A Survey on How to Solve a Decentralized Congestion Control Problem for Periodic Beacon Broadcast in Vehicular Safety Communications

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Abstract— **For decades, vehicular industries have made an investment in developing cooperative vehicular systems to satisfy the current and future needs for reducing car accidents and increasing traffic safety and efficiency on the road. To satisfy these requirements, vehicular ad hoc networks (VANETs) based on wireless communications have been emerging as one of the promising solutions in recent years. Several research efforts have been conducted for various applications in VANETs and especially cooperative collision warning (CCW) using vehicular safety communication has been getting the spotlight because this is one of the most important and critical applications in VANETs. To realize CCW, however, the existing technical challenges, such as congestion control of periodic beacon broadcast and reliable dissemination of emergency messages in congested situation, should be solved. In this paper, we present the existing congestion control techniques for CCW in decentralized vehicular environments and point out their limitations and technical challenges. The question about how to solve these problems is also discussed in this paper.**

Keywords— **Vehicular ad hoc network (VANET), vehicular safety communication (VSC), cooperative collision warning (CCW), decentralized congestion control (DCC)**

I. Introduction

A World Health Organization (WHO) report said that the second most common cause of death for 5-29 year olds in 2002 was road traffic injuries [1]. As shown in this report, the traffic accident is one of the most important problems that should be solved in our society. Therefore, for last decades, vehicular industries have made an investment in developing cooperative vehicular systems to satisfy the current and future needs for reducing car accidents and increasing traffic safety and efficiency on the road. To satisfy these requirements, vehicular ad hoc networks (VANETs) based on wireless communications have been emerging as one of the promising solutions in recent years. As the low-cost global positioning system (GPS) receivers and wireless local area network (WLAN) transceivers have been available and each country has allocated wireless spectrum for vehicular communication, the research for VANETs has been more accelerated.

VANETs have different characteristics from other kinds of wireless networks, such as mobile ad hoc networks (MANETs) and wireless sensor networks (WSNs). While abundant power supply and relatively predictable mobility can be attractive features, large-scale network size, high mobility condition, dynamic network topology and connectivity, and extreme multipath environments are challenging characteristics that must be considered in VANETs [2]. Therefore, the previous studies on MANETs or WSNs cannot be applied directly to VANETs and the unique characteristics of VANETs should be considered carefully.

VANETs comprise vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications. The V2I communication provides Internet or traffic information services using communications infrastructure. The V2V communication is used for vehicle's safety when there are no central infrastructures existed in the vicinity of vehicles. Because it is hard to support infrastructures over a whole country within a few years, if we consider the financial aspects of construction expenses, the V2V communication-based VANET research is essential for reducing traffic accidents.

Several research efforts have been conducted for various applications in V2V communications. Among them, especially safety applications have been getting the spotlight because these are the most important and critical ones. There exist many safety applications such as forward collision warning, emergency electronic brake lights, blind spot warning and intersection movement assist [3]. However, above all, cooperative collision warning (CCW), where vehicles broadcast periodic short messages for driver's situational awareness and warning using V2V communications [4], is the first priority application to increase traffic safety in vehicular environments.

To support and enable safety applications including CCW, the dedicated short-range communication (DSRC) has been developed in the 1990's. In October 1999, the U.S. Federal Communications Commission (FCC) has allocated licensed 75 MHz spectrum in the 5.9 GHz band for DSRC. The spectrum is divided into seven 10 MHz channels, one control channel (CCH) for safety communications and six service channels (SCHs) for non-safety communications [5].

The DSRC technology is based on wireless communication standards and protocols designed for vehicular safety communications. In 2004, the IEEE 802.11 working group initiated the development of an amendment to the IEEE 802.11 standard for vehicular environments called IEEE 802.11p [6] and the IEEE 1609 working group also specified the operation and the services of four different layers (1609.1 for resource manager, 1609.2 for security service, 1609.3 for networking service and 1609.4 for multi-channel operation) in the protocol suite [7]. The collection of the IEEE 802.11p and the IEEE 1609.x is called a wireless access in vehicular environments (WAVE) standard.

