Effect of Network Coding and Multi-hop Beaconing on the Channel Load of Vehicular Networks

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***Abstract*- Vehicular networks are based on the periodic exchange of beacons on the so called control channel using the IEEE 802.11p technology. The critical nature of this channel has fostered significant efforts in the research and standardization communities to design congestion control protocols that dynamically adapt the transmission parameters to control the channel load. In this context, network coding has been demonstrated to improve the bandwidth efficiency in many different types of networks, but limited efforts have been conducted to date for its application to vehicular networks. This paper presents our first results on the use of network coding for the beaconing process in vehicular networks. The results obtained show the potential of network coding to reduce the congestion control problem and motivate the design of efficient multi-hop beaconing algorithms that exploit network coding. Network coding could present a significant impact on the design of the Decentralized Congestion Control (DCC) module that is currently being studied under the ETSI Technical Committee on ITS.**

***Keywords*- Network coding, multi-hop beaconing, congestion control, vehicular networks, connected vehicle**

I. INTRODUCTION

Network coding can be considered a routing technique with which intermediate network nodes process (encode) the information to be forwarded. 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. As a result, network coding can improve resource efficiency (e.g. bandwidth and power) [1] and therefore the capacity, throughput, link reliability, spectral efficiency and transmission range. Network coding has been widely used in different types of networks, ranging from Internet to wireless sensor networks, traditional wireless networks, video multicast networks, Peer-to-Peer (P2P) networks and many others [2]. However, limited efforts have been conducted to date to analyze the potential of network coding in vehicular networks.

Vehicular networks are being designed to improve traffic safety and efficiency thanks to the exchange of positioning and basic status information between vehicular nodes. This exchange is based on the periodic transmission and reception of beacons (1-hop broadcast messages) using the IEEE 802.11p technology. To effectively support vehicular safety applications, each vehicle needs to continuously receive updated information from all neighboring vehicles. To this aim, a number of awareness control protocols have been proposed in the literature [3]. Awareness control protocols are aimed at ensuring each vehicle's capacity to detect, and possibly communicate with the relevant vehicles and infrastructure nodes present in their local neighborhood. All vehicles will periodically transmit their beacons on the so called control channel. This can lead to possible channel congestion, in particular under high traffic densities. The critical nature of the control channel has fostered significant efforts in the research and standardization communities to design congestion control protocols that ensure the scalability and adequate operation of vehicular networks by adapting the transmission parameters of beacons [3]. In fact, the ETSI communications architecture that future connected vehicles will implement includes a key Decentralized Congestion Control (DCC) module that is currently under development [4].

Limited studies have analyzed the use of network coding in vehicular networks. The work in [5] demonstrates that network coding can improve the performance of repetition-based error recovery mechanisms in vehicular networks. With these mechanisms, each vehicle retransmits each beacon k times to recover packets lost due to propagation errors or collisions. The work in [5] 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. Network coding can also be used to improve the performance and efficiency of multi-hop beaconing schemes. The study in [6] analyzes the potential of multi-hop beaconing to improve cooperative awareness in vehicular networks. The theoretical results obtained 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 that multi-hop beaconing improves the awareness performance of single-hop beaconing. Finally, the work in [7] was one of the first studies to propose multi-hop beaconing algorithms that exploit network coding to improve cooperative awareness in vehicular networks. 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.

In this context, this paper analyzes the potential benefits of network coding and multi-hop beaconing to reduce the channel load in vehicular networks. While previous studies evaluated network coding schemes based on fixed transmission powers, this paper considers that the transmission power is adapted to satisfy the application requirements. The first results obtained in this paper show that multi-hop beaconing with network coding could reduce the channel load experienced, which would be important to mitigate the congestion control problem of vehicular networks.

II. BEACONING STRATEGIES

To evaluate the potential of network coding and multi-hop beaconing in vehicular networks, the beaconing strategies depicted in Fig. 1 have been studied. In all of them, all vehicles periodically transmit beacons to support cooperative active safety applications. The applications require that such beacons are successfully received by all vehicles within certain communication range (*CR*) with certain probability (p_{app}). For example, an application could require that 10 beacons per second are received at a certain communication range (*CR*) with p_{app}=0.99 probability. Both *CR* and p_{app} are application requirements that depend on the vehicular context. Such requirements can be satisfied with a single-hop (SH) or a multi-hop (MH) strategy. With the multi-hop strategy, 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.

