A Performance Study of Cooperative Awareness in ETSI ITS G5 and IEEE WAVE

David Eckhoff*, Nikoletta Sofra† and Reinhard German*
* Computer Networks and Communication Systems, Dept. of Computer Science, University of Erlangen, Germany
† Audi Electronics Venture GmbH, Gaimersheim, Germany
{eckhoff, german}@cs.fau.de, nikoletta.sofra@audi.de

***Abstract*—The idea of wirelessly connected vehicles has long ceased to be a vision as researchers from both academic and industrial institutions and field operational tests all over the world are contributing to bringing this technology to life. Both ETSI and IEEE have been working on respective standards (ETSI ITS G5 in Europe, IEEE WAVE in North America) to enable this new application of wireless communication. In this paper we compare medium access in these systems by means of an extensive simulation study while focusing on the transmission of periodic safety messages on the control channel.**

We observe that for different reasons high node density scenarios appear to be critical for the overall performance of both systems. This includes end-to-end delay, packet error rates and a non-optimal channel utilization that leaves room for improvement. We find that the approach proposed by ETSI ITS G5 with Decentralized Congestion Control (DCC) may access the channel rather conservatively but still outperforms IEEE WAVE in most of the scenarios.

I. Introduction

Because of their unique characteristics, vehicular networks can not simply be realized using already existing technology but pose a challenge to both academic and industrial researches alike. Highly dynamic topologies, high relative speeds and thereby short connection times, but yet a seemingly large resource of power make vehicular networks more than just a special application of MANETs. They require new protocols and mechanisms and a standard to guarantee interoperability among all vehicles in this so called Intelligent Transportation System (ITS).

ETSI in Europe and the IEEE in North America follow similar, but not identical approaches in standardizing the wireless communication to enable information exchange not only between vehicles but also between vehicles and infrastructure. These efforts aim to provide the underlying technologies that will facilitate increased traffic safety, ensure the reliability of Intelligent Traffic Systems and provide a platform for further vehicular networks applications. While both standards cover almost all aspects of vehicular networks, this work focuses on the Medium Access Control (MAC) and Physical Layer (PHY), as they can be seen as the basis of the communication architecture and the efficiency of the respective algorithms strongly affects the performance of the whole system. Without properly working congestion control and fair channel access, the functionality of both safety and comfort applications can be compromised.

Different channels in the 5.9 GHz band have been reserved in Europe and North America. Wireless Communication in this 5.9 GHz band has been standardized in the IEEE 802.11p [1] standard, on which both ETSI ITS G5 and IEEE Wireless Access in Vehicular Environments (WAVE) are based. However, there are differences in the ways the standards use to access the channel and address its usage. While IEEE WAVE uses an alternating access scheme [2] with Enhanced Distributed Channel Access (EDCA) subsystems for each respective channel type, ITS G5's approach includes model consisting of state machines and different tunable parameters to control medium access of all nodes [3].

We take a closer look at both standards and evaluate their performance in an extensive simulation study, giving valuable information about possible flaws and bottlenecks. The fact that both standards have not been fully finalized yet increases the relevance of our findings even more.

Our contribution can be summarized as follows: We examine both approaches and compare them in terms of channel usage, congestion of the wireless medium, and metrics that show potential impact on safety and non-safety applications. We also identify noteworthy side effects in both systems with a special focus on ETSI ITS G5 and outline advantages and disadvantages of both systems.

II. Related Work

Performance evaluation of medium access mechanisms in vehicular networks has been a hot topic for years. In 2007 Eichler et al. identified problems with an earlier version of WAVE and found that the collision probability is even higher for high priority access categories [4]. They also came to the conclusion that especially in dense scenarios the periodic switching between channels can lead to long message queues and higher delays. However, realistic node movement and road topologies were not considered and there was no further investigation on packet error rates depending on the distance between two nodes – something that is of high importance when it comes to safety in vehicular networks.

