How Shadowing Hurts Vehicular Communications and How Dynamic Beaconing Can Help

Christoph Sommer*, Stefan Joerer*, Michele Segata*†, Ozan Tonguz‡, Renato Lo Cigno† and Falko Dressler*
*Computer and Communication Systems, Institute of Computer Science, University of Innsbruck, Austria
†Systems and Networks, Dept. of Information Engineering and Computer Science, University of Trento, Italy
‡Electrical and Computer Engineering Dept., Carnegie Mellon University, Pittsburgh, PA
{sommer,joerer,segata,dressler}@ccs-labs.org; locigno@disi.unitn.it; tonguz@ece.cmu.edu

***Abstract*—We study the effect of radio signal shadowing dynamics, caused by vehicles and by buildings, on the performance of beaconing protocols in Inter-Vehicular Communication (IVC). Recent research indicates that beaconing, i.e., one hop message broadcast, shows excellent characteristics and can outperform other communication approaches for both safety and efficiency applications, which require low latency and wide area information dissemination, respectively. We show how shadowing dynamics of moving obstacles hurt IVC, reducing the performance of beaconing protocols. At the same time, shadowing also limits the risk of overloading the wireless channel. To the best of our knowledge, this is the first study identifying the problems and resulting possibilities of such dynamic radio shadowing. We demonstrate how these challenges and opportunities can be taken into account and outline a novel approach to dynamic beaconing. It provides low-latency communication (i.e., very short beaconing intervals), while ensuring not to overload the wireless channel. The presented simulation results substantiate our theoretical considerations.**

I. Introduction

Inter-Vehicular Communication (IVC) has become one of the major fields of research in the networking community. Depending on the use case, applications can be categorized into safety, efficiency, and entertainment [1]. In this paper, we concentrate on the first two classes of applications, which are at the center of short range radio communication based systems.

In the last couple of years, it turned out that, here, beaconing based dissemination concepts are not only adequate but clearly outperform classical routing approaches [2]–[4]. In this context, the term *beacon* refers to periodic application messages, which are broadcast to all one-hop neighbors. These beacons can be rebroadcast, i.e., relayed, if necessary. ETSI (TC ITS) and the Car-to-Car Communication Consortium (C2C-CC) took up the idea of beaconing when standardizing Cooperative Awareness Messages (CAMs) based on IEEE 802.11p/DSRC [5]. These messages, which are designed to be broadcast periodically with a fixed beaconing frequency in the range of 1 Hz to 10 Hz, form the basis for establishing cooperative awareness among vehicles in communication range.

Mainly based on simulation experiments, it has been extensively discussed that fixed period beaconing easily leads to severe channel congestion. As a result, adaptive beaconing protocols have been developed [2]–[4], [6]. More recently, Decentralized Congestion Control (DCC) has been suggested in ETSI ITS-G5 to cope with congestion problems [7], [8].

All these works, however, assumed optimal (i.e., unobstructed) channel conditions. Most recently, theoretical modeling approaches supported by measurement campaigns have clearly shown that signal shadowing and fading could substantially impact the wireless communication between neighboring vehicles [9]–[11].

In this paper, we investigate this impact considering both mobile obstacles (i.e., other vehicles) and stationary obstacles (i.e., buildings) in the context of beaconing based information dissemination. To the best of our knowledge, this is the first study on the identification of problems caused by radio shadowing due to mobile and stationary obstacles and the consequent challenges.

We show that fixed period beaconing as well as moderately reactive adaptive approaches cannot cope with the increased network dynamics caused by shadowing. However, according to our findings, shadowing effects not only lead to new *challenges* such as how to ensure low transmission latency for safety applications and wide range data dissemination for efficiency applications, but they also provide *opportunities* due to an inherently reduced channel load.

The contributions of this paper can be summarized as follows:

- We study the negative effects of signal shadowing on IVC caused by neighboring vehicles and by buildings, going beyond recent studies on the impact of buildings only.
- We investigate how dynamic beaconing could also benefit from these effects and present a novel algorithm, Dynamic Beaconing (DynB), that provides substantially improved beaconing performance in the presence of radio signal shadowing by both static and mobile obstacles.
- We carefully investigate the resulting performance compared to related approaches under different radio shadowing models. As can be seen from our results, the proposed approach can aggressively speed up beaconing, leading to very low transmission delays, while very quickly reacting to overload situations.

