Simulation-based Performance Evaluation of Enhanced Broadcast Schemes for IEEE 802.11-based Vehicular Networks

Yvonne Mertens, Matthias Wellens and Petri Mähönen
Department of Wireless Networks, RWTH Aachen University
Kackertstrasse 9, D-52072 Aachen, Germany
Email: {yme, mwe, pma}@mobnets.rwth-aachen.de

***Abstract*—Car-to-car communication (C2CC) enables cars to exchange information that can be used to, e.g., improve the drivers' safety or comfort. Recently, WLANs based on the IEEE 802.11 family of standards have been identified as promising communication technology for C2CC. Often, the information exchange between vehicles is of interest for all nearby vehicles so that the communication should be broadcast-based. However, such use cases have not been considered when the IEEE 802.11 systems have been initially designed and a significant scalability problem exists in broadcast scenarios. We present the reasons for this problem and propose several algorithms for dynamic protocol parameter adaptations. Our simulation-based evaluation shows that the suggested enhancements clearly improve the scalability of IEEE 802.11-based systems in vehicular scenarios without changing the main protocol characteristics.**

I. Introduction

During the past decades there has been a rapid evolution of electronic systems embedded into common vehicles. Nowadays, the requirements that a car has to meet do not only include transportation but a wide range of applications which should increase the driver's comfort and safety. An important contribution to this aim is to increase the driver's range of awareness. Via car-to-car communication (C2CC) the driver is able to obtain additional information about the current traffic situation, potential dangers or weather conditions collected by other vehicles. Since most of the gathered information is of interest for all nearby vehicles many concepts for vehicular networks assume that this information dissemination is accomplished by broadcasting the relevant messages periodically [1].

Extensive research has been conducted in order to identify a wireless technology which is suitable to enable C2CC. In recent years the IEEE 802.11 WLAN standard has emerged as a promising candidate. In consequence, the upcoming IEEE 802.11p standard is focused to solve the particular difficulties that might arise within a vehicular network [2]. However, since the standardization process for IEEE 802.11p is still ongoing the suitability of other IEEE 802.11 standards within a vehicular network is of high interest, especially as a basis for contemporary C2CC deployment applications.

Several researchers have performed measurements to investigate the performance of existing IEEE 802.11 hardware in vehicular scenarios [3]–[8]. However, all of them were focused on the performance of few links and did not study the scalability of such systems. The broadcast-scenario was addressed in [9] with a focus on how safety-related broadcast messages could be prioritized. In [10] the authors used a static measurement setup in order to evaluate the impact of physical layer capture. The scalability of broadcast-based communication was mostly addressed in the context of higher layer protocols such as in [11] and [12]. Both works present approaches how the amount of information that is forwarded on application layer can be limited. Such techniques reduce the amount of transferred data and thus increase the scalability of the system but do not consider the MAC-protocol.

In this work we will focus on the shortcomings of the original IEEE 802.11 standard implementation with respect to a broadcast-based vehicular network. We discuss the scalability problem and propose feasible enhancements to overcome these constraints. Our simulations show that a combination of the proposed MAC contention window (CW) size adaptation and the dynamic physical layer data rate selection clearly improves IEEE 802.11-based systems in the vehicular context.

The remainder of the paper is structured as follows. In section II we discuss the reasons why IEEE 802.11-based systems do not scale well for broadcast-based communication. We propose several algorithms to cope with these shortcomings in section III and evaluate those using simulations in section V after introducing our simulation environment in section IV. We conclude the paper in section VI.

II. Scalability-problem of IEEE 802.11-based systems in broadcast mode

In classical IEEE 802.11-based networks the broadcast mode is only used for management and control frames, e.g., association frames sent during the network formation [13]. In order to reach the highest possible probability to successfully receive such important management frames they are always sent using a data rate out of the basic rate set, for instance 6 Mbps in the case of IEEE 802.11g or 3 Mbps in the case of IEEE 802.11p. This cautious rate selection is also motivated by the fact that several main features of the IEEE 802.11 MAC protocol that enhance the robustness of the data transmissions cannot be applied to broadcast messages:

The receiver will acknowledge unicast frames after successful frame reception. However, in the case of broadcast frames no single node is addressed so that all nodes in the surroundings would acknowledge the frame and multiple acknowledgements (ACKs) would collide at the transceiver of the initially sending node.