Among others [5], [6], Chen et al. confirmed these findings and gave additional insights on the reception probabilities depending on the physical distance between nodes [7]. While their configuration of the physical layer (Transmit Power, Sensitivity, Fading) was simplified and not based on real

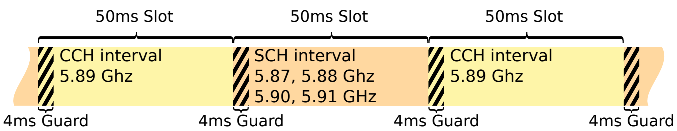


Figure 1: WAVE's Alternating Access Scheme changing the operation frequency of the radio periodically

measurements or hardware, they highlight important issues that come with the IEEE 1609.4 standard.

Kloiber et al. showed that depending on the beacon frequency, the update delay, that is the delay between two decodable messages from the same sender, can exceed values where safety applications can no longer function [8], [9]. While their study was based on ITS G5 MAC layers and the transmission of Cooperative Awareness Messages (CAMs) they could not include the Decentralized Congestion Control (DCC) state machine at this point in time. We use a derived metric of their *update delay* in order to quantify the extent to which safety functions are influenced by packet loss.

Subramanian et al. also compare ITS G5 with WAVE and give valuable input on how to improve channel access in vehicular environments [10]. We confirm some of their findings but not all. The reason for this that our parametrization of the physical channel is closer to real hardware when it comes to transmission ranges (and fading) or carrier sense thresholds. Also, the configuration of the DCC state machine seems to differ from the current values suggested by the standard. Lastly, it is unclear whether realistic mobility models were used to simulate both MAC layer models.

In summary, although various performance evaluations of IEEE 802.11p based systems exist, we are not aware of a study of similar extensiveness as this work, while at the same time focusing on the comparative evaluation of the published standardized algorithms and employing realistic mobility models and wireless channel parameters.

III. IEEE 1609.4, IEEE 802.11p and ETSI ITS G5

In 2004 the IEEE started work on the standardization of the WAVE architecture. The MAC and PHY layers are specified in the IEEE 1609.4 [2] and IEEE 802.11p [1] standards. The envisioned European system ETSI ITS G5 is similar: it also makes use of a IEEE 802.11p PHY Layer, however, it specifies own algorithms for medium access.

IEEE WAVE allows nodes to transmit and receive messages on different channels (i.e. the Control Channel (CCH) and one of the Service Channels (SCHs)) without the need for a dual transceiver system, by means of a method called alternating access as shown in Figure 1.

Nodes may synchronously change their radio frequency in 50 ms intervals with every second interval being a CCH interval. In the remaining intervals the radio can be tuned to an arbitrary service channel. It has been shown that the probability of packet loss at the beginning of a CCH, or SCH interval respectively, is much higher [5].

Alternating Access directly leads to the conclusion that the Control Channel (and thus the transmission of broadcast safety messages) can only be utilized half of the time. While the available bandwidth for safety messages decreases by more than 50 %, benefits include the deployment of a single transceiver system that can potentially support more applications and the fact that safety messages do not have to compete against messages transmitted on the service channels.

