On the Potential of Network Coding for Cooperative Awareness in Vehicular Networks

Miguel Sepulcre, Javier Gozalvez, Jose Ramon Gisbert
UWICORE, Ubiquitous Wireless Communications Research Laboratory, www.uwicore.umh.es
Universidad Miguel Hernández de Elche (UMH). Avda. de la Universidad, s/n, 03202, Elche, Spain
{msepulcre, j.gozalvez, jgisbert}@umh.es

***Abstract*—Vehicular active safety applications require the continuous exchange of positioning and basic status information between neighboring vehicles. This exchange is based on the periodic transmission/reception of 1-hop broadcast messages on the control channel. The critical nature of this channel requires mechanisms to control the channel load while guaranteeing each vehicle's capacity to communicate with its relevant neighboring nodes (awareness). Different studies have analyzed the capacity of network coding to improve the bandwidth efficiency in many different types of networks, but few studies have investigated its implementation in vehicular networks. This paper explores the potential of the combined use of network coding and multi-hop beaconing in vehicular networks in order to improve the vehicles' communications reliability and awareness.**

***Keywords*— Network coding; multi-hop beaconing; awareness; vehicular networks; connected vehicles.**

I. INTRODUCTION

Network coding can be considered as a forwarding technique where intermediate nodes process (encode) the information to be routed. In particular, intermediate nodes can use network coding to combine multiple packets into a single coded packet, and transmit the coded packet instead of transmitting each packet separately. Network coding can hence improve the bandwidth and power efficiency, and therefore the link reliability, transmission range, throughput and capacity [1]. Network coding has been applied to different types of networks, including the Internet, wireless sensor networks, conventional wireless networks, video multicast networks and Peer-to-Peer (P2P) networks [2]. However, limited efforts have been conducted to date to analyze the potential of network coding in vehicular networks.

The studies reported in [3] and [4] demonstrate that network coding can improve the performance of repetition-based error recovery mechanisms in vehicular networks. The studies focus on the periodic transmission and reception of beacons (1-hop broadcast messages) using IEEE 802.11p. These beacons are critical to support cooperative vehicular applications as they enable the exchange of positioning and basic status information between vehicles using the so called control channel. The mechanisms reported in [3] and [4] result in that each vehicle retransmits each beacon k times to recover lost packets as a result of propagation errors or collisions. In particular, [3] proposes that each vehicle XORs its own packet with the packet received from its closest neighbor to improve the probability of successful reception of beacons. A similar approach was proposed in [4], but taking into account the channel load experienced to adapt the number of repetitions. Network coding can also be used to improve the performance and efficiency of multi-hop beaconing schemes. The study in [5] analyzes the potential of multi-hop beaconing to improve cooperative awareness in vehicular networks. Awareness is defined as the capacity of each vehicle to detect, and possibly communicate with the relevant vehicles and infrastructure nodes present in their local neighborhood. The theoretical results obtained in [5] show that the channel load could be reduced with multi-hop beaconing. However, the conducted simulations showed that packet collisions, the radio channel variability and suboptimal relaying prevent multi-hop beaconing from improving the vehicles' awareness performance with respect to conventional single-hop beaconing. The study reported in [6] was one of the first studies to propose multi-hop beaconing algorithms that exploit network coding to improve cooperative awareness in vehicular networks. Different strategies were proposed and evaluated using a Markov-chain based communication model obtained from a real vehicular network composed of five vehicles. In this case, the results obtained showed that the performance (average information age and probability of experiencing a situational-awareness black-out of at least 1 second) can be improved thanks to network coding.

The previous studies evaluated the use of network coding in vehicular networks considering fixed beacon transmission frequencies. However, future cooperative vehicular networks will require the implementation of congestion and awareness control protocols [7] to control the load of the critical control channel by adapting the transmission parameters of beacons. In fact, the ETSI TC ITS communications architecture that future connected vehicles will implement includes a key Decentralized Congestion Control (DCC) module that is currently under development [8]. Some of the most relevant congestion control protocols being discussed in the standardization process are [9] and [10]. Both protocols adapt the transmission parameters of beacons based on the Channel Busy Ratio (CBR), defined as the percentage of time that the channel is sensed as busy. Their objective is to operate close to certain pre-defined CBR levels, irrespective of the traffic density. In this context, this paper improves the state of the art by investigating the potential benefits of network coding and multi-hop beaconing when considering variable beacon transmission frequencies to account for the effect of

