How Shadowing Hurts Vehicular Communications and How Dynamic Beaconing Can Help

Christoph Sommer, *Member, IEEE*, Stefan Joerer, *Student Member, IEEE*, Michele Segata, *Student Member, IEEE*, Ozan K. Tonguz, *Member, IEEE*, Renato Lo Cigno, *Senior Member, IEEE*, and Falko Dressler, *Senior Member, IEEE*

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. To mitigate the broadcast storm problem, adaptive beaconing solutions have been proposed and designed. We show how shadowing dynamics of moving obstacles hurt IVC, reducing the performance of beaconing protocols. To the best of our knowledge, this is one of the first studies on identifying the problem and the underlying challenges and proposing the opportunities presented by such challenges. Shadowing also limits the risk of overloading the wireless channel. 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.

Index Terms—Inter-Vehicular Communication, Vehicular Ad Hoc Network, Parked Vehicles, Roadside Unit, Road Safety Applications

1 INTRODUCTION

INTELLIGENT Transportation Systems (ITSs) have become one of the major fields of research in the networking community. Essentially, infrastructure based approaches (e.g., using cellular networks like 3G/4G) and direct communication between vehicles using short range radio broadcast can be distinguished as two complementary approaches. In the scope of this paper, we focus on the latter concept for IVC.

Depending on the application scenario, IVC can be categorized into several classes ranging from safety critical applications (e.g., intersection assistance) to efficiency applications (e.g., traffic information systems) and finally to entertainment applications (e.g., video streaming) [2]. We concentrate on the first two classes of applications, which are clearly at the center of short range radio broadcast communication based systems.

IEEE 802.11p DSRC (Dedicated Short-Range Communication) has been standardized as a new protocol for inter-vehicle communication [3]. Protocols used for information dissemination are application centric, i.e., the design was driven and motivated by specific requirements. Safety applications demand extremely low transmission latency; at the same time it is assumed that the message frequency is rather low. In addition, each message is required to reach as many neighboring vehicles as possible in due time [4].

Efficiency applications, on the other hand, aim to disseminate messages over a much larger area. Here, timeliness being not that critical [4], the optimal use of the wireless channel is particularly important [5].

In the last couple of years, it turned out that, in the context of IVC safety and informational applications, beaconing based dissemination concepts are not only adequate, but clearly outperform classical routing approaches [5], [6], [7], [8]. 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 [3]. These messages, which are designed to be broadcast periodically with a fixed beaconing interval in the range of 0.1 s to 1 s, form the basis for establishing cooperative awareness among vehicles in communication range.

- *C. Sommer and F. Dressler are with the Department of Computer Science, University of Paderborn, Paderborn, Germany. E-mail: {sommer, dressler}@ccs-labs.org.*
- *S. Joerer is with the Department of Computer Science, University of Innsbruck, Innsbruck, Austria. E-mail: joerer@ccs-labs.org.*
- *M. Segata is with the Department of Computer Science, University of Innsbruck, Innsbruck, Austria, and the University of Trento, Trento, Italy. E-mail: segata@ccs-labs.org.*
- *O.K. Tonguz is with Carnegie Mellon University, Pittsburgh, PA. E-mail: tonguz@ece.cmu.edu.*
- *R. Lo Cigno is with the Dipartimento di Ingegneria e Scienza dell'informazione, University of Trento, Trento, Italy. E-mail: locigno@disi.unitn.it.*

Manuscript received 7 July 2013; revised 15 Sept. 2014; accepted 18 Sept. 2014. Date of publication 12 Oct. 2014; date of current version 1 June 2015. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below. Digital Object Identifier no. 10.1109/TMC.2014.2362752

Mainly based on simulation experiments, it has been extensively discussed that fixed period beaconing easily leads to severe channel congestion, similar to what has been described as the broadcast storm problem [9]. As a result, adaptive beaconing protocols have been developed [5], [6], [8]. More recently, Decentralized Congestion Control (DCC) has been suggested in ETSI ITS-G5 to cope with congestion problems [10], [11]. All these works, however, assumed optimal (i.e., unobstructed) channel conditions.

Only in the past 2-3 years, theoretical modeling approaches supported by measurement campaigns have clearly shown that signal shadowing and fading could substantially impact the wireless communication between neighboring vehicles [12], [13], [14]. Radio signals are attenuated over distance; fading characterizes the deviation from this attenuation over time and space due to multi-path effects or blocking obstacles [15]. We use the term *shadowing* to describe slow fading effects caused by the additional attenuation due to obscuring obstacles between transmitter and receiver.

In this paper, which is based on our earlier work in [1], 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 in the context of IVC that identifies problems caused by radio shadowing due to mobile and stationary obstacles and analyzes the consequent challenges.

We show that fixed period beaconing as well as moderately reactive adaptive approaches as currently suggested by standardization bodies like ETSI 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.