DynB opens up the road for a new generation of dynamic beaconing solutions that react more aggressively to dynamics in the network – caused, for example, by time-variant signal shadowing effects.

978-1-4673-5946-7/13/$31.00 ©2013 IEEE

II. Related Work

There is a considerable amount of scientific work on cooperative awareness and safety applications using periodic beacon messages [2], [3]. To elaborate on one example, Ros et al. proposed a protocol to increase the reliability while minimizing the number of beacon retransmissions [12]. In their approach, local position information is used by cars to determine whether they belong to a connected dominating set and subsequently reduce waiting periods before retransmissions.

The main challenge for not just this but all beacon systems, however, is that they are very sensitive to environmental conditions such as network topology and load.

The key challenge of adaptive beaconing is to dimension the system in such a way that the available capacity of the channel is carefully used in high density scenarios. Recently, building on earlier approaches to cope with congestion problems [7], [8] DCC has been proposed in ETSI ITS-G5 and it has been suggested to combine beaconing with geographical knowledge [13]. In earlier work, we have presented our Adaptive Traffic Beacon (ATB) protocol, which carefully adjusts the beaconing period according to an estimate of the available channel capacity and message utility [3], [6].

Yet, studies of all these approaches assumed an optimal channel model, i.e., freespace radio propagation. Considering effects of signal shadowing and fading –especially caused by other vehicles and buildings– is changing the conditions substantially. Due to these reasons, we take the resulting opportunities and challenges into account for designing a novel approach to dynamic beaconing.

III. Dynamic Beaconing

Beacons support cooperative awareness, so they should be sent at a rate ensuring the delivery to all interested receivers within a proper deadline. The correct rate depends on network conditions and propagation scenario, as in congested or bad networking conditions it is preferable to have a lower rate than high collision rates and congestion. How to adapt the inter-beacon interval I is the issue that needs to be addressed.

ETSI ITS-G5 has standardized the DCC Transmit Rate Control (TRC) mechanism [8] to adapt I based on a simple state machine as depicted in Figure 1. State transitions are driven by b_t, a measure of the channel busy time, given a sampling interval T_{m}; this means that b_t is the fraction of time the channel has been sensed busy between t and $t - T_m$.

T_{DCC} is the inter-decision interval (i.e., state transitions occur after every T_{DCC}), while T_{up} and T_{down} are filtering (time) windows applied to take the decisions on whether to increase or decrease the interval, respectively. The times T_{DCC}, T_{up}, and T_{down} are integer multiples of T_{m}. The decision variables of the algorithm are $b_{\text{up}} = \min\left\{b_{t-T_{\text{up}}}, \ldots, b_t\right\}$ and $b_{\text{down}} = \max\left\{b_{t-T_{\text{down}}}, \ldots, b_t\right\}$; they are compared against threshold values b_{min} and b_{max}. Table I reports the ITS-G5 default values for the parameters, which we use in the performance evaluation.

Note that, because we only use TRC, we also adapt the beacon interval when entering the second state. Thus, each of the three states corresponds to a different interval in $\{I_{\text{min}}, I_{\text{def}}, I_{\text{max}}\}$, as shown in Figure 1.

Table I
Parameters of the implemented algorithms.

Variant	Parameter	Value
TRC	I_{min}, I_{def}, I_{max}	0.04 s, 0.5 s, 1 s
	b_{min}, b_{max}	0.15, 0.40
	T_{M}, T_{DCC}, T_{up}, T_{down}	1 s, 1 s, 1 s, 5 s
DynB	I_{des}	0.01 s
	b_{des}	0.25

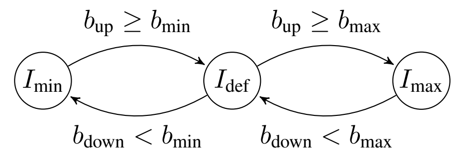


Figure 1. State machine of the TRC algorithm.