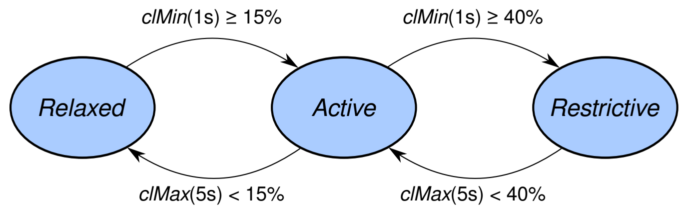


Figure 2: DCC state machine for the Control Channel

Table I: ETSI ITS G5 settings for the DCC state machine for the CCH

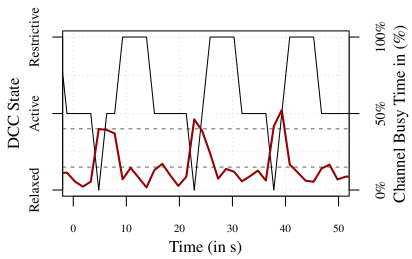
	State					
	Relaxed	Active				Restrictive
		Access Category				
		VI	VO	BE	BK	
Power [dBm]	33	ref	25	20	15	-10
Interval [s]	0,04	ref	ref	ref	ref	1
Rate [Mbit/s]	3	ref	ref	ref	ref	12
Sens. [dBm]	-95	ref	ref	ref	ref	-65

One of the main differences in ITS G5 is that there is no alternating access scheme; while this would increase the cost for an onboard unit supporting both applications running on the CCH and SCHs, it eliminates the packet loss caused by synchronization effects after channel switching and utilizes the available bandwidth for the transmission of safety messages.

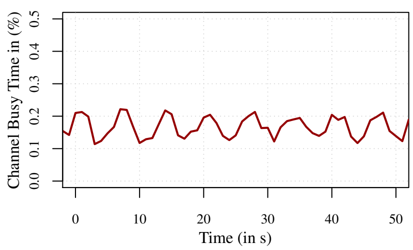
In IEEE WAVE and ETSI ITS G5 channel access and prioritization is managed by the use of EDCA (with slightly different parameterization). The idea is that packets do not only compete for channel access with packets from other vehicles but also internally with packets from the same node. Each packet can have one of four possible access categories (VO, VI, BE, BK). For each access category and channel type (CCH, SCH) there is one transmit queue resulting in a total of eight queues. Internal congestion control is performed separately for two groups of packets: those scheduled for SCHs and those scheduled for the CCH, respectively.

Additionally, ETSI ITS G5 deploys a system called Decentralized Congestion Control (DCC), which is supposed to dynamically adapt to channel conditions by changing certain parameters of the MAC and PHY, such as the transmit power, the minimum packet interval, the data rate and the sensitivity of the radio. The radio sensitivity defines the signal level that determines whether the channel is treated busy or idle.

The core of DCC is a state machine that changes its state (and with it MAC and PHY parameters, cf. Table I) depending on the observed busy time of the medium, with 15 % and 40 % being the recommended thresholds for the CCH. Figure 2 shows the state machine for the CCH with its one designated *Active* state.While the states *Relaxed* and *Restrictive* do not change settings for each access category separately, transmit power settings in the *Active* state affect access categories

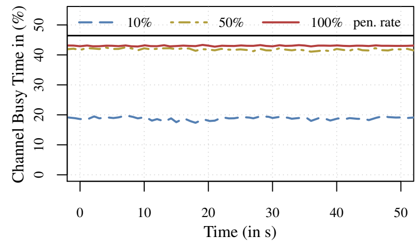


(a) DCC state (black line) and channel load (red line) for a random vehicle

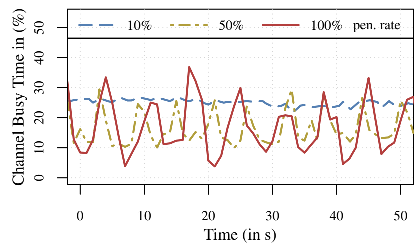


(b) Average Channel load of all vehicles

Figure 3: Local and Global Oscillation caused by ITS G5 DCC's state machine over a 50 s window

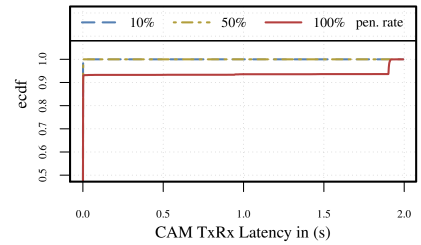


(a) Average Channel load of all vehicles, IEEE WAVE

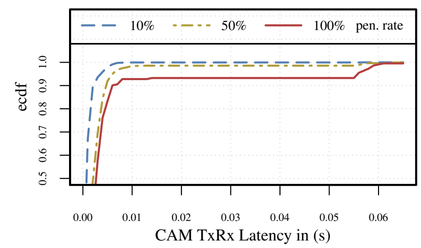


(b) Average Channel load of all vehicles, ITS G5

Figure 4: Channel load: motorway junction, medium traffic density, different penetration rates