M. Sepulcre, J. Gozalvez, J. R. Gisbert, "On the Potential of Network Coding for Cooperative Awareness in Vehicular Networks", Proc. IEEE International Workshop on Automotive IoT (IEEE Auto-IoT 2015), Milan, Italy, 14-16 December 2015. DOI: 10.1109/WF-IoT.2015.7389042

congestion control protocols. In particular, this study investigates whether (and the conditions under which it is possible) network coding (combined with multi-hop beaconing) can improve the communications reliability and therefore the cooperative vehicular awareness. To this aim, the implementation simulation scenario accurately models packet collisions and interferences, which are relevant factors affecting the performance and efficiency of single-hop and multi-hop beaconing strategies in vehicular networks. The results obtained in this study show that the combined used of network coding and multi-hop beaconing can improve cooperative awareness in vehicular networks under certain conditions.

II. BEACONING STRATEGIES

To evaluate the potential of network coding and multi-hop beaconing, the beaconing strategies depicted in Fig. 1 have been studied. For all of them, all vehicles periodically transmit beacons to support cooperative applications. This study considers active safety applications as they have more strict application requirements. In particular, this study considers that applications require that at least one transmitted beacon is correctly received every *PIR* (Packet Inter-Reception Time) by all vehicles within certain communication range (*CR*) with probability (p_{app}). For example, an application could require that at least 1 beacon per second is correctly received at a certain communication range with p_{app}=0.99 probability. *CR*, *PIR* and p_{app} are application requirements that depend on the vehicular context. These requirements should be satisfied independently of whether a single-hop or multi-hop beaconing strategy is employed. In the latter case, each vehicle forwards other vehicles' beacons. For simplicity and based on previous studies [6], only two hops have been considered in this study for the multi-hop beaconing strategies.

When a single-hop beaconing strategy is considered (SH, Fig. 1a), vehicles periodically transmit their beacons using the transmission parameters configured by e.g. congestion and awareness control protocols. The transmission parameters, the propagation conditions and packet collisions influence the Packet Delivery Ratio (PDR) experienced at a distance equal to *CR*, and therefore influence the p_{app} probability. PDR and p_{app} can be related as follows considering a single-hop beaconing strategy and independent packet receptions:

$$p_{app} = 1-(1-p_{CR})^N \tag{1}$$

where p_{CR} represents the PDR experienced at a distance equal to *CR*, and *N* is the number of beacons that are transmitted every *PIR* period. *N* can be calculated as $N=PIR\cdot T_f$, where T_f is the beacon transmission frequency.

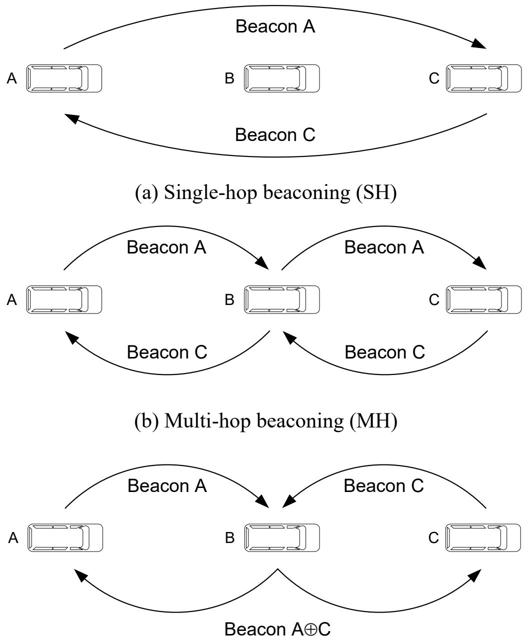
When a multi-hop beaconing strategy is considered (MH, Fig. 1b), vehicles do not only transmit their own beacons, but also forward beacons transmitted by other vehicles. In this case, vehicle C can directly receive a beacon from vehicle A or receive it following the forwarding process from vehicle B. In this study, we consider that beacons are always forwarded by vehicles located at *CR*/2 distance from the initial transmitter. This situation represents the optimal case and therefore allows us obtaining performance bounds. The following equation models the probability that one or more beacons are correctly received at *CR* when considering that all beacons are forwarded by a vehicle at *CR*/2:

$$p_{2hops} = \sum_{i=1}^{N}\left(p_{CR/2}\left(1-p_{CR/2}\right)^{i-1}\left(1-\left(1-p_{CR/2}\right)^{N-i}\right)\right) \tag{2}$$