With a single-hop beaconing strategy (Fig. 1a), vehicles periodically transmit their beacons using the transmission power needed to reach *CR* with probability p_{app}. The transmission power for single-hop transmissions (P_t^{SH}) needs to be configured so that the Packet Delivery Ratio (PDR) at a distance equal to *CR* is p_{app}:

$$p_{app} = PDR(P_t^{SH}, CR) \tag{1}$$

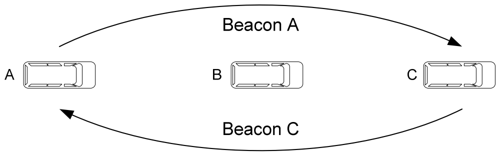
With a multi-hop beaconing strategy (Fig. 1b), vehicles do not only transmit their own beacons, but also forward beacons transmitted by other vehicles. Since all beacons are forwarded by intermediate vehicles, they can be transmitted with lower transmission power levels to reach the target communication range with the desired probability p_{app}. Following the illustration in Fig. 1b, a beacon will be successfully received by vehicle C if either the direct transmission from vehicle A to vehicle C is successful, or if vehicle B successfully receives such transmission from vehicle A and successfully forwards it to vehicle C. While different forwarding strategies are possible, we consider for our analysis that beacons are always forwarded by vehicles located at *CR*/2 distance from the initial transmitter. As a result, the transmission power for multi-hop strategies (P_t^{MH}) needs to satisfy the following equation to satisfy the application requirements:

$$p_{app} = 1 - \left(1 - PDR\left(P_t^{MH}, CR\right)\right) \cdot \left(1 - PDR\left(P_t^{MH}, CR/2\right)^2\right) \tag{2}$$

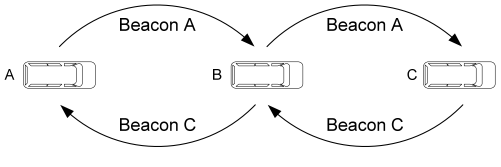
Ec. (2) considers independent transmissions. With the multi-hop beaconing strategy, the transmission power can be reduced to satisfy Ec. (2), but the number of transmissions per vehicle increases. In fact, in a scenario with vehicles uniformly distributed, the average number of packets transmitted per second per vehicle would be 3 times the beacon transmission frequency, 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 A and C).

With a multi-hop beaconing strategy combined with network coding (Fig. 1c), beacons can be transmitted with the transmission power that satisfies Ec. (2). However, 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 a scenario with vehicles uniformly distributed, the number of packets to be transmitted per second per vehicle would be 2 times the beacon transmission frequency, because the two beacons to be forwarded are combined with network coding before transmission.

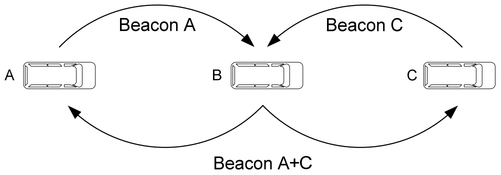
To avoid limiting this study to a specific forwarding strategy (with or without network coding), we will consider a network of vehicles uniformly distributed. Each vehicle will configure its transmission power to achieve the target packet reception probability p_{app} following Ec. (1) or (2). For the analysis of multi-hop beaconing (with and without network coding), vehicles will forward all beacons received from vehicles located at *CR*/2. While more complex situations are obviously possible (e.g. vehicles do not need to be located at *CR*/2 meters), this simplification allows this study to be independent of specific forwarding algorithms, and to quantify in a simple but effective way the potential of network coding and multi-hop beaconing. The fundamental question to be solved is whether a vehicle transmitting a high number of beacons at low power is more efficient than a vehicle transmitting a lower number of beacons, but with higher power. To fairly compare all approaches, all of them need to be configured to satisfy the application requirements.



(a) Single-hop beaconing (SH)



(b) Multi-hop beaconing (MH)



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

Fig. 1. Beaconing strategies evaluated.

III. EVALUATION

A. Simulation settings

The performance and efficiency of the beaconing strategies analyzed have been evaluated using the network simulator ns-2.35. The simulations conducted consider a straight highway with 6 lanes. In this scenario, vehicles are uniformly distributed and the traffic density considered is 20 vehicles/km/lane.

In this scenario, each vehicle transmits 10 beacons per second using IEEE 802.11p at 6Mbps. The transmission power is adjusted for each simulation to satisfy the application requirements, i.e. to successfully receive all beacons at *CR* with p_{app} probability in an scenario without interferences. Both *CR* and p_{app} influence the transmission parameters needed and therefore the channel load generated. To avoid limiting this study to a given application, different combinations of *CR* and p_{app} have been analyzed.