The V2V safety communication for CCW application under IEEE 802.11p-based DSRC technology is generally operated by periodically broadcasting vehicles' status information (e.g. the vehicles' speed, position, direction, acceleration) on CCH. The messages containing the vehicles' information are called cooperative awareness messages (CAMs) or just beacons. Within the vehicle's communication range, the neighbor vehicles' status can be easily obtained by beacons. However, if we consider a high vehicle density scenario, the channel can be heavily congested by periodic beacon broadcast and more important time-critical emergency messages (e.g. traffic accident notification messages) cannot be informed in time by channel saturation. Therefore, the reliable and scalable congestion control of periodic beacon broadcast for decentralized V2V safety communications are required.

In this paper, we present the existing congestion control techniques for CCW in decentralized vehicular environments and point out their limitations and technical challenges. The question about how to solve these problems is also discussed in this paper. There are many survey papers about MAC protocols for V2V communications but, to the best of our knowledge, there is no paper on the survey and discussion about the decentralized V2V congestion control yet.

The paper is organized as follows. We first introduce characteristics of periodic beacon broadcast on IEEE 802.11p CCH in Section II. Section III explains the previous works related to our topic and their limitations. In Section IV, challenging issues of decentralized congestion control (DCC) in V2V safety communications are presented. Finally, we conclude this paper with future works in Section V.

II. Periodic Beacon Broadcast on IEEE 802.11p CCH

While the IEEE 802.11p-based DSRC technology has been developed considerably in recent years, the wide-scale deployment of a vehicular safety communication system has not been implemented yet [8]. The main reason is because constructing the efficient, reliable and scalable decentralized DSRC system is very challenging due to the broadcast nature of the IEEE 802.11p CCH and the time-limited feature of safety beacon broadcast [9].

Vehicles increase their awareness of the surrounding traffic condition by periodically broadcasting beacons. In the contention-based IEEE 802.11p MAC protocol, broadcast shows three different features from unicast [10].

First of all, each vehicle cannot send an acknowledgment (ACK) to a sending vehicle due to the ACK explosion problem. Therefore, there is no solution to detect collision. Secondly, a request to send/clear to send (RTS/CTS) handshake mechanism cannot be used because collisions occur more frequently in broadcast than in unicast. This leads to a hidden node problem. Lastly, regardless of the success or the failure of message delivery, the initial contention window (CW) size remains the same because the delivery failure in broadcast could not be detected. For these reasons, the performance of periodic beacon broadcast in terms of reliability and latency is a big concern in VANETs [10].

The second challenging property of the periodic beacon broadcast is its limited lifetime. Beacons are not just simple broadcast messages. The vehicle's status information contained in its beacon is only useful until the next beacon is produced because the information should be regularly updated for traffic safety [9]. In [11], periodic beacon shows different performance results from regular broadcast messages. The optimal CW size decreases with the increase in vehicle density in the case of periodic beacons, but the result is opposite in the case of pure broadcast messages.

Therefore, in order to control beacon congestion in the high vehicle density scenario, these two challenging properties should be taken into account when considering a DCC algorithm.

III. Previous Works on DCC in V2V Safety Communications

As mentioned in Section II, the design and development of an IEEE 802.11p-based DSRC system which supports reliable and scalable DCC is crucial for traffic safety in VANETs. Up to now, several research efforts have been conducted to validate and evaluate the performance of the congestion control algorithms.

Various approaches for the performance evaluation of a wireless communication system have existed. The two most common methods are a simulation and a field test. Especially in the case of VANET research, the field test is not an effective way for performance evaluation because it is very difficult to cope with high research costs when the number of experimented vehicles is increased. Therefore, many existing researches on DCC have been evaluated by simulation [12].

The common assumptions that the previous works surveyed in this paper have made are as follows.

- Each vehicle follows the IEEE 802.11p standard.
- Each vehicle installs a GPS receiver.
- All nodes share IEEE 802.11p CCH.
- Emergency messages have higher priority than periodic beacons.

The first step towards DCC is to evaluate the performance of the existing IEEE 802.11p MAC protocol with various aspects. Table I shows a summary of the previous works on the performance of the IEEE 802.11p MAC protocol in terms of beacon reception rate (BRR), emergency message reception rate (ERR), channel access delay, channel busy time ratio, etc. They simulate by varying transmission power, transmission frequency, packet size, vehicle density and channel model. They are classified into seven attributes: variation factors, performance metric, traffic scenario (highway or urban), application type (periodic beacon or time-critical emergency