In a static scenario, this scheme (which we will refer to as TRC) was shown to successfully manage channel access, albeit at the cost of synchronized oscillations in channel load and a pronounced under-utilization of channel capacity [7]. Moreover, in highly dynamic scenarios (cf. Section IV) we show that the algorithm can also lead to the opposite: a pronounced over-utilization of channel capacity and, thus, packet loss.

Reasons of the DCC TRC mechanism failure can be easily found in its poor adaptation properties and a coarse design of the controlling algorithm. For this reason we propose a novel, more sophisticated and theoretically sound adaptation algorithm, named DynB.

First of all we get rid of all the additional sampling and windowing parameters, as the beacons themselves offer a natural and very convenient sampling process. Moreover, elementary control theory shows that in a sampled system, using sampling processes different from the fundamental one can lead to instabilities, which is exactly what is observed with ETSI ITS-G5 DCC TRC.

DynB uses only two control variables: b_t (the fraction of busy time between $t - I$ and t) and N (the simple one-hop neighbor count). These variables are used to force the beacon interval I as close as possible to a desired value I_{des} as long as the channel load does not exceed a desired value b_{des}.

Let $r = b_t / b_{\text{des}} - 1$, clipped in $[0, 1]$, be a measure of the distance by which the actual channel load b_t exceeds a desired load b_{des}. The beacon interval is calculated as

$$I = I_{\text{des}} \left(1 + rN\right). \tag{1}$$

The rationale is clear: I should increase as the network becomes denser (more neighbors), and it must do so only when the channel occupancy is above the target value. The algorithm is fully distributed and each node adapts its beaconing interval to the local conditions. Computing N is trivial, as a neighbor is defined as a node j whose beacons are received at node i, so a good estimate of N is simply the number of nodes whose beacons have been received in the time interval I_{max}.

In order to determine a target value of the desired channel load b_{des}, we start by calculating an upper bound t_{busy} for transmitting a payload of $l = 512\,\text{bit}$ at $18\,\text{Mbit}\,\text{s}^{-1}$ according to the operation of the PLME-TXTIME.*confirm* primitive described in [14, Section 17.4.3]:

$$t_{\text{busy}} = T_{\text{preamble}} + T_{\text{signal}} + T_{\text{sym}} \left\lceil \frac{16 + l + 6}{N_{\text{DBPS}}} \right\rceil . \quad (2)$$

With default values of the preamble duration $T_{\text{preamble}} = 32\,\mu\text{s}$, the SIGNAL symbol duration $T_{\text{signal}} = 8\,\mu\text{s}$, the duration of a symbol $T_{\text{sym}} = 8\,\mu\text{s}$, and the number of data bits per symbol $N_{\text{DBPS}} = 72$, we obtain $t_{\text{busy}} = 104\,\mu\text{s}$.

For a packet transmitted on the CCH with an application layer priority that maps to AC_VO, default parameters according to [5, Section 7.3.2.29] dictate a TXOP limit of one frame, resulting in a minimum idle time of one Arbitration Interframe Space (AIFS), $t_{\text{aifs}} = T_{\text{sifs}} + \text{AIFSN} \times T_{\text{slot}}$. With default values of $\text{AIFSN} = 2$, $T_{\text{sifs}} = 32\,\mu\text{s}$, and $T_{\text{slot}} = 13\,\mu\text{s}$, we obtain $t_{\text{aifs}} = 58\,\mu\text{s}$. Providing for a true channel idle time t_{idle}, one can then obtain

$$b_t = \frac{t_{\text{busy}}}{t_{\text{busy}} + t_{\text{aifs}} + t_{\text{idle}}} . \quad (3)$$

For $t_{\text{idle}} = 0$ (i.e., a continuous stream of data without respecting the contention protocol) we obtain a theoretical maximum busy ratio $b_t \approx 0.64$. Taking into account contentions, as a first approximation, one can add the average initial backoff counter to $t_{\text{idle}} = 1.5 \times 13\,\mu\text{s} = 20.5\,\mu\text{s}$ ($CW_{\text{min}} = 3$) and obtain $b_t \approx 0.57$.