where $p_{CR/2}$ represents the PDR experienced by vehicles at a distance of *CR*/2. Equation (2) considers that the vehicle located at *CR*/2 correctly receives the transmitted beacon after i-1 incorrect transmissions, and therefore it has *N-i* opportunities to correctly forward a beacon so that it is successfully received at *CR* before *PIR* elapses. p_{app} can be then estimated considering p_{2hops} and the probability that the beacon is successfully received by the vehicle located at *CR* without retransmissions (i.e. directly from the source):

$$p_{app} = 1-\left(1-p_{CR}\right)^N\left(1-p_{2hops}\right) \tag{3}$$

Equation (3) shows that p_{app} can be improved with multi-hop strategies for a fixed p_{CR}, since beacons can be received at the destination directly from the transmitter or from an intermediate vehicle at *CR*/2. However, when beacons are forwarded the probability of packet collision can increase, which has a negative influence on p_{CR} and therefore in p_{app}. In fact, the average number of packets transmitted per second per vehicle would be 3 times the beacon transmission frequency in a scenario where uniformly distributed vehicles employ a multi-hop beaconing strategy. This is the case because each vehicle would have to forward at least the beacons received from two of its neighbors (e.g. vehicle B in Fig. 1b would transmit its own beacons plus the beacons received from vehicles A and C).



(a) Single-hop beaconing (SH)

(b) Multi-hop beaconing (MH)

(c) Multi-hop beaconing with network coding (MH+NC)

Fig. 1. Beaconing strategies evaluated.

M. Sepulcre, J. Gozalvez, J. R. Gisbert, "On the Potential of Network Coding for Cooperative Awareness in Vehicular Networks", Proc. IEEE International Workshop on Automotive IoT (IEEE Auto-IoT 2015), Milan, Italy, 14-16 December 2015. DOI: 10.1109/WF-IoT.2015.7389042

This is an author-created postprint version. The final publication is available at: https://ieeexplore.ieee.org/document/7389042/

Equation (3) is also valid for a multi-hop beaconing strategy combined with network coding (MH+NC, Fig. 1c). When using network coding, the beacons forwarded by each vehicle are a combination (XOR operation) of two previously received beacons. In the example shown in Fig. 1c, vehicle B transmits beacon A⊕C, which is the XOR operation of beacon A and beacon C. Vehicle C can retrieve beacon A from beacon A⊕C because it knows beacon C. In this case, the number of packets transmitted per second per vehicle would be 2 times the beacon transmission frequency in a scenario with uniformly distributed vehicles. This is the case because two beacons to be forwarded would be combined with network coding before transmission.

III. EVALUATION

A. Simulation settings

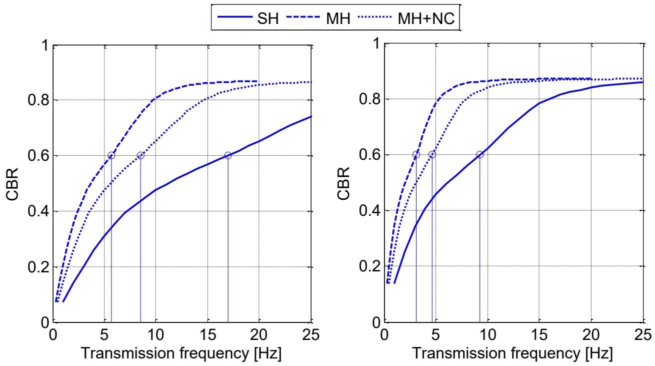
The simulations conducted (using the network simulator ns-2.35) consider a straight highway with 6 lanes where vehicles are uniformly distributed. Two traffic densities have been simulated: 10 and 20 vehicles/km/lane. Each vehicle transmits T_f beacons per second using IEEE 802.11p at 6Mbps. The transmission power is fixed to 23dBm. The application requirements *CR*, *PIR* and p_{app} influence the transmission parameters needed and the channel load generated. To avoid limiting this study to a particular application, different combinations of *CR*, *PIR* and p_{app} have been analyzed. Taliwal et al. showed in [11] that the Nakagami-m distribution suitably describes the radio propagation conditions in vehicular networks on highways in the absence of interferences. Following [12], this study utilizes the Nakagami-m propagation model with m=3 and a quadratic path-loss according to the Friis model. Table I summarizes the main communication and simulation parameters.