(a) ITS G5, traffic circle, high traffic density, traffic circle



(b) WAVE, freeway, high density

Figure 5: End-to-end Delay: time from the creation of the CAM until successful reception

Table II: Simulation settings

Parameter	Value
Scenarios	{freeway, motorway junction, traffic circle, Grid, city}
Path loss	Two-Ray-Interference [15] Obstacle Shadowing
Traffic Density	{low, medium, high}
Penetration rate	{10%, 50%, 100%}
Run-Time	500 s - 1000 s
Transmission Range	Path loss (≈ 900 m)
CAM frequency & AC	10 Hz, AC_VO
CAM Size	210 Byte (+125 Byte Certificate)

differently. A `ref` value means that this parameter is not changed after a transition into the respective state.

In both ETSI ITS G5 and IEEE WAVE all vehicles periodically transmit broadcast messages containing information about their current state, such as location, speed or heading [11]. In ITS G5 these messages are called CAMs (or Basic Safety Message (BSM) for WAVE [12]) and are to be broadcast with a frequency of 1–10 Hz [11] (WLOG we refer to both messages as CAMs in this paper). To allow for direct comparison we assume same message sizes in both systems and a static frequency of 10 Hz to examine the worst case scenario as far as channel load is concerned.

IV. Evaluation

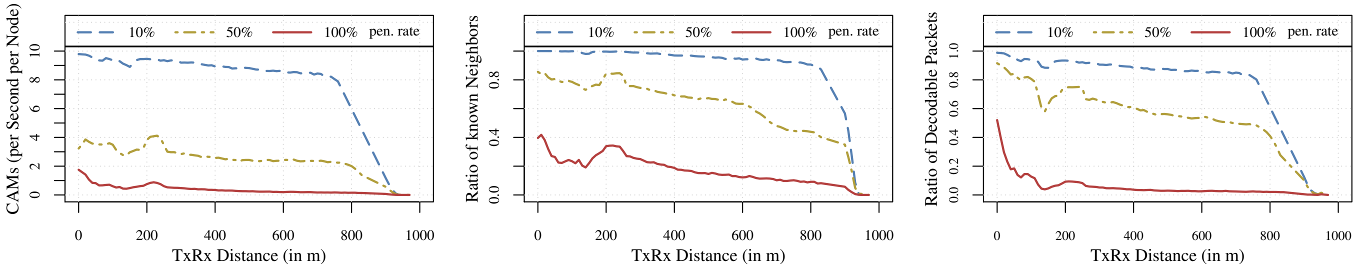
We extended the Veins framework [13] by adding complete IEEE 802.11p and ETSI ITS G5 MAC and PHY models [5]. Some of them are publicly available and are already in use by the research community, allowing to make simulation studies more comparable as this is still a significant issue in the field of vehicular network simulation [14].

A complete overview of our simulation parameters can be found in Table II. We have simulated every possible permutation of the listed parameters but – due to space constraints – we will only highlight the most significant simulation scenarios and findings. Settings for DCC, Queue and CAMs were taken from the corresponding ETSI standards [3], [11], [16] at the time of writing. Traffic densities were chosen to cover possible real traffic conditions from free-flowing to slow-moving traffic but no gridlocks.

A. Channel load measurements

Throughout all scenarios we observed that with high enough node density and penetration rate the DCC state machine oscillated between its states, as illustrated in Figure 2a (moving traffic, ≈ 170 vehicles/km, 100 % penetration rate). The state machine continuously switches its states from *Relaxed* over *Active* to *Restrictive* and back, the switching intervals approaching the minimum delay necessary for a state transition. These transitions instantly affect the channel load causing the system to go into a loop as long as the observed channel load repeatedly exceeds the channel load threshold.