Additionally, the fact that no single device is addressed precludes the nodes also from using further protocol functions, which require specific feedback, such as retransmission schemes, the Request-To-Send/Clear-To-Send (RTS/CTS) control frames to lower the impact of the hidden-node problem, or the binary exponential backoff [13].

Furthermore, most of the automatic rate selection algorithms, which aim at selecting the most appropriate physical layer transmission rate, are also not applicable without the required feedback in terms of ACKs. Such rate adaptation algorithms are not defined in the initial standard [14] but applied by all nowadays used device drivers [15], [16].

The lack of all these countermeasures and features leads to a severe scaling problem of IEEE 802.11 networks in the case mostly broadcast traffic is sent. No participating node is aware of the network load or has any standardized way to measure it. Therefore, no parameter adaptation will take place in the case of network overload and in consequence thereof the probability of frame collisions will significantly increase. Scenarios focused on broadcast-based communication were not considered during the initial protocol design so that appropriate extensions have to be developed before IEEE 802.11 systems can be efficiently used in vehicular scenarios.

III. Proposed enhancements

In this paper we concentrate on two methods to enhance the scalability of IEEE 802.11-based vehicular networks: The dynamic adaptation of the CW size and a context-sensitive selection of the physical layer data rate to be used for the next frame. Proposals to apply power control [1] for congestion control in vehicular networks are not considered here.

It is important to note that one of our primary goals was, in contrast to approaches presented in [17], to avoid profound modifications to the original IEEE standard. This ensures simpler integration with existing solutions and unicast-based applications such as providing Internet-access to car occupants via access points.

A. Adaptation of the MAC-layer contention window size

In literature it was shown that also in the standard unicast mode the protocol parameter CW_{min} (contention window minimum) should be chosen based on the network size [18]. Such ideas can also be adapted to the broadcast case.

We differentiate three approaches how the new CW size could be determined. All of them assume that a node keeps track of all nodes in one hop distance in a simple neighbour table[1]. If a frame with a new source address is received a corresponding entry is added to the table. The decision when to delete a node from the neighbour table is based on a timeout T_i during which no further frame was received from node i in the table:

$$T_i = \begin{cases} \min(\frac{range(R)}{v}, 4\,\text{s}), & \text{if } v > 0 \text{ km/h} \\ 4\,\text{s}, & \text{if } v = 0 \text{ km/h} \end{cases}, \quad (1)$$

where *range*(R) is the communication range of the currently used data rate R, which should be taken from a predetermined table in a real-life implementation[2]. Additionally, we assume that the entity dealing with the CW size adaptation has access to the current velocity v of the vehicle. The timeout tries to estimate how quick the network topology will change although it is only a rough estimation especially because velocity and direction of the other cars are not considered. It is limited to a maximum of four seconds.

1) Packet error rate based adaptation: As discussed at the beginning of this paper applications in a vehicular scenario are very often based on periodic transmissions of status information. Therefore, a vehicle will periodically receive a data frame from every other vehicle in its surroundings. We assume here that the CW size adaptation implementation knows the application layer transmission rate *ALR* via cross-layer mechanisms. If the *ALR* is not fixed throughout the network this information will have to be included in the packets' payloads. Based on the neighbour table and the *ALR* our first proposed method estimates a packet error rate (*PER*) for each node in the surroundings.

