Transactions Letters

Contextual Communications Congestion Control for Cooperative Vehicular Networks

Miguel Sepulcre, Javier Gozalvez, Jérôme Härri, and Hannes Hartenstein

***Abstract*—The wide scale deployment of cooperative vehicular ad-hoc networks will require the design of efficient congestion control policies that guarantee stable and reliable communications between vehicles and with infrastructure nodes. These policies should reduce the load on the communications channel, while satisfying the strict application's reliability requirements. To this aim, this letter proposes and evaluates a contextual cooperative congestion control policy that exploits the traffic context information of each vehicle to reduce the channel load, while satisfying the vehicular applications requirements.**

***Index Terms*—Vehicular ad-hoc networks, congestion control, cross-layer, context information.**

I. Introduction

VEHICULAR Ad-Hoc Networks (VANETs) are currently being investigated to improve road safety and traffic management through the real-time exchange of information between vehicles, and between vehicles and road side units, using the WAVE/IEEE 802.11p technologies (or its European adaptation) on the 5.9GHz band. The operation of VANETs is based on the periodical broadcast of 1-hop CAMs (Cooperative Awareness Messages) on a common channel, referred to as the control channel. The data exchanged through CAMs is used to support different safety and non-safety applications. The reference status of the control channel can cause channel congestion situations in highly dense areas. This congestion is particularly critical for the 802.11p standard that is based on the CSMA/CA protocol, since it could increase its instability and collapse its operation. To avoid this situation, the channel load can be reduced and controlled by the efficient and dynamic adaptation of transmission power, packet transmission frequency and packet duration, which represents the time needed to transmit a packet of a certain payload with a given datarate. Some congestion control algorithms for VANETs limit the channel load generated by CAMs through distributed power control techniques [1]. Other policies try to prevent channel congestion by reducing the packet transmission frequency to the minimum level that is able to properly monitor surrounding vehicles [2]. In this context, it is interesting to note that the performance of congestion control techniques could be further improved through the cooperation among vehicles.

Cooperation has lately received much attention to enable an efficient resources sharing from different perspectives. For example, at the PHY layer, two VANET nodes can cooperate to enable transmit diversity with single-antenna devices [3], while at the network layer vehicles cooperate when they participate in a multihop network to relay other vehicles' information [4]. However, limited work has been done on the use of cooperation to improve the operation of VANET congestion control policies. In [5], vehicles implicitly cooperate based on a prioritization and a re-scheduling technique using application-specific utility functions. Another interesting approach is proposed in [6] where each vehicle modifies its packet transmission frequency and power based on its own speed to reduce the interference generated. These studies demonstrate the potential benefit of cooperation and assigning a different priority or bandwidth to vehicles with diverse road safety application requirements as well as traffic context. However, the communications requirements imposed by CAM-based road safety applications have not been normally considered. In addition, the use of traffic context information could be further exploited to improve congestion control.

In this context, this letter proposes and evaluates a contextual cooperative congestion control policy that exploits the traffic context information of each vehicle to reduce unnecessary interferences and diminish the channel load, while satisfying the strict VANET applications requirements. To illustrate the channel load reduction that can be obtained through the proposed policy, this letter considers a lane change assistance application in a highway scenario. In addition to highlighting the possibility to adapt the proposed policy to the context and requirements of other applications and scenarios, the letter finally discusses a proposal to consider multiple simultaneous applications.

II. Cooperative Road Safety Case Study: Lane Change Assistance

The lane change assistance application informs the driver about whether a potential lane change manoeuvre can be

Manuscript received January 18, 2010; revised May 14, 2010 and September 17, 2010; accepted November 10, 2010.

This work was supported in part by the iTETRIS Project (FP7 224644), Ministerio de Fomento (T39/2006) and GVA (BFPI06/126). J. Härri acknowledges the support of the Ministry of Science, Research and the Arts of Baden-Württemberg (Az: Zu 33-827.377/19,20), the Klaus Tschira Stiftung, INIT GmbH and the PTV AG.

M. Sepulcre and J. Gozalvez are with the Uwicore Lab., University Miguel Hernandez of Elche, Spain (e-mail: {msepulcre, j.gozalvez}@umh.es).