Interestingly, this oscillation does not only take place in a local context but also on a global scale (see Figure 2b). Within a cluster of connected vehicles, nodes tend to synchronize their DCC state transitions, causing the globally observed channel load to periodically increase and decrease. The reason for this lies within the parametrization of the different DCC states: we find the *Restrictive* state to have a large influence on the medium access of a node, reducing the number of possible packets to one per second and also changing the transmit power to a value of −10 dBm. Vehicles in *Restrictive* state hardly try to access the channel anymore at all, possibly

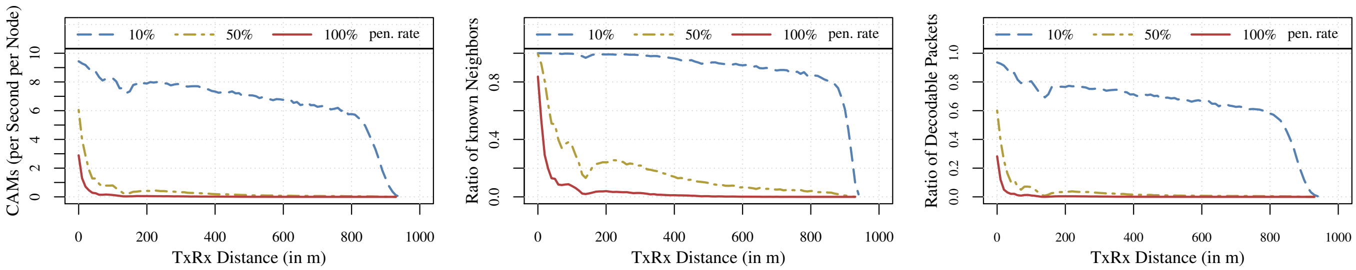


(a) CAMs per second per neighbor

(b) Ratio of known neighbors

(c) Packet delivery rate

Figure 6: Packet Delivery Rate Metrics, Motorway Junction, High Traffic Density, Different Penetration Rates, ITS-G5



(a) CAMs per second per neighbor

(b) Ratio of known neighbors

(c) Packet delivery rate

Figure 7: Packet Delivery Rate Metrics, Motorway Junction, High Traffic Density, Different Penetration Rates, WAVE

rendering them temporarily invisible to other vehicles.

As a next step we compared the channel load measurements for both systems to better understand how the MAC layer mechanisms affect the channel conditions. Figure 4 shows our findings for the 3-lane motorway junction scenario with a medium vehicle density ($\approx$ 50 vehicles/km^2).

Naturally, the channel load for the WAVE system does not exceed 46 % due to synchronous channel switching. (50 % SCH + 4 % CCH guards). However, the remaining channel capacity is almost fully utilized with high enough node density and remains at a steady level. Observed channel busy times for the ETSI ITS G5 system show a substantially different behavior (Figure 3b). While at a low penetration rate the curve is almost a straight line at about 25 %, the channel load increasingly oscillated with higher penetration rates due to the reasons mentioned above. Although the full channel capacity is available, DCC does not efficiently utilize the available bandwidth at higher penetration rates. The average channel load observed at high penetration rates was lower than when only 10 % of all vehicles were equipped with onboard units.

Safety applications depend on the freshness of data in order to function in a reliable and robust way. We compared both systems in terms of end-to-end delay, that is the latency between creation of a CAM at the sender and successful decoding at the MAC of the receiver. This delay includes the time the packet spent in the MAC layer of the sender, the more or less negligible airtime and no additional processing time.