Denote $\overline{PER}$ as the average *PER* over all entries in the neighbour table. Usually, $\overline{PER} > 8\,\%$ is assumed to be unacceptable [20]. Therefore, the *PER* based approach adapts the CW with the goal $5\,\% \leq \overline{PER} \leq 8\,\%$:

$$CW_{t+1} = \min(2 \cdot CW_t, CW_{max}), \quad \text{if } \overline{PER_t} > 0.08. \quad (2)$$

$$CW_{t+1} = \max(CW_t/2, CW_{min}), \quad \text{if } \overline{PER_t} < 0.05, \quad (3)$$

$$CW_{t+1} = CW_t, \qquad \textit{otherwise}. \quad (4)$$

2) Estimation of the theoretically optimal contention window size: In [18] an optimal CW value for a given number of nodes is derived for the unicast case. We adapted the Markov chain based argumentation to the simpler broadcast case and determined the optimal CW based on the number of entries in the neighbour table n and the average number of time slots T_c a single transmission takes:

$$CW^*_{t+1} \approx n_t\sqrt{2T_c} - 1. \quad (5)$$

The advantage of this approach is its independence of the *ALR*. Hence, no cross-layering is needed. However, the derivation is based on the assumption that each node always has a packet to send, which will not be the case in scenarios with low values for the *ALR*.

3) Combined method: The third approach can be seen as combination of the two presented methods. The main idea is to calculate the CW size according to (5) but to refine the CW size with respect to the observed $\overline{PER}$. The algorithm calculates a basic CW size each time n changes. Afterwards,

[1] We assume that each node is able to differentiate nodes participating in the C2CC and other WLAN devices.

[2] Such a table could be based either on measurements such as presented in [5], [6], [8] or on theoretical calculations such as discussed in [19].

as long as n stays constant the CW size will be further increased or decreased by one percent, depending on the current $\overline{PER}$. As soon as n changes, the basic CW size will be recalculated. However, the new value will only be adopted if it exceeds the previous value in the case n increases, or otherwise if it is lower than the old value provided a decreasing n. Altogether, the new CW size is determined as follows:

$$CW_{t+1} = \left\lceil n\sqrt{2T_c}+1 \right\rceil, \quad \text{if } n_t > n_{t-1} \wedge CW_{t+1} > CW_t, \quad (6)$$

$$CW_{t+1} = \left\lceil n\sqrt{2T_c}-1 \right\rceil, \quad \text{if } n_t < n_{t-1} \wedge CW_{t+1} < CW_t, \quad (7)$$

$$CW_{t+1} = CW_t + \left\lceil \frac{CW_t}{100} \right\rceil, \quad \text{if } n_t = n_{t-1} \wedge \overline{PER_t} > 0.08, \quad (8)$$

$$CW_{t+1} = CW_t - \left\lceil \frac{CW_t}{100} \right\rceil, \quad \text{if } n_t = n_{t-1} \wedge \overline{PER_t} < 0.05, \quad (9)$$

$$CW_{t+1} = CW_t, \qquad \textit{otherwise}. \quad (10)$$

B. Selection of the data rate

In the case of network congestion it was shown that the deployed data rate has significant impact on the network performance [21], [22]. In a vehicular network the communication range is usually one of the most important metrics because a larger range often results in a higher number of nodes that can decode the broadcasted frame. Therefore lower data rates are preferable because they lead to higher communication ranges. Channel congestion is an exception because a high probability of collisions will lower the reception rates also for lower data rates. We propose to increase the data rate to improve the network capacity and lower the probability of collision in the case of high network load.

We estimate the channel load L_c as a summation of the load generated by all nodes $i = 1 \ldots n$ in the surroundings. The load generated by node i is based on the average packet transmission time $T_{p,i}$, which includes all required interframe spaces, and the $ALR(i)$:

$$L_c = \sum_{i=1}^{n} ALR(i) \cdot T_{p,i}. \quad (11)$$

We increase or decrease the data rate R in the case L_c crosses certain thresholds [21]:

$$R_{t+1} = \min(inc(R_t), R_{max}), \quad L_c > 0.8, \quad (12)$$

$$R_{t+1} = \max(dec(R_t), R_{min}), \quad L_c < 0.6. \quad (13)$$

IV. Simulation Environment

All simulations presented here were conducted with the Qualnet v4.0 network simulator [23] extended by implementations for the proposed dynamic adaptations. Furthermore, we made a number of adjustments in order to provide a realistic vehicular environment for the evaluation of our algorithms. We chose the IEEE 802.11g standard for simulation. As Qualnet does not provide a model for this standard, we adjusted the IEEE 802.11a parameters to meet the requirements of IEEE 802.11g. We did not use IEEE 802.11p, the standard foreseen for vehicular networks [2], since its characteristics are not fully specified, yet. In vehicular scenarios the mobility model is of special interest [24]. We based the mobility in our simulations on the SUMO model [25], [26], which provides a realistic approximation of the characteristics of car traffic in urban scenarios. Table I gives an overview of the main parameters used for simulation.

TABLE I
Simulation parameters.

Parameter	**Value**
Frequency range	2.4 GHz
Number of vehicles	5, 25, 50, 75, 100, 125, 150, 175, 200
Packet size [bytes]	1000
ALR [packets per second]	10
Frame reception model	Bit error rate based
Path loss model	Log-normal shadowing ($\sigma = 4.0$)
Fading model	Rayleigh
Mobility model	SUMO
Terrain dimensions	2000 m x 2000 m

A. Evaluation of occurred number of collisions

In the Qualnet simulator a frame drop will be counted as collision if another ongoing transmission lowers the signal to noise and interference ratio (SNIR) severely enough so that the probabilistic decision later on leads to an erroneous reception. The involved probabilities depend on the modulation and coding scheme and thus on the data rate used during the frame transmission. If faster data rates are used the increased SNIR requirements will shorten the communication range. However, the interference range [27] of each transmission will not change so that the probability of collision will be higher in consequence of parallel transmissions lowering the SNIR. Therefore, in the case that the data rate adaptation selects a faster data rate a higher number of collisions is to be expected.

V. Simulation Results

In this section we shall report about our simulation results. All simulations were run ten times with different random seeds using a simulation duration of 1800 s. All presented graphs include the standard deviation over all simulation runs which is often negligible.

A. Evaluation of CW size adaptation

At the beginning we compared the different approaches for the CW size adaptation and did not apply the data rate selection. Figure 1 shows the number of collisions that occurred when simulating with varying numbers of vehicles in the scenario. The proposed algorithms clearly improve the legacy protocol. Furthermore, the algorithm based on the optimum CW size mostly outperforms the *PER* based approach. Only when rather few vehicles participate in the network the *PER* based approach performs slightly better. The third approach combines the good characteristics of both algorithms, reaches overall the best performance, and lowers the number of collisions by about 35-40 % depending on the number of vehicles.

In the case the CW size is increased by the CW adaptation also the protocol overhead and average delay are increased. For

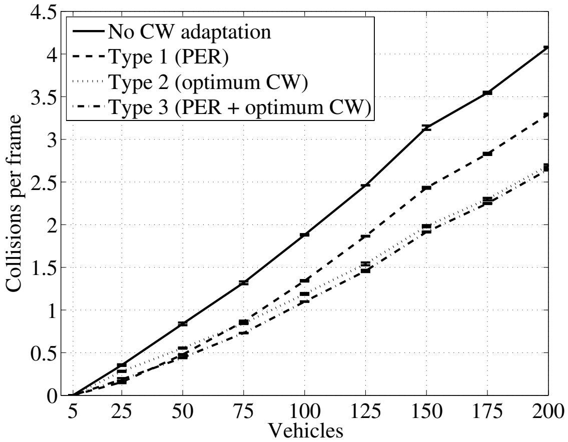

Fig. 1. Average number of collisions that occurred per sent frame when applying different approaches to adapt the CW size. Each car generates one packet of 1000 bytes each 0.1 sec.