J. Härri and H. Hartenstein are with the DSN Research Group at the KIT, Karlsruhe, Germany.

Digital Object Identifier 10.1109/TWC.2010.120610.100079

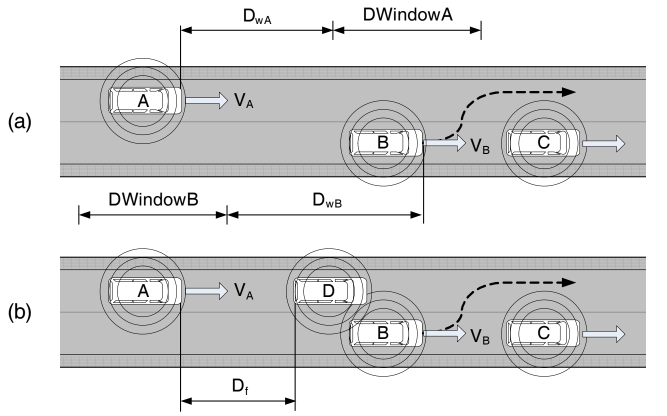

Fig. 1. Lane change assistance application: (a) metrics; (b) traffic contextual information.

performed in a safe way or not based on positioning and movement information received from surrounding vehicles by means of CAMs. Following the illustration in Fig. 1a, vehicle B would consider its lane change as unsafe if another vehicle A is approaching on the left lane and they are closer than a certain distance D_w (Warning Distance). D_w represents the minimum separation distance between the two vehicles allowing vehicle B to change the lane without making vehicle A reduce its speed. D_w can be computed as:

$$D_w = \frac{1}{2}\frac{(v_B - v_A)^2}{|a_A - a_B|} + L + D_s \quad (1)$$

where v_A and v_B represent the vehicles speed in m/s, a_A and a_B their acceleration in m/s^2, L is the vehicle length in m, and D_s is the safety distance ($L = 4m$ and $D_s = 30m$ in average in this work). It is important to note that neither of the two vehicles knows the speed of the other vehicle before receiving its first CAM. Consequently, they need to assume the worst case scenario in terms of speed to calculate their respective D_w. This corresponds to vehicle A calculating D_w considering that vehicle B is moving at the minimum speed allowed in the road, and it has the lowest possible acceleration in the overtaking manoeuvre ($v_B = v_{min}$, $a_B = a_{min} = 1m/s^2$). Vehicle B will consider that vehicle A is moving at the maximum constant speed allowed in the road ($v_A = v_{max}$, $a_A = 0m/s^2$). This results in different D_w distances for vehicles with different driving context situations.

In the scenario depicted in Fig. 1a, the deployment of VANETs will allow avoiding a potential collision caused by a lane change manoeuvre if vehicles A and B correctly exchange at least one CAM at a distance equal or larger than their D_w. To quantify the performance of the lane change assistance use case, the application's reliability (p_{app}) has been defined as the probability of receiving at least one CAM before D_w and during a given time window $TWindow$ [7] (see Fig. 1a, where the $TWindow$ is mapped to the $DWindow$ distances according to the vehicles' speed).

III. From Autonomous to Contextual Congestion Control

To illustrate the benefits of contextual cooperative congestion control policies, three different operational modes have been analysed with increasing cooperation and usage of traffic context information: autonomous (AM), cooperative (CM), and contextual cooperative modes (CCM).

Autonomous mode (AM): in AM, vehicles do not exploit the traffic context information. Based on the previous application analysis and following equation 1, each vehicle is able to autonomously update its application requirements (the minimum separation distance required to initiate a lane change manoeuvre in this letter, D_w) before every CAM transmission. Then, to satisfy the target application reliability level p_{app}, each vehicle accordingly adapts its communications parameters. For a given CAM transmission frequency, $TWindow$ and payload, the transmission power required to satisfy the application reliability level at the D_w distance has been obtained following the methodology proposed in [8]. In particular, the work reported in [8] calculates the minimum transmission power required to successfully exchange at least one message with p_{app} probability at a given distance taking into account the propagation effects. In addition, [8] also considers a compensation policy based on the increment of the transmission power to combat the negative effects of packet collisions on the packet reception probability and application reliability. In a three-lane road scenario, a vehicle in the middle lane would need to compute the D_w distance for its communications with fast approaching vehicles behind, and a different D_w for its communications with slow vehicles ahead. A vehicle in the middle lane would then consider the maximum of these two D_w values to adapt its communications parameters:

$$D_{wA}(AM) = max\left(\frac{1}{2}\frac{(v_{max} - v_A)^2}{a_A} + L + D_s, \frac{1}{2}\frac{(v_{min} - v_A)^2}{|a_A - a_{min}|} + L + D_s\right) \quad (2)$$

