j \leq 11$.

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 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 [2], [14], 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 to 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.

Finally, two models for beacon transmission can be adopted:

1) *Synchronous model*: here, we assume that all the transmissions are performed simultaneously, or, equivalently, that the information in all the lookup tables is updated only at the end of each time slot, where each time slot has a $0.1\ sec$ duration, corresponding to the beaconing period;
2) *Asynchronous model*: here, we assume that the transmission of each node occur in a randomly chosen instant of the time slot. This implies that the nodes transmit subsequently in an order which is set at the beginning of the simulation, and is kept unaltered (jitter and/or small discrepancies among local oscillators are considered negligible).

Under the assumption made herein that congestion on the radio channel is low, the two models turn out to provide very similar estimates of the quality of situational information as a function of the hop distance to the transmitter. For this reason, in the following we adopt the simpler synchronous model.

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], [10] 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 [2], 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.

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 $C-1$ information 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 $C-1$ information 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 $C-1$ 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 behaviour is probably very similar to that of the *NI* strategy, and is probably 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 $i \pm 4$. 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.

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, as we show in the following a few bytes are sufficient, which are already available in the current beacon format.
- 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 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 [2], 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. 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

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 [11], 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 [7], [8]), 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

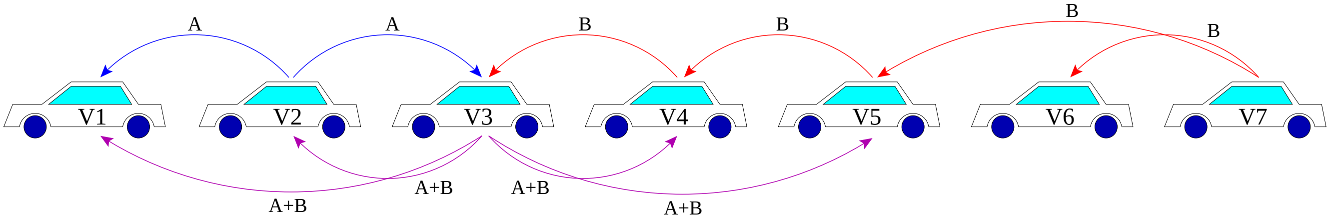

Figure 1. Example of Network Coding used in a linear vehicular network. Node $V3$ fills one of the data fields of its beacon with the combination of packets A, generated by $V2$, and B, generated by $V7$. In this way, up to 4 nodes can receive useful information: nodes $V1$ and $V2$ can obtain packet B, while nodes $V4$ and $V5$ can extract packet A.

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). Please 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 [11].

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 [3], [9]. 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 h-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. 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.

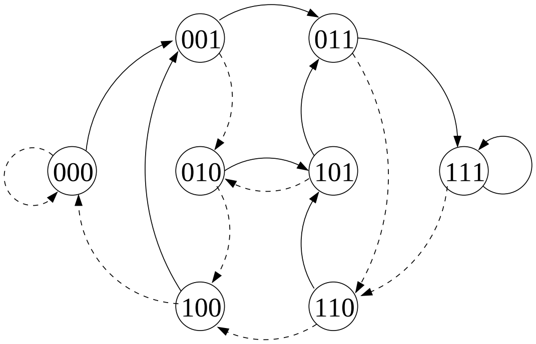

Figure 2. Representation of a Markov chain which $h = 3$: the continuous lines represent successful beacon reception transitions, while the dotted ones represent beacon reception failure transitions.

To model beaconing packet reception, 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). 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 M 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 M and the success (conversely the failure) on each channel, we can simulate an arbitrary number of time slots (in our case 100,000) and determine the beacon propagation on a N vehicles queue.