Taliwal et al. showed in [8] that the Nakagami-*m* distribution suitably describes the radio propagation conditions in vehicular networks on highways in the absence of interferences. Following [9], 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 considered in this study.

Table I
COMMUNICATION AND SIMULATION PARAMETERS

Parameter	Value
Number of lanes	6
Road length [km]	8
Traffic density [veh/km/lane]	20
Packet transmission frequency [Hz]	10
Payload size [Bytes]	250
Data rate [Mbps]	6
Carrier frequency [GHz]	5.9
SINR min for packet reception [dB]	8
Noise floor [dBm]	-99
Communication Range (*CR*)[m]	100, 200,…, 500
Probability of successful reception (p_{app})	0.99, 0.999, 0.9999
Simulation time [s]	50
Simulation runs	5

B. Results

To analyze the potential channel load benefits of the use of network coding and multi-hop beaconing, the transmission parameters need to be fairly configured. To this aim, the packet delivery ratio curves for a wide range of transmission power levels have been obtained. Fig. 2 shows as an example, the PDR curves for five different transmission power levels when considering the Nakagami-*m* propagation model with m=3 and quadratic path-loss without interferences. These PDR curves have been used to identify the minimum transmission power level needed to satisfy the application requirements, i.e. to achieve the target probability of packet reception (p_{app}) at the required communication range (*CR*). Ec. (1) and (2) have been used to find the relationship between PDR and p_{app} for single-hop and multi-hop strategies. The resulting transmission power levels needed to achieve p_{app}=0.99, 0.999 and 0.9999 at varying communication ranges are shown in Fig. 3 for both single-hop and multi-hop beaconing strategies. As it can be observed, the transmission power can be reduced between 6.5dB and 8dB when multi-hop transmissions are considered, while satisfying the application requirement p_{app} at the target *CR*. The transmission power reduction is higher as the p_{app} parameter increases. For the specific case of p_{app}=0.99 and *CR*=200m, Fig. 4 shows the PDR curves for single-hop and multi-hop beaconing strategies when the transmission power is accurately calculated to satisfy the application requirements. As it can be observed, while a PDR of 0.99 needs to be obtained at *CR*=200m for single-hop transmissions, the PDR (and therefore the transmission power) can be reduced when multi-hop transmissions are allowed.

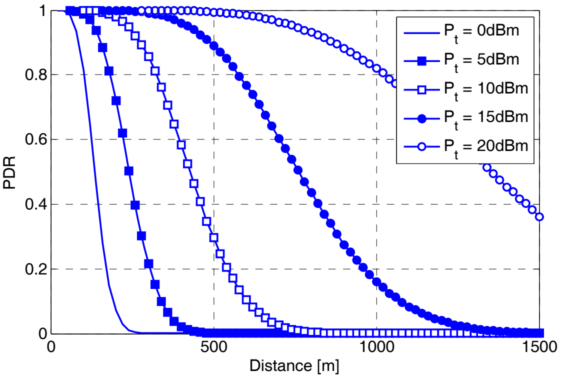


Fig. 2. PDR (Packet Delivery Ratio) for different transmission power levels considering Nakagami-*m* propagation model with m=3 and quadratic path-loss without interferences.

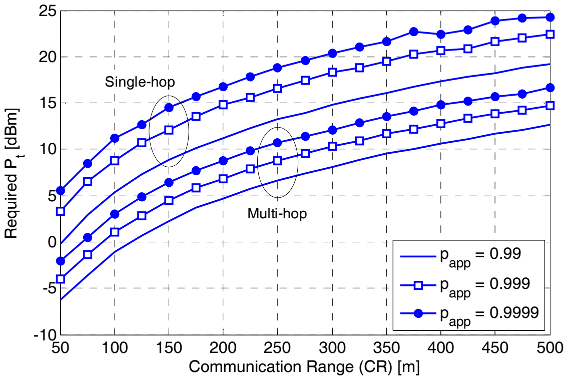


Fig. 3. Required transmission power to obtain a given probability of successful reception (p_{app}) at a certain communications range (CR) without interferences.