In AM, the application's reliability for each vehicle would be $p_{appA} = p_{appB} = 0.99$. The potential collision in a lane change assistance scenario could be avoided if either vehicle A or vehicle B receives from each other at least one CAM before D_w. If only one of these messages is correctly received, the application is still able to detect a risk in a lane change manoeuvre, and at least alert one of the two vehicles. The overall application's reliability is $p_{app} = 1 - (1 - p_{appA})(1 - p_{appB}) = 0.9999$. Following this process, all vehicles are able to individually and dynamically adapt their transmission power to the minimum level required to satisfy the application's reliability requirements, and reduce the channel load and the interference generated.

Cooperative mode (CM): in this mode, vehicles do not fully exploit the traffic context information, but assume that all vehicles are adapting their own application requirements and transmission power/range following the procedure defined in AM. As a result, in the scenario illustrated in Fig. 1a, vehicle B will not try to communicate with vehicle A, since it assumes that vehicle A is already trying to communicate with it. Therefore, vehicle B can reduce its transmission power, and wait for the reception of a CAM from A to know if its lane change manoeuvre is safe or not. If vehicle A has adapted its communications parameters following the AM mode, and vehicle B does not receive a CAM before starting its lane change manoeuvre, then the manoeuvre is safe. Following this reasoning, in CM, all vehicles adapt their application requirements and transmission parameters to those needed to communicate with potential dangerous vehicles ahead in a different lane. Therefore, it is the role of the overtaking high-speed vehicle (vehicle A in Fig. 1a) to notify the potential lane changing vehicles (vehicle B in Fig. 1a) about the danger, and D_w is estimated as:

$$D_{wA}(CM) = \frac{1}{2}\frac{(v_{min} - v_A)^2}{|a_A - a_{min}|} + L + D_s \quad (3)$$

In CM, only one vehicle (vehicle A in the scenario depicted in Fig. 1a) will adapt its communications parameters to avoid a potential collision in a lane change manoeuvre. To fairly compare AM and CM, the application's reliability must be set to $p_{app} = p_{appA} = 0.9999$.

Contextual cooperative mode (CCM): vehicles operating in this mode exploit their traffic context information to reduce unnecessary interferences and the channel load without sacrificing the application's reliability. To this end, each vehicle utilizes the specific positions of neighbouring vehicles to reconfigure its application requirements and the resulting transmission parameters. For the lane change assistance application, typical situations such as the one depicted in Fig. 1b can be detected and exploited to reduce the channel load. In this situation, vehicle B knows that its lane change manoeuvre is unsafe due to the presence of vehicle D (i.e. vehicle B previously received at least one CAM from vehicle D). As a result, it is not necessary that vehicle A communicates with vehicle B at high distances, since vehicle B already knows that it cannot change the lane. This results in that vehicle A can reduce its transmission parameters to those needed to communicate with vehicle D, located at a distance D_f from vehicle A (see Fig. 1b). Following this reasoning, each vehicle's operation is as follows. Based on the received CAMs, each vehicle continuously monitors its distance to the vehicle in the same lane ahead, D_f. Based on its individual operating parameters, each vehicle periodically calculates D_w based on CM. They configure their transmission parameters based on the minimum of the two distances calculated:

$$D_{wA}(CCM) = min\,(D_{wA}(CM), D_f) \quad (4)$$

In the scenario illustrated in Fig. 1b, this results in that vehicle A will configure its transmission power to directly communicate with vehicle B only when there is no vehicle D in the same lane ahead located at $D_f < D_w(CM)$. Therefore, unnecessary interferences are reduced and the channel load can be decreased. Given that CCM is partially based on CM, the application's reliability has been set to $p_{app} = p_{appA} = 0.9999$ to fairly compare their performance. It is interesting to highlight that the potential location inaccuracies affecting the distance to the vehicle ahead could be handled by considering the positioning errors in the D_f distance definition.