TABLE 1. CLASSIFICATION OF STUDIES ON PERFORMANCE EVALUATION OF AN IEEE 802.11P MAC PROTOCOL

Paper	Variation factors	Performance metric	Traffic scenario	Application type	Network simulator	Mobility model	Propagation model
Effects of priority access and channel model [20]	Tx power, packet size, channel	BRR	Highway	Periodic beacon	ns-2	Not used	TwoRayGround, Nakagami
Communication density: a channel load metric [21]	Tx power, Tx freq., density	BRR, channel access delay	Highway	Periodic beacon	ns-2	Not used	Rayleigh fading
Optimal data rate selection [22]	Data rate, packet size, density	BRR	Highway	Periodic beacon	ns-2	Not used	Rayleigh fading
Single-hop and multi-hop comparison [23]	Hop count, density, channel	Channel load, BRR, beacon age	Highway	Periodic beacon	ns-2	Not used	TwoRayGround, Nakagami
Sensitivity analysis of packet reception ratio [24]	Tx power, Tx freq., packet size, density, channel	BRR, average change rate of BRR	Highway	Periodic beacon	ns-2	Not used	TwoRayGround, Nakagami
Suitability of IEEE 802.11p MAC protocol [25]	Tx power, Tx freq., packet size, density, channel	Packet level incoordination, incoordination delay profile	Highway	Periodic beacon	ns-3	Not used	Deterministic, Determinitic + Log-Normal Shadowing, Rayleigh fading
Contention window analysis [26]	CW size, Tx freq., density	BRR, delay, inter-arrival time	Highway	Periodic beacon	OMNeT++	Not used	No propagation loss
Invisible neighbor problem [27]	Tx power, Tx freq., density, channel	Invisible neighbors in ROI	Highway and urban	Periodic beacon	Not mentioned	Not used	TwoRayGround, Nakagami
Three beacon congestion control comparison [28]	Tx power, Tx freq., density	BRR, ERR, channel busy time ratio	Urban	Periodic beacon and emergency	ns-2	Not used	Nakagami

message), network simulator (ns-2 [13], ns-3 [14], OMNeT++ [15], JiST/SWANS [16] or OPNET [17]), mobility model (SUMO [18] or STRAW [19]) and propagation model (Two ray ground, Rayleigh fading or Nakagami).

We summarize the simulation results of the evaluation on the IEEE 802.11p MAC protocol as follows.

- BRR is one of the most important performance metrics in V2V safety communications.
- Ns-2 is used as a popular network simulator in VANET research community.
- The Nakagami's distribution is more suitable to VANETs than log-normal or Rayleigh shadowing [20].
- In the same communications density, we can get almost the same performance results in different scenarios [21].
- The commonly assumed 6 Mbps data rate turns out to be the best in VANETs [22].
- Multi-hop beacon broadcast generally does not show better performance than single-hop case [23].
- The IEEE 802.11p MAC protocol can effectively coordinate multiple access as long as the channel load does not approach the maximum channel capacity [25].
- The CW values show little impact on BRR. However, a long delay is caused by a large CW size [26].

The results show that the existing V2V MAC protocol is not effective in high channel load and the simulation environments are not sufficient to construct more realistic VANET simulation.

The next research step is naturally to propose a new DCC scheme and demonstrate its excellence in comparison with the existing ones. Table 2 shows the summary of the DCC schemes in V2V safety communications. They can be classified according to their control methods: transmission power control, transmission frequency control, carrier sensing threshold control, and the joint control of more than two parameters.

The analysis of the DCC schemes for V2V safety communications are summarized as follows.

- Rayleigh fading and Nakagami's distribution are used in most cases as a propagation model.
- Several researches on adjusting vehicle's transmission power [29]-[32] or transmission frequency [33]-[37] have been extensively conducted. However, these transmitter-based schemes are difficult to estimate the receiver's status and need to control the vehicle's radio hardware.
- To overcome these problems, the receiver-based carrier sensing threshold control method has been studied recently [38], [39]. The advantage of this method is that it can be realized by software.