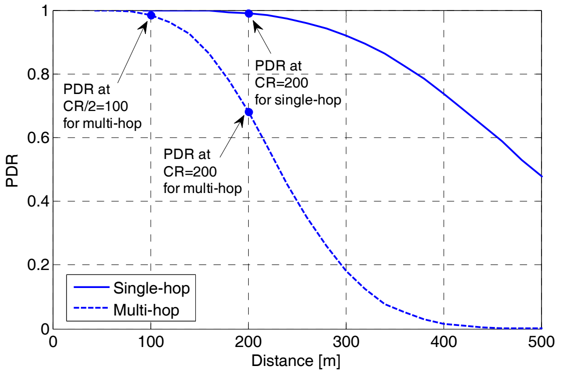


Fig. 4. PDR (Packet Delivery Ratio) curves for the transmission power levels needed to achieve p_{app}=0.99 at *CR*=200m for single-hop and multi-hop strategies.

To evaluate the channel load benefits of network coding and multi-hop beaconing, this study considers that all vehicles in the scenario have the same application requirements (p_{app} and CR), and configure their transmission power to satisfy them. Therefore, for the single-hop strategy, all vehicles are configured to transmit 10 beacons per second using the transmission power level shown in Fig. 3 for the p_{app} and CR parameters considered. For multi-hop strategies, we will consider that each vehicle forwards all beacons received from vehicles located at $CR/2$ on the same lane. As a result, when considering a multi-hop strategy without network coding, each vehicle will forward 20 packets per second (10 from a vehicle located $CR/2$ meters ahead, and 10 from a vehicle located at $CR/2$ behind). When considering network coding, only 10 packets per second need to be forwarded. This is the case because each beacon from the vehicle located at $CR/2$ meters ahead is combined (XOR) with the beacon received from the vehicle located at $CR/2$ meters behind. As a consequence, in average, all vehicles transmit 10Hz with the single-hop beaconing strategy, 30Hz with the multi-hop beaconing strategy without network coding, and 20Hz with the multi-hop beaconing strategy with network coding.

The trade-off between transmission power and packet transmission frequency for the different strategies is illustrated in Fig. 5. This figure represents the number of packets that would be sensed per second by a vehicle located at a certain distance from a given transmitter. The transmitter is configured with the transmission power needed to achieve p_{app}=0.99 at CR=200m and the number of packets transmitted per second include the packets that would be forwarded if a multi-hop strategy was considered. The channel load experienced is directly related to the time the radio interface is busy sensing packets sent by other radio interfaces. A multi-hop beaconing strategy increases the number of packets sensed per second at short distances, but decreases it at medium and high distances.

Fig. 6 shows the channel busy ratio (CBR) experienced by a vehicle located in the center of the scenario for different beaconing strategies and varying application requirements (CR and p_{app}). The CBR represents the percentage of time that the radio interface of a vehicle is busy and is widely used as a channel load metric. As it can be observed, the CBR increases as the application requirements (CR and p_{app}) increase. This is the case because the increase of the application requirements augments the transmission power needed to satisfy them in absence of interference, as previously shown in Fig. 3. As it can be observed, the channel starts saturating for CBR values higher than 0.8, and therefore further increasing the CR does not significantly increase the channel load.

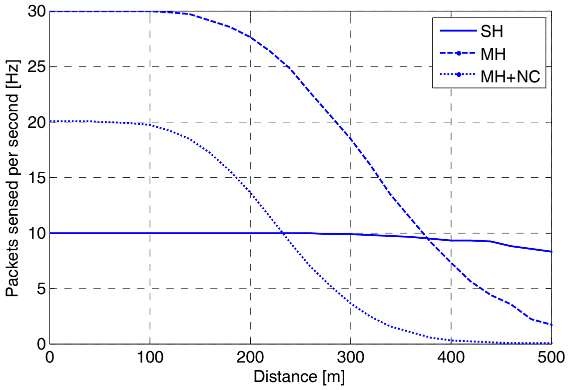
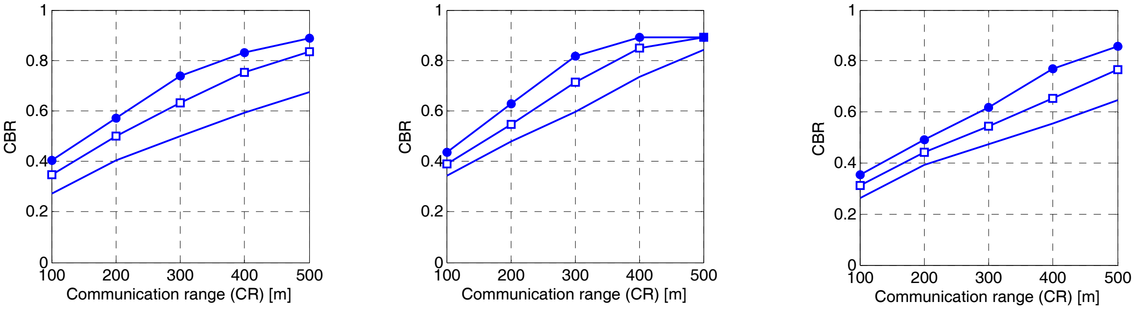


Fig. 5. Number of packets sensed per second as a function of the distance to a transmitter considering the transmission power levels needed to achieve p_{app}=0.99 at CR=200m for single-hop and multi-hop strategies (with and without network coding).