The impact of collisions on safety applications is catastrophic, thus we want to keep the channel load to a level that guarantees a marginal collision rate, let's say $p_{\text{coll}} \leq 0.05$. The computation of collision rates in 802.11 networks is complex, and to the best of our knowledge there are no simple models available to do it. However, disregarding the backoff freezing on successive attempts, we can approximate it with the probability that two or more stations have a beacon to transmit while the channel is busy multiplied by the probability that at least two stations chose the same backoff within the contention window. Easy combinatorics (not reported here for the sake of brevity) leads to a desired channel busy ratio of $b_{\text{des}} = 0.25$ for values of N compatible with vehicular networks.

IV. Simulation Setup and Scenarios

In order to cross-check our analytical considerations we conducted a simulative study using the vehicular network simulation framework Veins [15], which integrates the OMNeT++ network simulator with the SUMO road traffic simulator. Veins builds on the MiXiM framework physical layer model, which allowed us to implement in our simulation the building shadowing model presented in [9] and the vehicular shadowing model presented by Boban et al. [11].

The used packet error and Medium Access Control (MAC) layer models are based on the IEEE 802.11p model presented in [16], using a rate of $18\,\text{Mbit}\,\text{s}^{-1}$, a transmission power of $20\,\text{mW}$, and a receiver sensitivity of $-94\,\text{dBm}$. For eliminating effects caused by channel switching between the Control Channel (CCH) and the Service Channel (SCH), we changed the model to use the CCH only. Further, we set the MAC queue size to one; in practice, beacons will never be queued, but instead be replaced with new information when available. In addition, all beacons use the same Access Category (AC) AC_VO, which results in parameters of $\text{CW}_{\text{min}} = 3$, $\text{CW}_{\text{max}} = 7$, and $\text{AIFSN} = 2$.

Building on this, we implemented simulation models of both the TRC and the DynB algorithm (cf. Section III) for adaptive beaconing in a wide range of scenarios. We obtained 5 to 20 repetitions for each simulation experiment for statistical confidence, keeping seeds for pseudo random number generation constant across experiments and varying across repetitions.

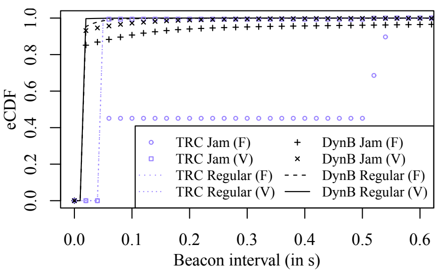
In order to study realistic vehicle-caused radio shadowing, we used a typical mix of different vehicles (90% cars and 10% trucks) with randomly distributed dimensions as listed in the SUMO documentation. All vehicles are moving according to the SUMO standard *Krauss* driver model.

In the *freeway scenario*, we simulated $10\,\text{km}$ of a straight freeway with two lanes in each direction, where trucks are only allowed to drive on the rightmost lane. We configured simulations of two densities that closely matched the inter-vehicle spacings of ~$exp(0.0039)\,\text{m}^{-1}$ and ~$exp(0.0238)\,\text{m}^{-1}$ presented in [17]. The jam scenario simply corresponds to choosing the minimum inter-vehicle space allowed by SUMO. Statistics for the evaluation have been recorded only for nodes in an $8\,\text{km}$ long Region of Interest (ROI), and after a warm-up period to fill the freeway with the desired vehicle density.

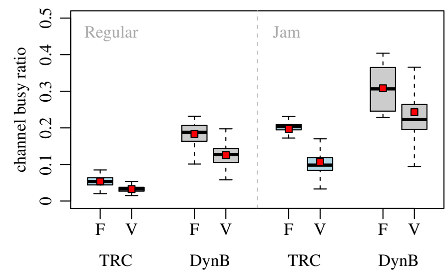
For the *suburban scenario*, we used real-world geodata [16] of the city of Ingolstadt, Germany from the OpenStreetMap project. We imported street (road geodata, speed limits, right-of-way, etc.) and building information (exact outlines of the buildings) into the road traffic simulator SUMO, configuring scenarios of three vehicle densities, $76.2\,\text{km}^{-2}$, $98.8\,\text{km}^{-2}$, and $171.5\,\text{km}^{-2}$. We simulated traffic in the whole city, but collected statistics only in a ROI of $1.5\,\text{km} \times 1\,\text{km}$.