TABLE 2. CLASSIFICATION OF DECENTRALIZED CONGSETION CONTROL SCHEMES IN V2V SAFETY COMMUNICATIONS

Paper	Control method	Performance metric	Traffic scenario	Application type	Network simulator	Mobility model	Propagati-on model
Distributed fair power adjustment & emergency message dissemination [29]	Tx power control	BRR, ERR, delay, channel access time	Highway	Periodic beacon and emergency	ns-2	Not mentioned	Nakagami
Distributed vehicle density estimation & segment-based power adjustment [30]	Tx power control	Channel load, Tx power	Highway	Periodic beacon	ns-2	Not mentioned	Two Ray Ground, Nakagami
Opportunistic adaptive radio resource management [31]	Tx power control	BRR, Tx power	Urban	Periodic beacon	ns-2	Not mentioned	WINNER
Network topology p-persistence scheme [32]	Tx power control	Average retransmission per hop, delay	Highway	Periodic beacon	ns-2	MOVE on top of SUMO	Not mentioned
Periodically updated load sensitive adaptive rate control (PULSAR) [33]	Tx freq. control	Channel busy ratio	Highway	Periodic beacon	ns-2	Not mentioned	Rayleigh fading, Nakagami
Adaptive traffic beacon (ATB) [34], [35]	Tx freq. control	CO_2 emission, speed, delay, number of collisions	Highway and urban	Periodic beacon	OMNeT++	SUMO	Not mentioned
Additive increase and multiplicative decrease (AIMD) method [36], [37]	Tx freq. control	Reception number, BRR, delay	Urban	Periodic beacon	Author's own simulator	Not mentioned	Not mentioned
CCA threshold adaptation depending on how long a packet has been waiting for medium access [38]	Carrier sensing threshold	Awareness quality, delay	Highway	Periodic beacon	JiST/ SWANS	SUMO	Rayleigh fading
Adaptive physical carrier sense control [39]	Carrier sensing threshold	BRR	Highway	Periodic beacon	JiST/ SWANS	STRAW	Not mentioned
Adaptive rate & power control based on the dynamics of a vehicular network and safety-driven tracking process [40]	Joint control of Tx power and Tx freq.	Tracking accuracy	Highway	Periodic beacon	OPNET	SHIFT	Rayleigh fading
Joint adaptation of Tx power and CW size [41]	Joint control of Tx power and CW size	Throughput, end-to-end delay	Highway	Emergency message	ns-2	Not mentioned	Nakagami
Safety Range CSMA (SR-CSMA) [42]	Joint control of Tx power, carrier sensing threshold, and CW size	BRR	Highway	Periodic beacon	JiST/ SWANS	Not mentioned	Not mentioned

- A joint control of multiple DCC-related parameters is proposed in [40]-[42], but the complexity of the proposed scheme is not considered.
- None of the existing approaches can be the solution of the DCC problem. The solution should be well adapted to dynamic vehicle density changes and be evaluated in both simulation conditions (e.g. highway and urban scenarios, periodic beacons and emergency messages).

As shown in Tables 1 and 2, the performance of the DCC algorithms has been evaluated by simulation. However, the performance results are not sufficient to satisfy the requirements of safety applications. The weaknesses found in the survey should be overcome and enhanced. We point out three weaknesses from survey of the previous works on DCC.

A. Lack of Realistic VANET Simulation

The existing simulation research has been conducted using network simulators. Most network simulators abstract physical characteristics (radio channels, traffic mobility, etc.). However, mobility and channel characteristics of VANETs cannot be easily applied to the simulation. To overcome this problem, an integrated and bi-directionally coupled simulator is a must for supporting mobility and channel characteristics of vehicular environments [43].

The simulators that tightly couples network simulation and traffic mobility simulation, such as Veins [44] and iTETRIS [45], have been developed recently. The research of DCC using these integrated simulators should be accelerated for more realistic VANET simulation.

B. Lack of Support for Both Safety Messages

For DCC schemes to support and enable CCW, they must be validated from two important points of view, whether the congestion caused by the periodic beacon broadcast is effectively controlled in dynamic vehicle density and whether emergency messages such as traffic accident notification messages are disseminated up to the required notification distance within the time limit of the applications. Therefore, periodic beacon broadcast and event-driven emergency message dissemination should be implemented and evaluated altogether. However, there have been little efforts to consider both because it is difficult to satisfy both the delay requirements of the time-critical emergency messages and the non-saturation condition of the periodic beacon messages.

C. Lack of Simulation in Urban Traffic Scenario

Highway and urban scenarios have different features in VANETs. While traffic density is homogeneous in one-dimensional highways, different traffic density conditions can be simultaneously occurred in two-dimensional urban scenarios [46]. Therefore, DCC schemes should be evaluated both in a highway and an urban scenario to verify the robustness of their performance.