To more clearly compare the CBR experienced with the different beaconing strategies, the relative variation (RV) of the CBR with respect to the single-hop strategy has been calculated. RV has been calculated with the following equation:

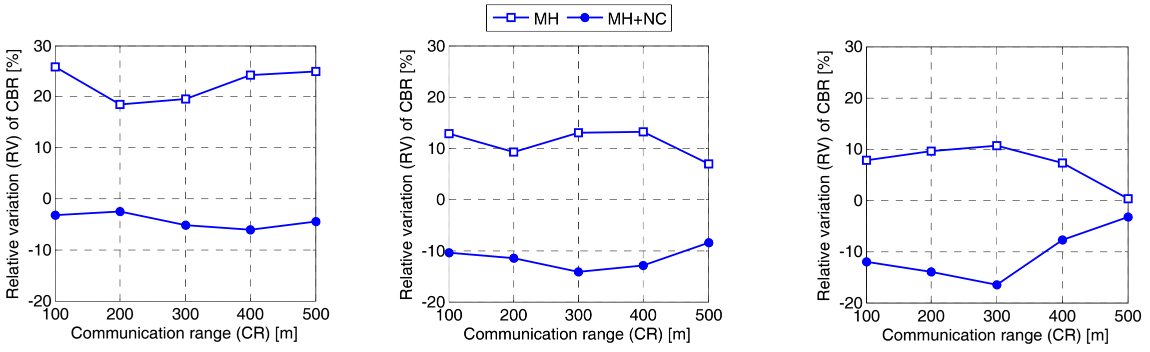
$$RV = 100 \cdot \frac{CBR - CBR_{SH}}{CBR_{SH}} \tag{3}$$

where CBR_{SH} is the CBR experienced with the single-hop strategy. While a positive RV value represents a channel load increase compared to the single-hop beaconing strategy, a negative value represents a channel load reduction. Fig. 7 depicts the relative variation of the CBR with respect to the single-hop strategy for varying application requirements. As it can be observed, the channel load can increase up to around 25% with multi-hop beaconing (MH) compared with the single-hop beaconing strategy. However, when multi-hop beaconing is combined with network coding (MH+NC), the channel load can be reduced. As shown in Fig. 7, the channel



(a) SH (b) MH (c) MH+NC

Fig. 6. CBR (Channel Busy Ratio) experienced by a vehicle in the center of the scenario for single-hop (SH), multi-hop (MH) and multi-hop combined with network coding (MH+NC) strategies. All vehicles are configured with the transmission parameters needed to satisfy the application requirements (CR and p_{app}) in absence of interference.



(a) $p_{app} = 0.99$ (b) $p_{app} = 0.999$ (c) $p_{app} = 0.9999$

Fig. 7. Relative variation of the CBR (Channel Busy Ratio) experienced by a vehicle in the center of the scenario for multi-hop (MH) and multi-hop combined with network coding (MH+NC) strategies. The values shown represent the relative variation with respect to single-op beaconing (SH), i.e. a positive (negative) value means an increase (decrease) of the channel load generated compared to SH.

load can be reduced with the strategy that combines multi-hop beaconing with network coding up to around 17%. This reduction is especially relevant given the critical nature of the control channel used for vehicular networks.