We plot the ECDF for the measured latency in a traffic circle at high traffic density ($\approx$ 100 vehicles) area and observe that almost 10 % of all packets received in the high penetration rate scenario are older than 1.9 s, a value which might compromise safety applications [17]. We chose the traffic circle to illustrate that these effects already occur in simple city scenarios; latencies on clogged freeways were higher and also observable in the Manhattan and city scenarios. Different policy and scheduling strategies (no FIFO tail drop) are expected to have significant impact on the observed end-to-end delay.

While packet loss was much higher in the WAVE system it can be said that successfully transmitted data was substantially more up-to-date (Figure 4b). The highest latencies we observed were around 60 ms and thereby still in a range useful to safety applications [17]. These latencies result from a congested wireless channel, forcing nodes to go into backoff and often making it impossible to send a packet in the current Control Channel (CCH) interval.

B. *Packet delivery rates*

As a second step we investigated packet error rates and their effect on cooperative awareness and the ratio of known neighbors of a vehicle. We plot these metrics against the TxRx distance, that is, the distance between sender and receiver, so that the combined effect of path loss and channel congestion can be evaluated. With regard to safety applications, it is potentially critical to miss CAMs, and therefore location and driver behavior updates, as the estimation becomes less accurate the later the next packet arrives. Receipt of regular updates is especially important for close-by vehicles.

In Figure 6 and Figure 7 we compare our findings for the motorway junction scenario with a high traffic density ($\approx$ 115 vehicles/km^2) for both ETSI ITS G5 and WAVE. Plotted are the average values for all vehicles that are possibly in communication range.

In Figure 6a it can be seen that while ITS G5 performs well at a low penetration rate the number of CAMs received by other nodes per second drops below 50 % for the medium penetration rate. This results in an average update delay of 250 ms and a worst case update delay of over 1 s. A penetration rate of 100 % amplifies this problem as the channel becomes more congested, forcing nodes to go into the *Restrictive* state.

When comparing this to the performance of the WAVE system (Figure 7a) we observe a deterioration in performance. Already at low penetration rates we observe packet loss, and thus an increasing update delay between vehicles. As soon as we increased the penetration rate the channel became fully congested and transmitting to nodes further away than 100 m was almost impossible. However, at very low distances, more CAMs per neighbor could be received, mainly because of the non down-regulated sending frequency.

In Figure 6b and Figure 7b we compare the ratio of known neighbors, that is the number of vehicles from which a node successfully received a message within 1 s over the number of vehicles from which reception was theoretically possible. We observe that ETSI ITS G5 performs better than WAVE at higher penetration rates but has problems even at low distances with only $\approx 40\,\%$ of vehicles visible to the radio receiver.

Interestingly, the reason for the low amount of visible neighbors and received CAMs is not the same for the ITS G5 and WAVE systems. While Figure 7c clearly shows that in WAVE these effects are caused by packet loss (compare to Figure 7a), the ITS G5 system still has a high ratio of decodable packets at the medium penetration rate. From this it follows that *if* nodes sent packets, there was a high probability that they could be decoded by the receiver. However, the DCC parameters seem overly conservative, forcing nodes to considerably reduce their sending frequency (by increasing the minimum packet interval) although the wireless channel may still have sufficient capacity.

In summary it can be said that the road topology did not have a substantial effect on the observed channel conditions, it merely affected the number of transmitting vehicles necessary to cause the observed problems. Throughout all scenarios, we discovered that – at higher penetration rates – realistic, usual traffic densities were sufficient to cause critical performance issues for both WAVE and ITS G5.

V. Conclusion and Future Work

In this paper we studied the upcoming systems IEEE WAVE and ETSI ITS G5 and their ability to handle high node densities, high penetration rates and the resulting channel congestion. We carried out extensive simulations with focus on a realistic simulation setup to better understand and to evaluate their performance.

We confirmed earlier findings that alternating access of IEEE 1609.4 causes problems by reducing the available bandwidth by more than a half and by introducing synchronization effects at interval borders. Decentralized Congestion Control in ETSI ITS G5 was evaluated with the current parameter set suggested in the standard. The mechanism improves the overall system performance to some extent, but introduces new effects, such as the local and global oscillation of the state machine.