TABLE I. COMMUNICATION AND SIMULATION PARAMETERS

Parameter	Value
Number of lanes	6
Road length [km]	8
Traffic density [veh/km/lane]	10 and 20
Transmission power [dBm]	23
Packet transmission frequency [Hz]	1-20
Payload size [Bytes]	250
Data rate [Mbps]	6
Carrier frequency [GHz]	5.9
SINR min for packet reception [dB]	8
Noise floor [dBm]	-99
Packet Inter Reception Time (PIR)	0.25s, 0.5s and 1s
Simulation time [s] and runs	30 and 10

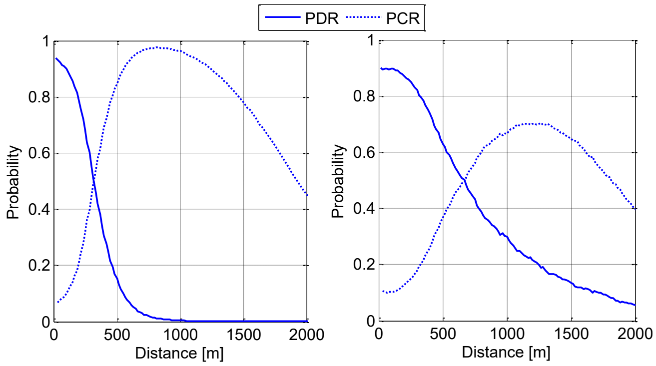
B. Results

Fig. 2 depicts the *CBR* experienced by the vehicles in the center of the scenario as a function of the beacon transmission frequency. The vertical lines highlight the beacon transmission frequencies needed to achieve *CBR*=0.6. Relevant congestion control protocols propose to operate close to *CBR*=0.6 [9], and this operating point (or target CBR*)* has been then considered as a reference in this study. As it can be observed from Fig. 2, each beaconing strategy should utilize a different beacon transmission frequency to operate at a given *CBR*. For example, MH+NC reaches a *CBR* equal to 0.6 with half the beacon transmission frequency compared to the SH strategy. This is the case because with MH+NC, all beacons are network-coded and forwarded by vehicles at *CR*/2, which results in that each vehicle transmits $2 \cdot T_f$ beacons per second. The target *CBR* influences the PDR and the Packet Collision Ratio (PCR). Fig. 3 plots the PDR and the PCR for a SH strategy as a function of the distance to the transmitter. The beacon transmission frequency was configured to generate two different *CBR* levels (Fig. 3a and Fig. 3b). The same results were obtained for the two traffic densities as vehicles adapt their transmission frequency to operate at the target *CBR*. In this case, if the *CBR* is fixed but the traffic density is doubled, vehicles will halve their packet transmission frequency to operate at the same *CBR*, and therefore will experience the same PDR and PCR.



(a) 10 veh/km/lane (b) 20 veh/km/lane

Fig. 2. CBR (Channel Busy Ratio) experienced with each beaconing strategy for two different traffic densities. The vertical lines highlight the beacon transmission frequency needed to achieve *CBR*=0.6.

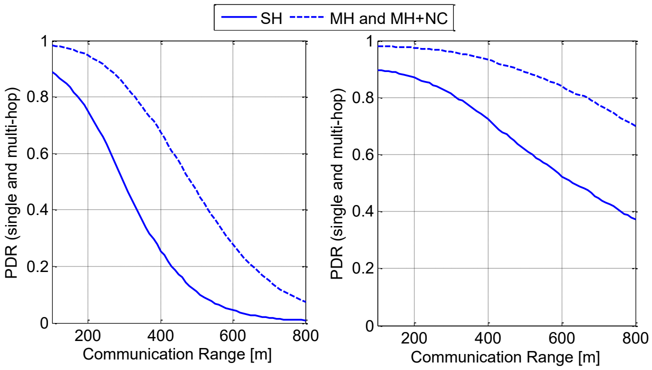


(a) *CBR*=0.6 (b) *CBR*=0.4

Fig. 3. PDR (Packet Delivery Ratio) and PCR (Packet Collision Ratio) for SH and two different *CBR* levels.