However, as shown in Section III, most of the studies considered only highway scenario. Reference [47] reveals that a substantial portion of traffic accidents (39.5, 52.5, and 54 % in the States of California, Missouri, and Pennsylvania, respectively) has occurred in urban areas. This shows the importance of a congestion control study in urban vehicular environments for traffic safety.

IV. CHALLENGING ISSUES OF DCC IN V2V SAFETY COMMUNICATIONS

A. Is the IEEE 802.11p MAC Protocol the Best Solution?

The exclusive characteristics of VANETs such as high mobility condition, dynamic network topology, and extreme multipath environments have made reliability and scalability the most important aspects in V2V safety communications. Therefore, most of the researches about DCC assumed a contention-based IEEE 802.11p standard as a basic V2V MAC protocol because the contention-based MAC schemes are more robust to network changes and require less configuration time than the contention-free schemes such as the time-division multiple access (TDMA).

However, the performance of the IEEE 802.11p MAC protocol significantly gets worse under high traffic load because of increased collisions and the broadcast nature of the IEEE 802.11p CCH shown in Section II [48]. Therefore, just only one medium access approach cannot solve the congestion control problem. We need to develop a V2V safety communication MAC protocol that can adaptively control beacon congestion based on vehicle density according to traffic condition.

B. How to estimate Vehicle Density?

In section III, the basic approach of the DCC mechanisms is to adjust vehicles' transmission power, transmission frequency, carrier sensing threshold, and CW size according to the measured and estimated channel load.

In order to choose optimal congestion control parameters, the accurate vehicle density estimation is an essential prerequisite for beacon congestion control in decentralized communication environments. Most of the studies on DCC assume that vehicle density is locally estimated by calculating the number of received neighbor vehicles' beacons or by measuring channel busy time ratio [49]. However, due to the collision of beacons and the dynamic nature of decentralized communication networks, the exact vehicle density estimation remains an unsolved problem.

The estimation problem is even worse when considering two dimensional urban vehicular environments. In urban traffic scenarios, it is difficult to address the impacts of non-uniform and heterogeneous traffic densities.

There exist several local vehicle density estimation mechanisms, e.g. the beacon-based neighbor estimation, the collided packets estimation, the idle time counting, the stop time neighbor estimation, and the speed-based neighbor estimation [49]. Their limitations shown in [49] are demanding more robust and accurate estimation mechanism to academies and industries.

V. CONCLUSIONS AND FUTURE WORKS

This paper presents the importance of DCC in V2V communications for safety applications and shows several previous efforts to reduce the congestion and their limitations. The existing DCC techniques are still in the early and the laboratory stage. Therefore, technically challenging issues, such as the suitability of IEEE 802.11p as a VANET MAC protocol, the development of the best strategy for DCC, and how to estimate vehicle density correctly, should be solved to meet the automotive industry's safety requirements.

Future works will aim to solve the aforementioned technical challenges for V2V safety communications. The modeling and numerical analysis of the existing V2V safety communication protocol, the development of an integrated simulator with consideration for mobility and channel characteristics of vehicular environments, and the enhancement of the existing VANET protocol and its validation by analysis and simulation can be also important future VANET studies.

Our ultimate goal is to develop a new V2V safety communication MAC protocol that can control channel congestion adaptively to vehicle density and traffic condition in highway and urban environments.

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REFERENCES

[1] E. Strom, H. Hartenstein, P. Santi, and W. Wiesbeck, "Vehicular communications," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1158-1161, July 2011.

[2] H. Moustafa and Y. Zhang, *Vehicular Networks: Techniques, Standards, and Applications*, Auerbach Publications, New York, 2009.

[3] (2007) Vehicle Safety Communications – Applications VSC-A, First Annual Report, U.S. Dept. Trans., Nat. Highway Traffic Safety Admin., Rep. DOT HS 811 073. [Online]. Available: http://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2008/811073.pdf

[4] T. Elbatt, S. K. Goel, G. Holland, H. Krishnan, and J Parikh, "Cooperative Collision Warning Using Dedicated Short Range Wireless Communications," in *Proc. ACM VANET 2006*, LA, CA, Sep. 2006.

[5] J. B. Kenney, "Dedicated Short-Range Communications (DSRC) Standards in the United States," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1162-1182, July 2011.

[6] *IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements; Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Amendment 6: Wireless Access in Vehicular Environments*, IEEE Std. 802.11p-2010, July 2010.