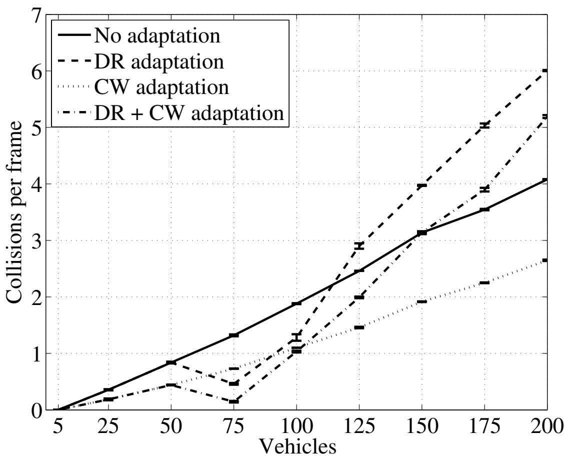

Fig. 2. Average number of collisions that occurred per sent frame when applying different approaches to adapt the CW size and the data rate. Each car generates one packet of 1000 bytes each 0.1 sec.

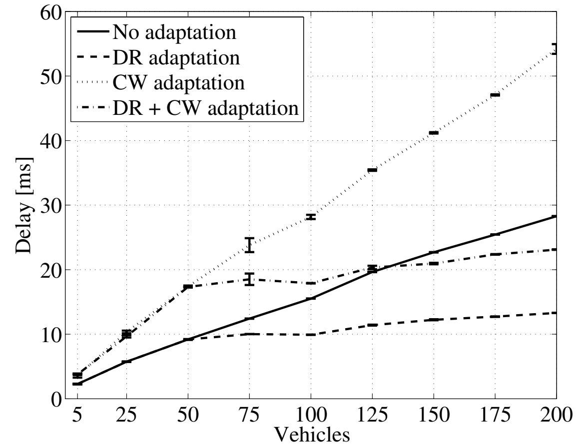

Fig. 3. Average delay of a single frame when applying different approaches to adapt the CW size and the data rate. Each car generates one packet of 1000 bytes each 0.1 sec.

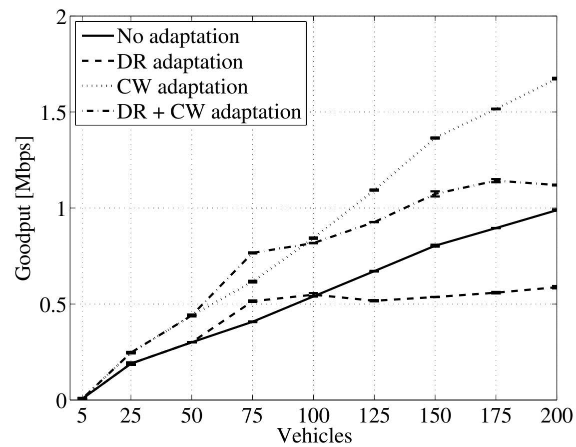

Fig. 4. Average goodput received at each vehicle when applying different approaches to adapt the CW size and the data rate. Each car generates one packet of 1000 bytes each 0.1 sec.

the highest network load with 200 vehicles the average delay increases from 28 ms for the unchanged protocol to 54 ms for the combined approach. The Vehicle Safety Communications Consortium postulates a maximum delay of 100 ms for DSRC[3] safety applications [28] which is still much higher than the delay induced by our algorithm. Hence, the higher delay can be accepted in order to lower the number of collisions.

B. Evaluation of the data rate selection

In the next step we also used the data rate selection method as introduced above. We always chose the combined method for the CW size adaptation because it showed superior performance. Figure 2 shows the number of collisions that occurred when simulating the same scenario with the new combination of algorithms. The increased number of collisions for very high numbers of vehicles is caused by the interpretation of collisions by the simulator. The selected faster data rates lead to higher requirements on the SNIR for successful reception and thus higher probability that parallel transmissions cause erroneous receptions.

When 75 vehicles are simulated the density of nodes in the scenario is still low enough so that the increase in the number of collisions due to the faster rates is not significant, yet, but the impact of the enhanced network capacity can already be seen.

When comparing the delay as shown in figure 3 the selected faster data rates show a clear improvement. The data rate selection starts to increase the data rate when 75 vehicles participate to the network and from there on the slope of the delay curve is decreased significantly.