V. Influence of Signal Shadowing on Beaconing Performance

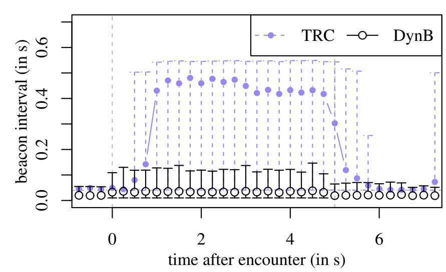
In a preliminary set of experiments, we evaluated the performance of static beaconing as was originally suggested by ETSI for cooperative awareness applications. We found that there is a substantial impact of the radio signal shadowing model on the suggested performance of the beaconing protocols. Investigating the number of neighbors, we found that it is substantially affected by radio signal shadowing, dropping by an order of magnitude in the suburban scenario (building and vehicle shadowing) and being cut in half in the freeway scenario (vehicle shadowing only). Thus, the level of cooperative awareness is much lower compared to the levels suggested by some previous studies. This negative effect does, however, come with a positive effect. Considering the number of collisions, we found that if building and/or vehicle shadowing is considered



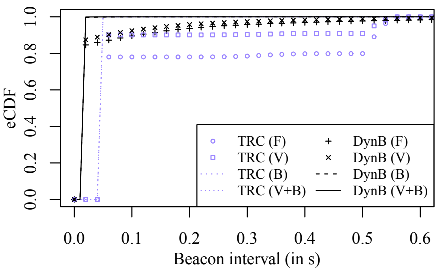
(a) beacon interval (freeway)



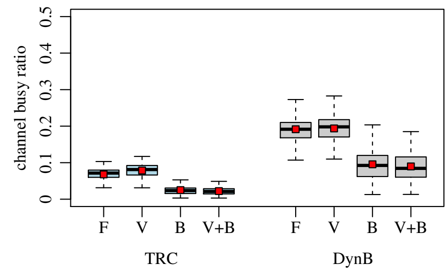
(b) channel busy ratio (freeway)



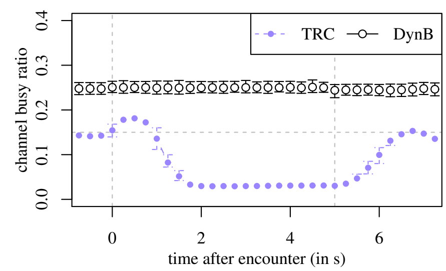
(c) Adaptation of beacon interval when the two clusters meet.



(d) beacon interval (suburban)



(e) channel busy ratio (suburban)



(f) Impact on channel busy ratio when the two clusters meet.

Figure 2. Comparison of TRC and DynB in the suburban and the freeway scenario, as well as when two clusters meet.

their number is reduced to manageable levels even in dense suburban and freeway scenarios.

Finally, our results also indicated that no specific beacon interval is clearly appropriate for all the scenarios, so it can be said that adaptive beaconing is not only needed but the only alternative. This finding is in line, even though differently motivated, with related works on adaptive beaconing [3], [4], [6], [8].

VI. Benefits of Dynamic Beaconing

The overall behavior of TRC and DynB is directly reflected in their dynamic and adaptive selection of the beacon interval. We plot this metric as an empirical Cumulative Density Function (eCDF) of chosen beacon intervals – by the nature of the algorithms this distribution is highly irregular. The individual plots show the channel busy ratio for radio shadowing models of four different fidelities: freespace only (F), shadowing by vehicles (V), by buildings (B), and by both (V+B).