[7] R. A. Uzcategui and G. Acosta-Marum, "`WAVE: A Tutorial," *IEEE Commun. Mag.*, vol. 47, no. 5, pp. 126-133, May 2009.

[8] X. Ma, J. Zhang, X. Yin, and K. S. Trivedi, "Design and analysis of a robust broadcast scheme for VANET safety-related services," *IEEE Trans. Veh. Technol.*, vol. 61, no. 1, pp. 46-61, Jan. 2012.

[9] R. Stanica, E. Chaput and A.-L. Beylot, "Properties of the MAC layer in safety VANETs," *IEEE Commun. Mag.*, vol. 50, no. 5, pp. 192-200, May 2012.

[10] Q. Yang, J. Zheng, and L. Shen, "Modeling and Performance Analysis of Periodic Broadcast in Vehicular Ad Hoc Networks," in *Proc. IEEE Globecom 2011*, Houston, TX, Dec. 2011.

[11] R. Stanica, E. Chaput and A.-L. Beylot, "Why VANET Beaconing is More than Simple Broadcast," *IEEE VTC2011-Fall*, San Francisco, CA, Sep. 2011.

[12] J. Mittag, S. Papanastasiou, H. Hartenstein, and E. G. Strom, "Enabling Accurate Cross-Layer PHY/MAC/NET Simulation Studies of Vehicular Communication Networks," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1311-1326, July 2011.

[13] Ns-2. [Online]. Available: http://www.isi.edu/nsnam/ns/

[14] Ns-3. [Online]. Available: http://www.nsnam.org/

[15] OMNeT++. [Online]. Available: http://www.omnetpp.org/

[16] JiST/SWANS. [Online]. Available: http://jist.ece.cornell.edu/

[17] OPNET. [Online]. Available: http://www.opnet.com/

[18] SUMO. [Online]. Available: http://sumo.sourceforge.net/

[19] STRAW. [Online]. Available: http://www.aqualab.cs.northwestern.edu/projects/

[20] 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. ACM VANET 2004*, Philadelphia, PA, Oct. 2004.

[21] D. Jiang, Q. Chen, and L. Delgrossi, "Communication Density: A Channel Load Metric for Vehicular Communications Research," in *Proc. IEEE MASS 2007*, Pisa, Italy, Oct. 2007.

[22] D. Jiang, Q. Chen, and L. Delgrossi, "Optimal data rate selection for vehicle safety communications," in *Proc. ACM VANET 2008*, San Francisco, CA, Sept. 2008.

[23] J. Mittag, F. Thomas, J. Harri, and H. Hartenstein, "A comparison of single- and multi-hop beaconing in VANETs," in *Proc. ACM VANET 2009*, Beijing, China, Sept. 2009.

[24] N. An, J. Mittag, F. Schmidt-Eisenlohr, and M. Torrent-Moreno, "Accurate knowledge of radio channel and network conditions - when does it matter?" in *Proc. IEEE WONS 2011*, Bardonecchia, Italy, Jan. 2011.

[25] J. Mittag and H. Hartenstein, "Is CSMA Able to Coordinate Multiple Access in Vehicular Radio Channels Effectively?" in *Proc. IEEE ITST 2012*, Taipei, Taiwan, Nov. 2012.

[26] R. Reinders, M. Eenennaam, G. Karagiannis, and G, Heijenk, "Contention Window Analysis for Beaconing in VANETs," in *Proc. IEEE IWCMC 2011*, Istanbul, Turkey, Jul. 2011.

[27] H. Lu and C. Poellabauer, "Analysis of application-specific broadcast reliability for vehicle safety communications," in *Proc. ACM VANET 2011*, Las Vegas, NV, Sept. 2011.

[28] L. Le, R. Baldessari, P. Salvador, A. Festag, and W. Zhang, "Performance Evaluation of Beacon Congestion Control Algorithms for VANETs," in *Proc. IEEE Globecom 2011*, Houston, TX, Dec. 2011.

[29] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein, "Vehicle-to-vehicle communication: fair transmit power control for safety-critical information," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3684-3703, Sept. 2009.

[30] J. Mittag, F. Schmidt-Eisenlohr, and M. Killat "Analysis and design of effective and low-overhead transmission power control for VANETs," in *Proc. ACM VANET 2008*, San Francisco, CA, Sept. 2008.