Finally, we investigated the average goodput measured on the application layer. In the broadcast scenario each successfully received frame contributes to this metric and thus a single

[3]Dedicated Short Range Communication.

packet transmission might be considered at multiple receivers as contribution to the goodput. Figure 4 compares the results for the different proposed methods to the legacy WLAN-system. The lowered range for high network load in the case of dynamic data rate selection lowers the goodput even below the legacy case but the combination of data rate and CW size adaptation is superior for all simulated numbers of vehicles and thus proves that our proposed enhancements improve the scalability of IEEE 802.11-based vehicular networks.

VI. Conclusion

In this paper we introduced the scalability problem of the IEEE 802.11 broadcast mode for vehicular scenarios. Furthermore, we proposed different algorithms how the contention window (CW) size of the IEEE 802.11 MAC protocol and the physical layer data rate could be dynamically adapted and evaluated the methods in extensive simulations based on a carefully selected scenario.

The CW size adaptation significantly lowers the probability of collision by considering the estimated number of vehicles in the surroundings and does not increase the transmission delay to unacceptable levels. Additionally, the data rate selection improves the network capacity and can thus help in situations of channel congestion. However, higher data rates lower the communication range so that a higher number of failed receptions has to be accepted. Finally, the combination of both approaches outperforms the goodput achieved by the legacy IEEE 802.11 system for all considered network load levels so that adaptations such as the proposed ones should be considered for commercial vehicular networks.

All proposed methods are based on dynamic adaptations of already existing protocol parameters instead of changing the basic protocol behaviour so that straightforward integration with existing WLAN solutions is ensured.

Some of our results showed that also the data rate adaptation has potential to lower the number of collisions in specific scenarios, e.g., when a high number of vehicles is accumulated at a single location so that the network topology gets highly clustered. In our future work we will investigate approaches how such topologies can automatically be recognized and classified based on statistical techniques [29].

Acknowledgment

The authors would like to thank RWTH Aachen University and the German Research Foundation (DFG) for providing financial support through the UMIC excellence cluster.

References

[1] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, "Design of 5.9 GHz DSRC-based vehicular safety communication," *IEEE Wireless Communications*, vol. 13, no. 5, pp. 36–43, October 2006.

[2] *Status of project IEEE 802.11p: Wireless access for the vehicular environment (WAVE)*, http://grouper.ieee.org/groups/802/11/Reports/tgp_update.htm [Visited on: 24th September 2007], 2007.

[3] J. Singh, N. Bambos, B. Srinivasan, and D. Clawin, "Wireless LAN performance under varied stress conditions in vehicular traffic scenarios," in *Proc. of IEEE VTC'02*, vol. 2, Vancouver, Canada, Fall 2002.

[4] P. Bergamo, D. Maniezzo, K. Yao, M. Cesana, G. Pau, M. Gerla, and D. Whiteman, "IEEE 802.11 Wireless Network under Aggressive Mobility Scenarios," in *Proc. of ITC 2003*, Las Vegas, USA, 2003.

[5] J. Ott and D. Kutscher, "Drive-thru Internet: IEEE 802.11b for "Automobile" Users," in *Proc. of IEEE INFOCOM'04*, March 2004.

[6] M. Grade, K. Meier, B. Rech, and A. Lübke, "Physical IEEE 802.11-measurements in automotive environment," in *Proc. of the 5th European Congress on Intelligent Transportation Systems and Services*, Hannover, Germany, June 2005.

[7] D. N. Cottingham, I. J. Wassell, and R. K. Harle, "Performance of IEEE 802.11a in vehicular contexts," in *Proc. of IEEE VTC'07*, Dublin, Ireland, April 2007.

[8] M. Wellens, B. Westphal, and P. Mähönen, "Performance evaluation of IEEE 802.11-based WLANs in vehicular scenarios," in *Proc. of IEEE VTC'07*, Dublin, Ireland, April 2007.

[9] M. Torrent-Moreno, D. Jiang, and H. Hartenstein, "Broadcast reception rates and effects of priority access in 802.11 based vehicular ad hoc networks," in *Proc. of VANET'04*, Philadelphia, USA, October 2004.