IV. Performance Evaluation

To demonstrate the benefits of the proposed contextual cooperative congestion control policy, a highway scenario with 6 lanes, 3 in each direction, has been investigated with the network simulator ns2, and considering the realistic Nakagami propagation model with $m = 3$ [1]. In this scenario, all vehicles periodically transmit CAMs on the control channel using the same packet transmission frequency and payload. The CAM transmission power is dynamically adapted to satisfy the defined application's reliability requirements p_{app} at the estimated D_w distances and the established $TWindow$. Table I details the rest of the traffic, communications and simulation parameters. The traffic parameters considered represent a common highway scenario with different traffic densities [9]. The communications parameters listed in Table I have been selected following default settings for the control channel defined in standardization[1] bodies [10] and research initiatives [11].

Fig. 2 illustrates the combination of power and transmission

TABLE I
Traffic, Communication and Simulation Parameters

Traffic parameters	
Length	3km
Speed (depending on the lane)	80 km/h 100 km/h 120 km/h
Boundary speed limits	$v_{min} = 60$ km/h $v_{max} = 120$ km/h
Traffic density	$D_1 = 7.2$ veh/km/lane $D_2 = 9.6$ veh/km/lane $D_3 = 14.4$ veh/km/lane
Communication parameters	
Frequency	5.9GHz
Bandwidth	10MHz
Antenna gain	0dB
Datarate	6 Mbps (1/2 QPSK)
Payload	250B or 500B[1]
Packet transmission frequency	Between 1pkt/s and 10pkts/s
Simulation parameters	
Propagation model	Nakagami ($m = 3$)
Simulation time	400s
Simulation runs	8
Confidence interval	$< 5\%$

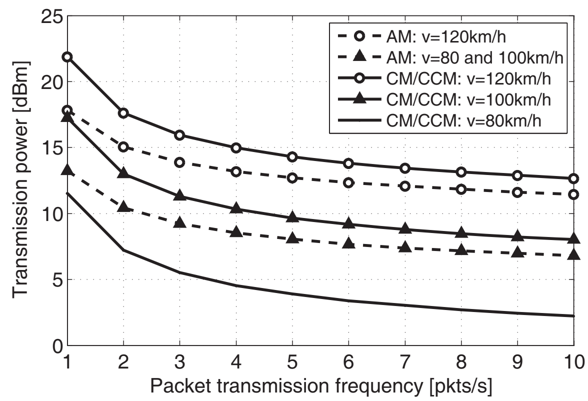

Fig. 2. CAM communications configurations that satisfy the target application's reliability p_{app} for the AM, CM and CCM modes. $TWindow = 2s$, traffic density $D_2 = 9.6$ veh/km/lane and CAM payload=250B.

[1]The mandatory fields of CAMs are around 55B [11], the security/authentication header can be around 200B, and many optional fields could also be included depending on the different applications running on each vehicle.

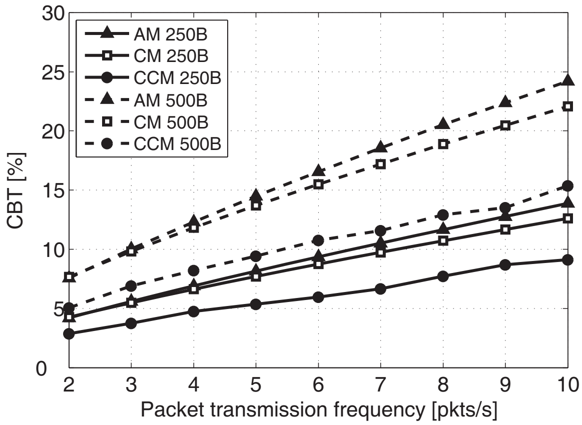

Fig. 3. Channel busy time for the CAM communications configurations that satisfy the target application's reliability p_{app}. $TWindow = 2s$, traffic density $D_2 = 9.6$ veh/km/lane and payloads of 250B and 500B. Each point in the figure corresponds to the combination of transmission frequency and power depicted in Fig. 2.