[31] J. Gozalvez and M. Sepulcre, "Opportunistic Technique for Efficient Wireless Vehicular Communications," *IEEE Veh. Technol. Mag.*, vol. 2, no. 4, pp. 33-39, Dec. 2007.

[32] K. A. Hafeez, L. Zhao, Z. Liao, and B. N.-W. Ma, "A New Broadcast Protocol For Vehicular Ad hoc Networks Safety Applications," in *Proc. IEEE Globecom 2010*, Miami, FL, Dec. 2010.

[33] T. Tielert, D. Jiang, Q. Chen, L. Delgrossi, and H. Hartenstein, "Design methodology and evaluation of rate adaptation based congestion control for vehicle safety communications," in *Proc. IEEE VNC 2011*, Amsterdam, Netherlands, Nov. 2011.

[34] C. Sommer, O. K. Tonguz, and F. Dressler, "Adaptive Beaconing for Delay-Sensitive and Congestion-Aware Traffic Information Systems," in *Proc. IEEE VNC 2010*, Jersey City, NJ, Dec. 2010.

[35] C. Sommer, O. K. Tonguz, and F. Dressler, "Traffic information systems: efficient message dissemination via adaptive beaconing," *IEEE Commun. Mag.*, vol. 49, no. 5, pp. 173-179, May 2011.

[36] J. He, "Adaptive Congestion Control for DSRC Vehicle Networks," *IEEE Commun. Letters*, vol. 14, no. 2, pp. 127-129, Feb. 2010.

[37] W. Guan, J. He, L. Bai, and Z. Tang, "Adaptive Rate Control of Dedicated Short Range Communications based Vehicle Networks for Road Safety Applications," in *Proc. IEEE VTC 2011*, Budapest, Hungary, May 2011.

[38] R. K. Schmidt, A. Brakemeier, T. Leinmuller, F. Kargl, and G. Schafer, "Advanced carrier sensing to resolve local channel congestion," in *Proc. ACM VANET 2011*, Las Vegas, NV, Sept. 2011.

[39] R. Stanica, E. Chaput, and A.-L. Beylot, "Physical Carrier Sense in Vehicular Ad-Hoc Networks," in *Proc. IEEE MASS 2011*, Valencia, Spain, Oct. 2011.

[40] C.-L. Huang, Y. P. Fallah, and R. Sengupta, "Adaptive intervehicle communication control for cooperative safety systems," *IEEE Network*, vol. 24, no. 1, pp. 6-13, Jan./Feb. 2010.

[41] D. B. Rawat, "Enhancing VANET Performance by Joint Adaptation of Transmission Power and Contention Window Size," *IEEE Trans. Parallel Distrib. Syst.*, vol. 22, no. 9, pp. 1528-1535, Sep. 2010.

[42] R. Stanica, E. Chaput, and A.-L. Beylot, "Congestion Control in CSMA-based Vehicular Networks: Do Not Forget the Carrier Sensing," in *Proc. IEEE SECON 2012*, Seoul, South Korea, June 2012.

[43] C. Sommer and F. Dressler, "Progressing toward Realistic Mobility Models in VANET Simulations," *IEEE Commun. Mag.*, vol. 46, no. 11, pp. 132-137, Nov. 2008.

[44] Veins. [Online]. Available: http://veins.car2x.org/

[45] iTETRIS. [Online]. Available: http://www.ict-itetris.eu/index.htm/

[46] W. Viriyasitavat, O. K. Tonguz, and F. Bai, "UV-CAST: An Urban Vehicular Broadcast Protocol," *IEEE Commun. Mag.*, vol. 49, no. 11, pp. 116-124, Nov. 2011.

[47] S. Bastani, B. Landfeldt, and L. Libman, "A Traffic Density Model for Radio Overlapping in Urban Vehicular Ad hoc Networks," in *Proc. IEEE Conf. Local Computer Networks*, Bonn, Germany, Oct. 2011.

[48] M. J. Booysen, S. Zeadally, and G.-J. van Rooyen, "Survey of media access control protocols for vehicular ad hoc networks," *IET Communications*, vol. 5, no. 11, pp. 1619-1631, July 2011.

[49] R. Stanica, E. Chaput, and A.-L. Beylot "Local Density Estimation for Contention Window Adaptation in Vehicular Networks," in *Proc. IEEE PIMRC 2011*, Toronto, Canada, Sep. 2011.