M. Sepulcre, J. Gozalvez, J. R. Gisbert, "On the Potential of Network Coding for Cooperative Awareness in Vehicular Networks", Proc. IEEE International Workshop on Automotive IoT (IEEE Auto-IoT 2015), Milan, Italy, 14-16 December 2015. DOI: 10.1109/WF-IoT.2015.7389042

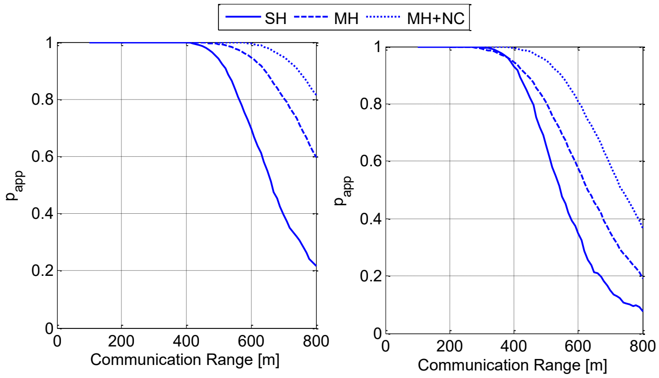
Fig. 4 depicts the probability of correctly receiving each beacon at various *CR* for the different beaconing strategies and two *CBR* levels. As it can be observed, the probability of correctly receiving a beacon at *CR* increases with MH and MH+NH compared to SH for a fixed *CBR*. This is the case because each beacon can be directly received from the initial transmitter, or received from a forwarder located at *CR*/2. These results illustrate the potential of multi-hop beaconing and network coding to improve the communications reliability and therefore the cooperative awareness. However, they only represent the performance on a per-packet basis, and the number of packets that can be transmitted per second with MH and MH+NH strategies decreases compared with SH for a fixed *CBR* (Fig. 2). To fairly evaluate the performance that can be achieved with the different beaconing strategies, the *PIR* parameter needs to be introduced.



(a) *CBR*=0.6 (b) *CBR*=0.4

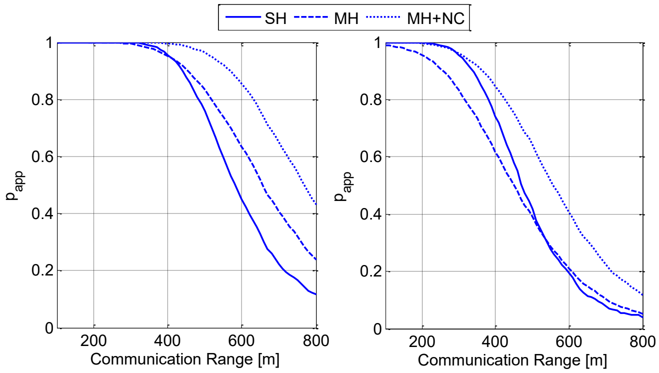
Fig. 4. Probability of correctly receiving each beacon at various *CR* for the different beaconing strategies and two different *CBR* levels. The same curves are obtained irrespective of the traffic density as long as the *CBR* is fixed.

Fig. 5 shows the probability of correctly receiving at least one beacon every *PIR*=1s at different *CR*s when operating at *CBR*=0.6. The depicted results show that MH+NC increases the reliability levels compared to SH. This results in a higher awareness since vehicles can reliably communicate with vehicles at larger distances. It is important noting that these results are obtained despite the fact that MH+NC results in lower packet transmission frequency levels when operating at a fixed *CBR* level (Fig. 2). As expected, the lower traffic density increases the packet transmission frequency when operating at a fixed CBR level and therefore the awareness (Fig. 5a) compared to scenarios with higher traffic densities (Fig. 5b). Similar conclusions can be obtained with more strict application requirements. Fig. 6 presents the results obtained when the application requires that at least one beacon is received every *PIR*=0.5s at *CR*. For low traffic densities (Fig. 6a), the same trends are observed as for *PIR*=1s. However, for higher traffic densities (Fig. 6b), the packet transmission frequency of each vehicle is reduced to operate at *CBR*=0.6 and the MH strategy generally produces the lowest reliability levels. This different trend can also be observed when increasing the application requirements. For example, with *PIR*=0.25s, SH can outperform MH and MH+NC in high traffic density scenarios (Fig. 7b). This is the case because when the traffic density increases, MH and MH+NC have to considerably decrease their beacon transmission frequency to maintain a fixed *CBR* level. This results in that the reliability required per packet for MH and MH+NC has to be very high in order to guarantee that at least one beacon is correctly received every *PIR*=0.25s. For example, the beacon transmission frequencies (T_f) for each strategy has to be set equal to 9.3Hz (SH), 4.65Hz (MH+NC) and 3.1Hz (MH) to operate under a *CBR* equal to 0.6 for a traffic density of 20 veh/km/lane. In this case, SH has a higher probability to correctly receive at least one beacon every 0.25s than MH+NC (Fig. 7b).