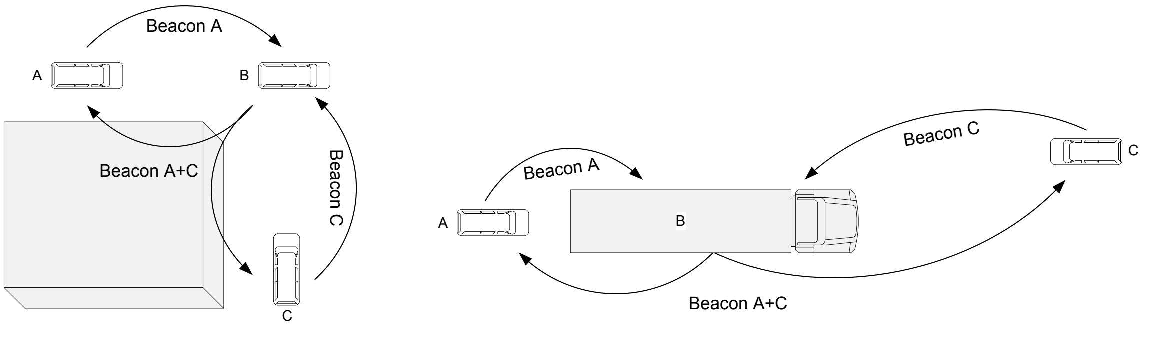
Interestingly, the performance and efficiency gain achieved with network coding is independent of certain communication parameters. In particular, it is independent of the packet payload and data rate. Both parameters affect the time duration of a packet, and therefore affect the channel load generated. However, the relative gain that can be achieved with network coding in terms of channel load is maintained irrespective of the specific values considered. The results have not included in this paper due to space limitations and small differences with the results presented.

IV. DISCUSSION

First results presented in this paper show that network coding and multi-hop beaconing can reduce the channel load of vehicular networks. The reduction of the transmission power and the combination of packets to be forwarded reduce the channel load in the scenario considered and therefore decrease the interferences generated. Further analysis will be needed to verify if the same conclusions can be obtained in different scenarios. The potential reduction of the channel load can be especially relevant for the vehicular control channel, which can be easily congested especially under high traffic density conditions. In fact, the fundamental limits of solutions based on IEEE 802.11p can be reached when the application requirements and traffic density are high [10]. If the benefits of network coding are verified for different scenarios and conditions, it could be part of a potential extension of the DCC algorithms being discussed at ETSI to ensure the scalability of vehicular networks, which will be especially challenging with the emergence of automated vehicles. Future automated vehicles will require the wireless exchange of richer information and higher traffic densities at higher speeds might be possible, which would notably increase the channel load and communication requirements.

In scenarios with large obstacles, such as buildings or trucks, the use of multi-hop beaconing could represent the only way to reach the target communication range with the required probability due to the power limitations. Large obstacles produce high propagation losses, especially due to the high carrier frequency of IEEE 802.11p [11][12]. As a result, the transmission power needed to satisfy the application requirements could be higher than the limits imposed by the standards (33dBm). Multi-hop beaconing can reduce the transmission power levels needed compared to single-hop beaconing. This reduction can be especially significant when single-hop transmissions are blocked by large obstacles, but multi-hop transmissions are produced under LOS (Line-of-Sight) conditions (see examples in Fig. 8). Since multi-hop beaconing can be very inefficient, as previously demonstrated in Fig. 7, network coding can be used to improve its efficiency, as demonstrated in the results obtained in section III.

To exploit the potential of network coding, an efficient forwarding algorithm that is compliant with the DCC



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

Fig. 8. Scenarios that are especially suitable for multi-hop beaconing and network coding.

architecture discussed at ETSI needs to be designed. The forwarding algorithm needs to dynamically select the neighboring vehicles whose beacons will be combined with network coding and transmitted [7]. This is one of the key elements of the algorithm to maximize the number of vehicles that are able to decode the forwarded beacon, while satisfying the application requirements. Moreover, a reliable and efficient power control algorithm needs to be designed to achieve the channel load gains shown in this paper. In fact, the application requirements can be dynamic and context dependent [13], which challenge the accurate adaptation of the transmission power. The forwarding algorithm should also be able to ensure that the application requirements are satisfied.

V. CONCLUSIONS

The results obtained in this paper show that network coding can reduce the channel load generated by the beaconing process of vehicular networks. The channel load generated when considering a multi-hop beaconing strategy combined with network coding can be up to around 17% lower than the channel load generated with a single-hop beaconing strategy. Both strategies have been fairly compared by adapting the transmission power to the minimum needed to satisfy the application requirements in absence of interference. The results obtained will need to be confirmed for different scenarios and conditions, but could motivate the design of efficient multi-hop beaconing algorithms that exploit network coding to reduce the channel load. These algorithms could be relevant for the future evolution of the DCC architecture being discussed at ETSI, especially due to the emergence of automated vehicles which will require the transmission of richer information. Further work will be needed to analyze the effect of multi-hop beaconing and network coding on packet collisions and interferences, which will especially depend on the forwarding algorithm.

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