[10] K. Ramanchandran, M. Gruteser, R. Onishi, and T. Hikita, "Experimental Analysis of Broadcast Reliability in Dense Vehicular Networks," in *Proc. of WiVec'07*, Baltimore, USA, September 2007.

[11] L. Wischhof, A. Ebner, H. Rohling, M. Lott, and R. Halfmann, "Adaptive Broadcast for Travel and Traffic Information Distribution Based on Inter-Vehicle Communication," in *Proc. of IEEE IV'03*, Columbus, USA, June 2003, pp. 6–11.

[12] S. Biswas and R. Tatchikou and F. Dion, "Vehicle-to-vehicle wireless communication protocols for enhancing highway traffic safety," *IEEE Communications Magazine*, vol. 44, no. 1, pp. 74–82, January 2006.

[13] M. S. Gast, *802.11 wireless networks: The definitive guide*, 2nd ed. O'Reilly & Associates, 2005.

[14] IEEE Computer Society LAN MAN Standards Committee, "802.11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," In IEEE Std 802.11-1999, 1999.

[15] M. Lacage, M. H. Manshaei, and T. Turletti, "IEEE 802.11 rate adaptation: a practical approach," in *Proc. of MSWiM'04*, Venezia, Italy, October 2004.

[16] J. C. Bicket, "Bit-rate selection in wireless networks," Master's thesis, Massachusetts Institute of Technology, February 2005.

[17] Q. Xu, T. Mak, and R. Sengupta, "Vehicle-to-Vehicle Safety Messaging in DSRC," in *Proc. of VANET'04*, Philadelphia, USA, October 2004.

[18] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, p. 535, March 2000.

[19] Y. Zang, L. Stibor, G. Orfanos, S. Guo, and H. J. Reumerman, "An error model for inter-vehicle communications in highway scenarios at 5.9 GHz," in *Proc. of PE-WASUN'05*, Montreal, Canada, 2005.

[20] J. Maurer, T. Fugen, and W. Wiesbeck, "Physical layer simulations of IEEE 802.11a for vehicle-to-vehicle communications," in *Proc. of IEEE VTC'05*, vol. 3, Dallas, USA, 2005.

[21] A. P. Jardosh, K. N. Ramachandran, K. C. Almeroth, and E. M. Belding-Royer, "Understanding Congestion in IEEE 802.11b Wireless Networks," in *Proc. of the IMC'05*, Berkeley, USA, 2005.

[22] G. R. Cantieni, Q. Ni, C. Barakat, and T. Turletti, "Performance analysis under finite load and improvements for multirate 802.11," *Computer Communications*, vol. 28, no. 10, pp. 1095–1109, 2005.

[23] Scalable Network Technologies, Inc., "Qualnet Network Simulator," http://www.qualnet.com [Visited on: 24th September 2007].

[24] A. K. Saha and D. B. Johnson, "Modeling mobility for vehicular ad-hoc networks," in *Proc. of VANET'04*, Philadelphia, USA, October 2004.

[25] F. Karnadi, Z. Mo, and K. C. Lan, "Rapid generation of realistic mobility models for VANET," in *Proc. of MobiCom'05*, Cologne, Germany, August 2005.

[26] D. Krajzewicz, G. Hertkorn, C. Rössel, and P. Wagner, "SUMO (Simulation of Urban MObility) - an open-source traffic simulation," in *Proc. of MESM'02*, Sharjah, United Arab Emirates, 2002, pp. 183–187.

[27] G. Anastasi, E. Borgia, M. Conti, and E. Gregori, "Wi-Fi in Ad Hoc Mode: A Measurement Study," in *Proc. of IEEE PERCOM'04*.

[28] Vehicle Safety Communications Consortium, "Task 3: Identify Intelligent Vehicle Safety Applications Enabled by DSRC - Interim Report," January 2003.

[29] P. Mähönen, M. Petrova, and J. Riihijärvi, "Applications of topology information for cognitive radios and networks," in *Proc. of IEEE DySPAN'07*, Dublin, Ireland, April 2007.