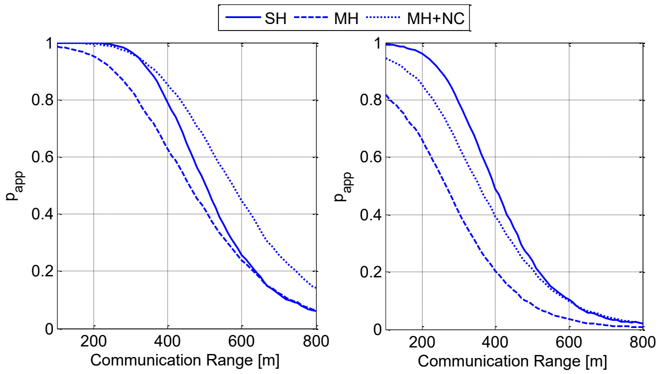
(a) 10 veh/km/lane (b) 20 veh/km/lane

Fig. 5. Probability of correctly receiving at least one beacon every *PIR*=1s at various *CR* for the different beaconing strategies and two traffic densities. Operating point: *CBR*=0.6.



(a) 10 veh/km/lane (b) 20 veh/km/lane

Fig. 6. Probability of correctly receiving at least one beacon every *PIR*=0.5s at various *CR* for the different beaconing strategies and two traffic densities. Operating point: *CBR*=0.6.



(a) 10 veh/km/lane (b) 20 veh/km/lane

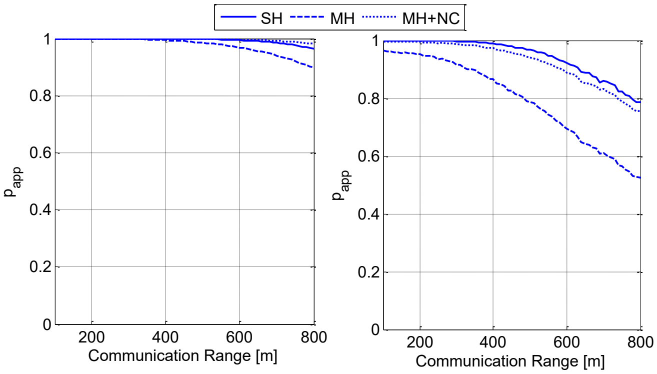
Fig. 7. Probability of correctly receiving at least one beacon every *PIR*=0.25s at various *CR* for the different beaconing strategies and two traffic densities. Operating point: *CBR*=0.6.

M. Sepulcre, J. Gozalvez, J. R. Gisbert, "On the Potential of Network Coding for Cooperative Awareness in Vehicular Networks", Proc. IEEE International Workshop on Automotive IoT (IEEE Auto-IoT 2015), Milan, Italy, 14-16 December 2015. DOI: 10.1109/WF-IoT.2015.7389042

Changing the target *CBR* level modifies the packet collision probability, and therefore the packet transmission frequency needed by each beaconing strategy to achieve the target *CBR*. If the target *CBR* is reduced to e.g. *CBR*=0.4, the packet collision probability and the beacon transmission frequency of the different strategies are reduced. Table II compares the average beacon transmission frequency established by each strategy to operate at a *CBR* equal to 0.6 or 0.4. A reduction in the beacon transmission frequency results in that higher per-packet reception probabilities are needed to maintain the capacity of a vehicle to communicate with other vehicles at larger *CRs*. Fig. 8b shows again that SH can outperform multi-hop beaconing strategies when considering a target *CBR* equal to 0.4 and high traffic densities. This is the case despite the relaxation of the application requirements (Fig. 8 corresponds to a *PIR* equal to 1s). On the other hand, Fig. 8a shows that MH+NC can slightly outperform SH with lower traffic densities.