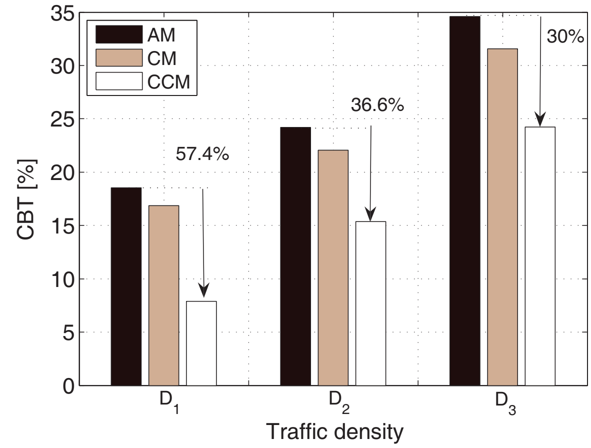

Fig. 4. Channel busy time for the CAM communications configurations that satisfy the target application's reliability p_{app} and different traffic densities. $TWindow = 2s$, transmission frequency of $10pkts/s$ and payload=500B.

frequency that allows satisfying the p_{app} requirements for the AM, CM and CCM modes despite packet collisions and propagation effects. As this figure shows, the transmission parameters used with CCM will be equal to CM if there is no vehicle ahead of vehicle A (e.g. if vehicle D is not present in the scenario depicted in Fig. 1b). If such vehicle is present, the transmission parameters will be defined following the methodology discussed in [8] so that a reliable communication between vehicles A and D can be established. As it can be observed, CM requires higher power levels than AM for speeds higher than $90km/h$. At these speeds, CM and AM are characterised by the same D_w. However, vehicles operating in the CM mode have higher individual p_{app} requirements than in AM, which results in their different power levels. On the other hand, the power level is reduced with CM for vehicles moving at $80km/h$ due to the lower D_w for the CM mode compared to AM.

The channel load can be measured by means of the channel busy time (CBT). This parameter is equal to the average fraction of time that the channel is sensed as busy. The CBT for the CAM communication configurations represented in Fig. 2 is shown in Fig. 3 for different CAM payloads. Although the x axis only represents the transmission frequency, each point in the figure corresponds to the combination of transmission frequency and power depicted in Fig. 2. As it can be observed, the channel load can be considerably reduced when adapting the transmission parameters based on the proposed contextual policy. With CCM, the channel busy time experienced can be reduced around 30% for the different transmission frequencies and payloads depicted in the figure. This is especially relevant when considering high packet transmission frequencies and payloads, since in these cases the channel busy time could almost reach the 25% common control channel occupation limit that is currently under discussion in standardization bodies [10]. It is important to note that this limit could be reached with only the lane change assistant application analysed if contextualised congestion control policies as those proposed in this letter are not employed.

The impact of the traffic density on the three operational modes is shown in Fig. 4 for a transmission frequency of $10pkts/s$. As it can be observed, the increase in the traffic density augments the CBT, but such increase can be considerably reduced with the proposed contextual congestion control policies. The figure also shows that the relative channel load reduction obtained with the proposed CCM mode is higher for lower traffic densities. The CBT reductions achieved with the CCM mode range from 19.1% to 57.4% for the different traffic densities, packet transmission frequencies and payloads analysed. These results clearly demonstrate the potential of the proposed contextual congestion control policy to reduce the control channel load by exploiting the traffic context information, and without sacrificing the application's reliability requirements.

V. Multi-Applications Extension Framework

The proposed contextual cooperative congestion control policy could also be adapted to other vehicular applications, for example, to the forward collision warning application, aimed at avoiding longitudinal collisions through the periodic exchange of broadcast messages. To avoid that all vehicles have to transmit at high powers in order to prevent forward collisions, the traffic context information could be exploited following the proposed policy. Let's consider the scenario where a given vehicle (vehicle A) could detect the presence of a vehicle behind it (vehicle B) moving at a similar speed. Vehicle A would then reduce its transmission power to that needed to communicate with vehicle B, and vehicle B would be the one transmitting with high power in order to warn high-speed vehicles that could be approaching vehicles A and B, and that could provoke a forward collision. A similar approach could be used for the intersection collision warning application in order to avoid multiple vehicles approaching an intersection to transmit with high power.