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

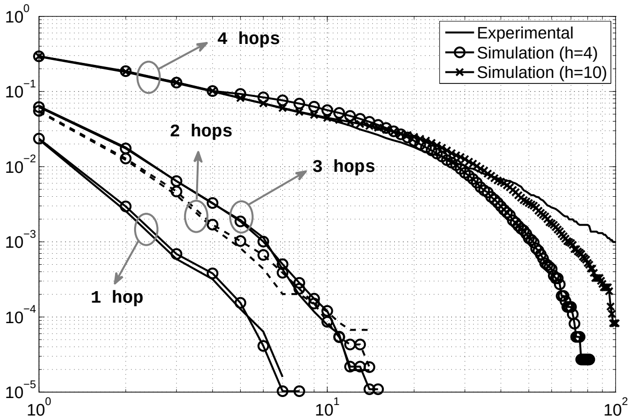

Figure 3. PIR probability distribution: comparing measured PIR with the one derived with the Markov-based model. The curves refer to the complementary cumulative density function (ccdf) of the distribution.

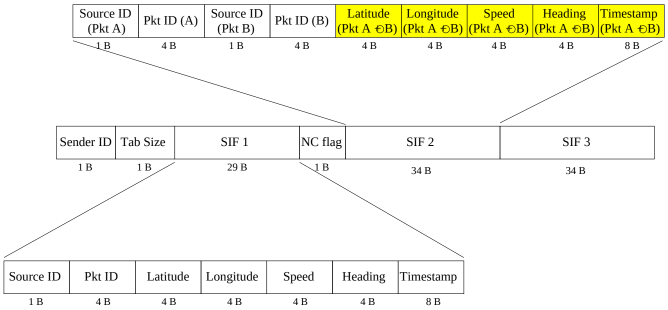

Figure 4. Beacon format. The yellow part highlights where the vehicle information to forward have been combined in SIF2 (similarly in SIF 3, if applies) when applying the *NC* strategy.

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.

VI. 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 $M = 3$. 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, 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 4. 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.

Figure 5 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 grants the best performance, with a halved average age with respect to the randomized strategy, the closest to the *Full Information* strategy, where no information-to-forward selection has been performed.

In Figure 6 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, 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.

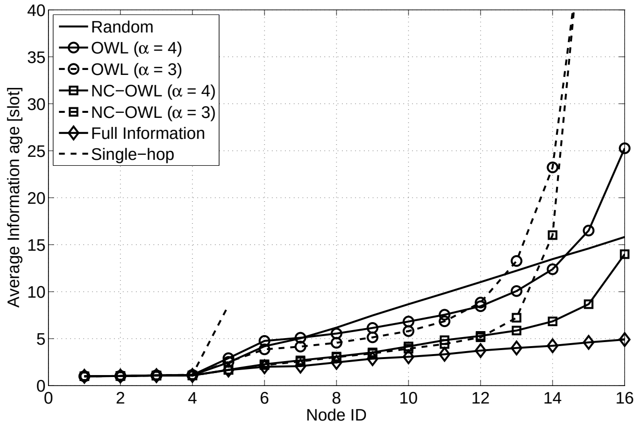

Figure 5. Average information age $\Lambda_{i,1}$, i.e. the age of information departed from node 1, measured for all the nodes in the network.

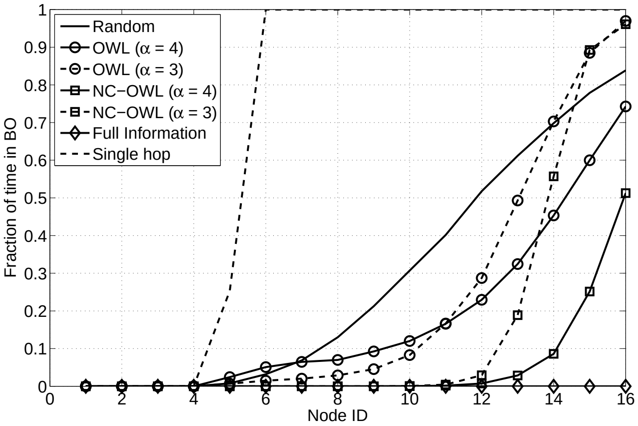

Figure 6. Black-out time fraction $\Gamma_{i,1}$ for the nodes in the network.

VII. 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. 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 the tradeoff between the overall situation awareness and the communication channel use, by modulating the transmission power.

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