The comparatively low density of vehicles in all regular freeway scenarios (plotted as lines in Figure 2a) allows TRC to always send at its highest configured rate ($I_{\min} = 40\,\text{ms}$). Similarly, even DynB can almost always pick its shortest configured interval ($I_{\min} = 10\,\text{ms}$). In the case of DynB, however, it is evident that this is only possible because other vehicles shield receivers from interference by neighbors: simulation runs that ignore shadowing by vehicles can be seen to force DynB to pick much larger beacon intervals, albeit infrequently (5 % of recorded observations).

The benefit of these shadowing effects is even more evident in jammed freeway scenarios (plotted as dots in Figure 2a). Here, simulations ignoring shadowing by vehicles would consistently suggest that much higher beacon intervals need to be picked. TRC, in particular, would send more than half of all beacons at a 0.5 s interval (note that, for TRC, we randomize beacon intervals in a range of 10 % to avoid the synchronized oscillation effects mentioned in Section III). The benefit of these shadowing effects is also very pronounced in suburban scenarios (cf. Figure 2d). Again, simulations ignoring shadowing by vehicles and/or shadowing by buildings would suggest that up to 20 % of beacons need to be delayed – in the case of TRC by up to 0.5 s.

For multihop information dissemination, as well as for any kind of safety applications, the behavior suggested by simulations ignoring shadowing effects would thus appear unacceptable. In reality, shadowing effects again allow both TRC and DynB to send at each of their configured minimum beacon interval ($I_{\min} = 40\,\text{ms}$ and $I_{\min} = 10\,\text{ms}$, respectively).

The channel load that results from these choices is illustrated in Figures 2b and 2e. Each graph shows the channel load distribution in the form of a boxplot. A box spans from the first to the third quartile and the median is marked with a thick line. Whiskers extend from the edges of the box towards the minimum and maximum of the data set, but no further than one and a half times the interquartile range. Furthermore, the mean is marked with a small red square.

The aggressive channel use of DynB is shown to lead to a channel busy ratio much closer to the value of $b_{\text{des}} = 0.25$ derived in Section III, a value that will keep the number of collisions at an acceptable level. This is in sharp contrast to the results suggested by simulations that ignore shadowing effects: these would suggest that DynB is prone to overloading the channel.

We thus follow that the more aggressive channel use is made possible, to a large part, because of radio shadowing by both vehicles and buildings.

In all three of the realistic simulation scenarios (highway, jam, and suburban environment) the more aggressive use of channel capacity thus allows for more information to be delivered. This affects both multihop data delivery efficiency, where the total throughput of data is important, and safety applications, such as a collision warning system, where a delay of 500 ms even on a single message can be unacceptable.

VII. Behavior in Highly Dynamic Scenarios

DynB was theoretically derived in Section III to be stable under heavy network congestion, and to be able to quickly react to density changes. To validate the theoretical results, we conduct simulations for an extreme case of topology dynamics: two disconnected clusters of 100 nodes each, both fully meshed, meet for 5 s.

The impact of each algorithm was then observed over the course of 30 s. For simulations that converge towards stable behavior (TRC at low node densities and DynB at any density) we discard observations in the transient phase; for simulations that keep oscillating (TRC at higher node densities) we fix the transient phase to 10 s. For the remaining 30 s, we calculate the mean value of the beacon interval and the channel busy ratio, as well as the 5^{th} and 95^{th} percentile.

Figure 2c illustrates that both algorithms successfully and dynamically choose the beacon interval according to changes in the number of neighbors. However, whereas TRC adapts the beacon interval with a delay and only to discrete values either too high or too low (the plotted percentiles span the whole range), DynB reaches its goal of reacting almost instantly to such changes and with only a minimal increase in the interval.

Figure 2f illustrates the background of this behavior, plotting values of the channel busy ratio, the core metric of both algorithms. TRC uses thresholds of the channel busy ratio to switch between states. As these measurements are averaged over time, this leads to a pronounced delay until it can react to changes in network topology. In order to compensate for this, it needs to target an overall under-utilization of the channel, as evidenced by the plots.

DynB succeeds at its goal of adjusting the channel utilization more quickly and more smoothly. No over- or undercompensation for the change in network topology can be observed; the adaptation is almost instant. Thus, DynB can target much smaller beacon intervals, always keeping the channel busy ratio as close as possible to $b_t = 0.25$.