In this context, scenarios with multiple applications running simultaneously represent a challenging task that has not been properly addressed by the research community. One of the first attempts to analyse it considered the combination of application data from different applications [12]. In this context, although the development of optimized solutions is left for future research, this letter presents an initial proposal on how the described policies could be adapted to the multi-applications scenario through the definition of a novel Communications Adaptation Layer (CAL). First, the communications parameters Pt (transmission power) and R (packet transmission frequency) needed to satisfy the reliability requirements of each individual application could be obtained through the use of the policies proposed in this letter. Once such parameters are defined, CAL is then applied to combine them and result in a more efficient communications operation that avoids unnecessary interferences. A basic operation of CAL would be as follows. Let us assume that a given vehicle is running N applications, each of them with communications requirements Pt_i and R_i, with $1 \leq i \leq N$. To satisfy the different R_i requirements, the total number of packets transmitted per second by this vehicle could be $R = max(R_1, R_2, ..., R_N)$. To satisfy the Pt_i requirements of the different applications, the applications would first be ordered as a function of their transmission power requirements so that $Pt_1 \geq Pt_2 \geq ... \geq Pt_N$. Then, the transmission power of the R packets transmitted per second could be distributed as follows. To satisfy the requirements of application 1, $n_1 = R_1$ packets per second would be transmitted with Pt_1 transmission power. To satisfy the requirements of application 2, $n_2 = max(0, R_2 - n_1)$ packets would need to be transmitted with Pt_2. This results in that $n_2 = R_2 - R_1$ packets are transmitted with Pt_2 if $R_2 > R_1$, and that no packets are needed with Pt_2 if $R_2 \leq R_1$ because in this case the requirements of application 2 would be satisfied with the R_1 packets transmitted with Pt_1. In general, to satisfy the requirements of application k, $n_k = max(0, R_k - n_{k-1} - n_{k-2} ... - n_1)$ packets would need to be transmitted per second with Pt_k. Following this distribution process for the N applications, at least R_i packets per second would be transmitted with a power equal or higher than Pt_i, and therefore the application requirements of the N applications could be satisfied.

VI. Conclusions

This letter proposes a contextual cooperative congestion control policy that exploits the traffic context information of each vehicle to reduce the communications channel load without sacrificing the traffic application's reliability. With the proposed policy, vehicles cooperate and are able to reduce unnecessary interferences by exploiting the knowledge of the traffic context obtained through the periodic exchange of broadcast messages. Considering the lane change assistance application, the proposed contextual policy can achieve channel load reductions ranging from 19.1% to 57.4% compared with autonomous congestion control techniques for the different parameters and traffic conditions analysed. In addition, this letter has proposed a framework to extend the proposed policy to multi-application scenarios through the design of a novel communications adaptation layer.

References

[1] M. Torrent-Moreno *et al.*, "Vehicle-to-vehicle communication: fair transmit power control for safety-critical information," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3684-3703, Sep. 2009.

[2] S. Rezaei *et al.*, "Reducing the communication required by DSRC-based vehicle safety systems," in *Proc. IEEE ITSC*, pp. 361-366, Oct. 2007.

[3] H. Ilhan, *et al.*, "Cooperative diversity for relay-assisted inter-vehicular communication," in *Proc. IEEE VTC-Spring*, pp. 605-609, May 2008.

[4] L. Zhou, *et al.*, "Cross layer rate control, medium access control and routing design in cooperative VANET," *Computer Commun.*, vol. 31, no. 12, pp. 2870-2882, July 2008.

[5] T. Kosch *et al.*, "The scalability problem of vehicular ad hoc networks and how to solve it," *IEEE Wireless Commun.*, vol. 13, no. 5, pp. 22-28, Oct. 2006.

[6] H. Ching-Ling *et al.*, "Analysis of aggregated power level and rate-power control designs for status update messages in VANETs," in *Proc. IEEE MASS*, pp. 615-620, Oct. 2009.

[7] F. Bai *et al.*, "Reliability analysis of DSRC wireless communication for vehicle safety applications," in *Proc. IEEE ITSC*, Toronto, Canada, pp. 355-362, Sep. 2006.

[8] M. Sepulcre and J. Gozalvez, "Wireless vehicular adaptive radio resource management policies in congested channels," in *Proc. IEEE ISWCS*, Norway, pp. 380-384, Oct. 2007.

[9] *Highway Capacity Manual*, Transportation Research Board, Washington, DC, 2000.

[10] ETSI TC ITS, "Harmonised channel specifications for intelligent transport systems operating in the 5 GHz range," ETSI TS Draft DTS/ITS-0040016 v0.0.3, June 2009.

[11] COMeSafety consortium, "D31: European ITS communication architecture: overall framework proof of concept implementation," COMeSafety Public Deliverable, Mar. 2009.

[12] C. Robinson *et al.*, "Efficient message composition and coding for cooperative vehicular safety applications," *IEEE Trans. Veh. Technol.*, vol. 56, no. 6, pp. 3244-3255, Nov. 2007.