TABLE II. BEACON TRANSMISSION FREQUENCIES FOR *20 VEH/KM/LANE*

Beaconing strategy	**CBR**	
	0.6	**0.4**
SH	9.3	3.9
MH	3.1	1.3
MH+NC	4.65	1.95



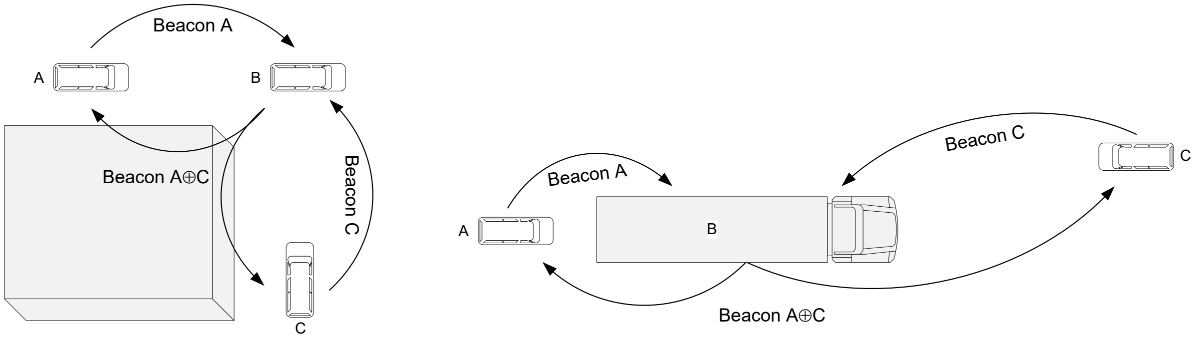
(a) 10 veh/km/lane (b) 20 veh/km/lane

Fig. 8. Probability of correctly receiving at least one beacon every *PIR*=1s at different *CR* for the different beaconing strategies and two different traffic densities. Operating point: *CBR*=0.4.

IV. CONCLUSIONS AND DISCUSSION

The results presented in this paper show that network coding and multi-hop beaconing can improve cooperative awareness in vehicular networks under certain traffic and application conditions. In particular, the combined use of network coding and multi-hop beaconing can guarantee higher communications reliability levels at large distances compared to single-hop beaconing strategies. The performance of the different strategies has been compared under certain channel load levels (defined by the target *CBR*), and the vehicles were assumed to adapt their beacon transmission frequencies to guarantee operating under the target *CBR*. The obtained results showed that the combined use of network coding and multi-hop beaconing can improve, under certain conditions, the capacity of vehicles to communicate with other vehicles at large distances (i.e. the cooperative awareness). However, this was not the case with strict application requirements (i.e. when *PIR* is significantly reduced) or when the target *CBR* was reduced but the traffic density increased. Further work would be needed to design adaptive beaconing protocols that are able to dynamically adapt the transmission parameters and the beaconing strategy to the operating conditions and application requirements. These protocols could be particularly relevant for the control channel as it easily get congested under high traffic density conditions [13]. These protocols could hence be relevant for the future evolution of the DCC architecture being discussed at ETSI, especially as connected automated vehicles will require the exchange of richer information. However, one of the main challenges for the design of such protocols would be their real-time operation since multiple context factors should be taken into account, including variable application requirements as a function of the vehicular and traffic context.

The combined use of multi-hop beaconing and network coding could also be beneficial to address the challenges resulting from large obstacles (e.g. buildings or trucks, Fig. 9). Large obstacles produce high propagation losses for the high vehicular frequency range [14][15]. These losses are challenging to combat considering that vehicular standards establish maximum transmission power levels. In this case, multi-hop beaconing could help reach a target communication range with the required reliability levels demanded by the application. This is especially the case when single-hop transmissions are blocked by large obstacles, but multi-hop transmissions are produced under LOS (Line-of-Sight)



(a) Building as obstacle between A and C (b) Truck as obstacle between A and C

Fig. 9. Scenarios that are especially suitable for multi-hop beaconing and network coding.

M. Sepulcre, J. Gozalvez, J. R. Gisbert, "On the Potential of Network Coding for Cooperative Awareness in Vehicular Networks", Proc. IEEE International Workshop on Automotive IoT (IEEE Auto-IoT 2015), Milan, Italy, 14-16 December 2015. DOI: 10.1109/WF-IoT.2015.7389042

conditions (see examples in Fig. 9). However, multi-hop beaconing increases the channel load level, and this effect could be addressed through the combined use of multi-hop beaconing and network coding. To exploit the potential of network coding, an efficient forwarding algorithm that is compliant with the DCC architecture discussed at ETSI needs to be designed. The forwarding algorithm should first decide the beaconing strategy based on the operating conditions, i.e. whether to use single-hop or multi-hop beaconing with network coding. The algorithm should also dynamically select which beacons will be combined with network coding and forwarded [6]. This should be one of the key features of the algorithm to maximize the number of vehicles that are able to decode the forwarded beacon while satisfying the application requirements.