Throughout all scenarios we observed that the ratio of known neighbors and the amount of received Cooperative Awareness Messages (CAMs) drops considerably when the penetration rate increases. In WAVE this is caused by collisions on the channel while in ITS G5 the reason for this are strict restrictions placed by the state machine, hindering vehicles from trying to access the wireless channel and in some cases also increasing the End-To-End delay.

References

[1] "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments," IEEE, Standard 802.11p-2010, 2010.

[2] Intelligent Transportation Systems Committee, "IEEE Trial-Use Standard for Wireless Access in Vehicular Environments (WAVE) - Multichannel Operation," IEEE, Tech. Rep., February 2011.

[3] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part," Tech. Rep. ETSI TS 102 687 V1.1.1, July 2011.

[4] S. Eichler, "Performance evaluation of the IEEE 802.11p WAVE communication standard," in *VTC2007-Fall*, Baltimore, MA, October 2007, pp. 2199–2203.

[5] D. Eckhoff, C. Sommer, and F. Dressler, "On the Necessity of Accurate IEEE 802.11p Models for IVC Protocol Simulation," in *VTC2012-Spring*, Yokohama, Japan, May 2012.

[6] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein, "Vehicle-to-Vehicle Communication: Fair Transmit Power Control for Safety-Critical Information," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 7, pp. 3684–3703, September 2009.

[7] Q. Chen, D. Jiang, and L. Delgrossi, "IEEE 1609.4 DSRC Multi-Channel Operations and Its Implications on Vehicle Safety Communications," in *VNC 2009*. Tokyo, Japan: IEEE, October 2009, pp. 1–8.

[8] B. Kloiber, T. Strang, M. Röckl, and F. de Ponte-Müller, "Performance of CAM Based Safety Applications Using ITS-G5A MAC in High Dense Scenarios," in *IV'11*, Baden-Baden, Germany, June 2011, pp. 654–660.

[9] B. Kloiber, T. Strang, F. de Ponte-Müller, C. Garcia, and M. Röckl, "An Approach for Performance Analysis of ETSI ITS-G5A MAC for Safety Applications," in *ITST'10*, Kyoto, Japan, November 2010.

[10] S. Subramanian, M. Werner, S. Liu, J. Jose, R. Lupoaie, and X. Wu, "Congestion Control for Vehicular Safety: Synchronous and Asynchronous MAC Algorithms," in *VANET 2012*. Low Wood Bay, Lake District, UK: ACM, June 2012, pp. 63–72.

[11] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service," Tech. Rep. ETSI TS 102 637-2 V1.1.1, April 2010.

[12] SAE Int. DSRC Committee, "DSRC Message Communication Minimum Performance Requirements: Basic Safety Message for Vehicle Safety Applications," SAE, Draft Std. J2945.1 Revision 2.2, April 2011.

[13] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," *IEEE Transactions on Mobile Computing*, vol. 10, no. 1, January 2011.

[14] S. Joerer, F. Dressler, and C. Sommer, "Comparing Apples and Oranges? Trends in IVC Simulations," in *VANET 2012*. Low Wood Bay, Lake District, UK: ACM, June 2012, pp. 27–32.

[15] C. Sommer, S. Joerer, and F. Dressler, "On the Applicability of Two-Ray Path Loss Models for Vehicular Network Simulation," in *VNC 2012*. Seoul, Korea: IEEE, November 2012, pp. 64–69.

[16] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band," Tech. Rep. ETSI ES 202 663 V1.1.0, November 2009.

[17] Q. Xu, R. Segupta, and D. Jiang, "Design and Analysis of Highway Safety Communication Protocol in 5.9 GHz Dedicated Short Range Communication Spectrum," in *VTC2003-Spring*, vol. 4. Jeju, Korea: IEEE, April 2003, pp. 2451–2455.