VIII. Conclusion

We studied the challenges of vehicular communications in the presence of radio signal obstructions caused by other vehicles and by buildings. Our simulation results clearly indicate that signal shadowing is the source of much higher dynamics leading to a substantially reduced performance for static period beaconing as well as for adaptive beaconing solutions that do not react properly to environment changes.

Yet, we have also identified opportunities such as a clearly reduced channel load that can be taken advantage of. As a result of these observations, we developed Dynamic Beaconing (DynB), a novel approach to adaptive beaconing that explicitly focuses on the mentioned opportunities. The presented simulation results substantiate our theoretical analysis.

In conclusion, it can be said that our approach, DynB, opens up the road for a new generation of dynamic beaconing solutions that react more aggressively to dynamics in the network – caused, for example, by time-variant signal shadowing effects.

References

[1] E. Schoch, F. Kargl, M. Weber, and T. Leinmüller, "Communication Patterns in VANETs," *IEEE Communications Magazine*, vol. 46, no. 11, pp. 119–125, November 2008.

[2] O. K. Tonguz, N. Wisitpongphan, and F. Bai, "DV-CAST: A distributed vehicular broadcast protocol for vehicular ad hoc networks," *IEEE Wireless Communications*, vol. 17, no. 2, pp. 47–57, April 2010.

[3] C. Sommer, O. K. Tonguz, and F. Dressler, "Traffic Information Systems: Efficient Message Dissemination via Adaptive Beaconing," *IEEE Communications Magazine*, vol. 49, no. 5, pp. 173–179, 2011.

[4] R. K. Schmidt, T. Leinmüller, E. Schoch, F. Kargl, and G. Schäfer, "Exploration of adaptive beaconing for efficient intervehicle safety communication," *IEEE Network Magazine*, vol. 24, no. 1, pp. 14–19, January 2010.

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

[6] C. Sommer, O. K. Tonguz, and F. Dressler, "Adaptive Beaconing for Delay-Sensitive and Congestion-Aware Traffic Information Systems," in *IEEE VNC 2010*, Jersey City, NJ, December 2010, pp. 1–8.

[7] M. Werner, R. Lupoaie, S. Subramanian, and J. Jose, "MAC Layer Performance of ITS G5," in *ETSI TC ITS Workshop*, Doha, Qatar, February 2012.

[8] 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," ETSI, TS 102 687 V1.1.1, July 2011.

[9] C. Sommer, D. Eckhoff, R. German, and F. Dressler, "A Computationally Inexpensive Empirical Model of IEEE 802.11p Radio Shadowing in Urban Environments," in *IEEE/IFIP WONS 2011*, Bardonecchia, Italy, January 2011, pp. 84–90.

[10] T. Mangel, F. Schweizer, T. Kosch, and H. Hartenstein, "Vehicular safety communication at intersections: Buildings, Non-Line-Of-Sight and representative scenarios," in *IEEE/IFIP WONS 2011*, Bardonecchia, Italy, January 2011, pp. 35–41.

[11] M. Boban, T. Vinhosa, J. Barros, M. Ferreira, and O. K. Tonguz, "Impact of Vehicles as Obstacles in vehicular Networks," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 1, pp. 15–28, 2011.

[12] F. J. Ros, P. M. Ruiz, and I. Stojmenovic, "Reliable and Efficient Broadcasting in Vehicular Ad Hoc Networks," in *IEEE VTC2009-Spring*, Barcelona, Spain, April 2009, pp. 1–5.

[13] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Vehicular communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 1: Media-Independent Functionality," Tech. Rep. ETSI TS 102 636-4-1 V1.1.1, June 2011.

[14] "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," IEEE, Std 802.11, 2007.

[15] 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, pp. 3–15, 2011.

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

[17] N. Wisitpongphan, F. Bai, P. Mudalige, and O. K. Tonguz, "On the Routing Problem in Disconnected Vehicular Ad-hoc Networks," in *IEEE IEEE INFOCOM 2007*, Anchorage, AK, May 2007, pp. 2291–2295.