ACKNOWLEDGEMENT

This work was supported in part by the Spanish Ministry of Economy and Competitiveness and FEDER funds TEC2014-57146-R, by the Spanish *Dirección General de Tráfico* (SPIP20141414) and by GVA (GV/2015/140).

REFERENCES

[1] P.A. Chou, Y. Wu, “Network Coding for the Internet and Wireless Networks”, *IEEE Signal Processing Magazine*, vol.24, no.5, pp. 77-85, Sept. 2007.

[2] M. Z. Farooqi et al., “A survey on network coding: From traditional wireless networks to emerging cognitive radio networks”, *Journal of Network and Computer Applications*, vol. 46, 166–181, 2014.

[3] Z. Wang; M. Hassan, “Network Coded Repetition: A Method to Recover Lost Packets in Vehicular Communications”, *Proc. IEEE International Conference on Communications (ICC)*, Kyoto, Japan, pp. 1-6, 5-9 June 2011.

[4] B. Hassanabadi, S. Valaee, “Reliable Periodic Safety Message Broadcasting in VANETs Using Network Coding”, *IEEE Transactions on in Wireless Communications*, vol. 13, no. 3, pp. 1284-1297, March 2014.

[5] J. Mittag, F. Thomas, J. Harri, H. Hartenstein, “A Comparison of Single- and Multi-Hop Beaconing in VANETs”, *Proc. ACM International Workshop on VehiculAr Inter-NETworking (VANET)*, Beijing, China, pp. 69–78, 25 Sept. 2009.

[6] F. Librino, M. E. Renda, P. Santi, “Evaluating Multi-Hop Beaconing Forwarding Strategies for IEEE 802.11p Vehicular Networks”, *Proc. IEEE Vehicular Networking Conference (VNC)*, Boston, USA, pp. 31-38, 16-18 Dec. 2013.

[7] M. Sepulcre et al., “Congestion and Awareness Control in Cooperative Vehicular Systems”, *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1260-1279, July 2011.

[8] ETSI TC ITS, “Intelligent Transport Systems (ITS); Cross Layer DCC Management Entity for operation in the ITS G5A and ITS G5B medium; Report on Cross layer DCC algorithms and performance evaluation”, *ETSI TR 101 612 V1.1.1*, Sept. 2014.

[9] G. Bansal, J. Kenney, and C. Rohrs, “LIMERIC: A linear adaptive message rate algorithm for DSRC congestion control,” *IEEE Transactions on Vehicular Technology*, vol. 62, no. 9, pp. 4182-4197, Nov. 2013.

[10] ETSI TC ITS, “Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part,” *ETSI TS 102 687 v1.1.1*, July 2011.

[11] V Taliwal, D Jiang, H Mangold, C Chen, R Sengupta, “Empirical determination of channel characteristics for DSRC vehicle-to-vehicle communication”, *Proc. ACM International Workshop on Vehicular Ad Hoc Networks (VANET)*, Philadelphia, USA, October 2004.

[12] M. Killat, H. Hartenstein, “An empirical model for probability of packet reception in vehicular ad hoc networks”, *EURASIP Journal on Wireless Communications and Networking*, Jan. 2009.

[13] M. Sepulcre, J. Gozalvez, O. Altintas, H. Kremo, “Integration of Congestion and Awareness Control in Vehicular Networks”, *Ad Hoc Networks*, DOI: 10.1016/j.adhoc.2015.09.010.

[14] M. Sepulcre and J. Gozalvez, “Experimental evaluation of cooperative active safety applications based on V2V communications”, *Proc. ACM international workshop on Vehicular inter-networking, systems, and applications (VANET)*, Low Wood Bay (United Kingdom), pp. 13-20, 25 June 2012.

[15] J. Gozalvez, M. Sepulcre and R. Bauza, “IEEE 802.11p Vehicle to Infrastructure Communications in Urban Environments”, *IEEE Communications Magazine*, vol. 50, no. 5, pp. 176-183, May 2012.

M. Sepulcre, J. Gozalvez, J. R. Gisbert, "On the Potential of Network Coding for Cooperative Awareness in Vehicular Networks", Proc. IEEE International Workshop on Automotive IoT (IEEE Auto-IoT 2015), Milan, Italy, 14-16 December 2015. DOI: 10.1109/WF-IoT.2015.7389042