As a result, we have come up with a new dynamic beaconing approach Dynamic Beaconing (DynB), which performs much better than the mechanisms adopted by ETSI, namely the Transmit Rate Control (TRC). Dynamic beaconing paves the way 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.

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 (Section 3).
- 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 (Section 4).
- 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 (Section 5).

2 Related Work

A diverse body of literature exists that describes a wide range of promising approaches to information dissemination in vehicular networks. Such approaches need to be able to deal with the highly dynamic network topology prevalent in vehicular networks, but can, at the same time, exploit specific characteristics of the deployment scenario. One example are Disruption Tolerant Networking (DTN) and opportunistic approaches, such as Distributed Vehicular Broadcast (DV-CAST), which can benefit from vehicles on opposite lanes to transmit data between disconnected clusters of vehicles [6]. Other approaches exploit patterns in inter-contact times for opportunistic information dissemination [16].

A different class of approaches targets undirected dissemination of information, e.g., for cooperative awareness applications. Originally, ETSI suggested CAM messages at fixed broadcasting intervals in the range of 0.1 s to 1 s for these applications. These include information such as speed, position, and heading. Vehicles are envisioned to periodically broadcast these messages to all nodes in their vicinity to inform them about their presence.

There is a considerable amount of scientific work on such cooperative awareness and safety applications using periodic beacon messages [5], [6], [7]. To elaborate on one example, Ros et al. proposed a protocol to increase the reliability while minimizing the number of beacon retransmissions [17]. 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 first adaptive beaconing system proposed was REACT [18]. Based only on neighbor detection, it can skip intervals for beacon transmission to support emergency applications. Recent approaches, also supported by ETSI, suggest to combine beaconing with geographical knowledge [19]. The resulting GeoCast provides means for more efficient channel use [20], [21].

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 [5], [21]. This is to prevent what is commonly known as the broadcast storm problem [9]. In selected cases, also the control of the transmission power helps to increase spatial reuse of the wireless channel [22]. Recently, building on earlier approaches to cope with congestion problems [10], [11], DCC has been proposed in ETSI ITS-G5 and it has been suggested to combine beaconing with geographical knowledge [19].

In earlier works, 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 [5].

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.

This shortcoming has been identified in the community and several groups started modeling the resulting shadowing effects. Based on empirical measurements, Mangel et al. came up with one of the first models covering realistic urban environments by using a mapping between street dimensions and available measurement results [13]. At the same time, a more detailed modeling approach of the shadowing caused by buildings has been presented [12]. This work considers the specific makeup of most buildings, especially in suburban environments: depending on how far a transmission has to penetrate through a building's interior, the attenuation that it will experience varies slightly; in addition, a thick outer wall heavily attenuates transmissions. Further effects, caused by neighboring vehicles, have been investigated in depth by Boban et al. [14] and a new routing approach has been proposed that favors tall vehicles.

To the best of our knowledge, this is one of the first studies on the identification of problems caused by radio shadowing due to mobile and stationary obstacles and the consequent challenges. We take the resulting opportunities and challenges into account for designing a novel dynamic beaconing algorithm that opens up new possibilities for a new generation of beaconing solutions that react more effectively to dynamics in the network caused, for example, by time-variant signal shadowing effects.

3 Modeling Radio Signal Shadowing

When modeling signal shadowing effects, two types of obstacles need to be considered: static and moving obstacles. In the domain of vehicular networks these are, first and foremost, buildings and vehicles. It has been shown in the literature that radio signal shadowing has a substantial impact on the performance of wireless communication protocols [12], [13], [14].

3.1 Buildings

Depending on the effects that should be captured, a different level of granularity—from a highly complex, fully deterministic model to a simple, fully stochastic one—is applicable. Accordingly, there exists a whole body of literature on how to properly model radio obstructions in wireless networks.

In the context of radio shadowing by buildings, we focus on the effects of repeated, reproducible medium-scale reception drop-outs only. In the interest of computational feasibility for large scale simulation, we thus rely on the simplest model that is still able to capture these effects.

We presented and validated such a model in [12]. The model abstracts from all reflection and diffraction effects and relies only on building outlines, which are commonly available in modern geodata bases (e.g., the OpenStreetMap project). We were able to show that, using model fitting, this model can quantitatively capture medium-scale path

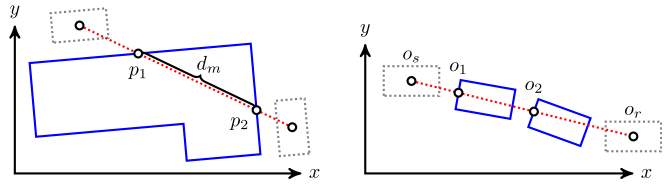


Fig. 1. Calculation of line of sight intersection points with buildings and vehicles, cast as a *red and blue line segments* intersection problem.

loss effects in suburban environments. Thus, even forgoing model fitting to a specific location, the model helps us achieve our goal of qualitatively capturing reproducible reception drop-outs.

We model the impact of buildings on power loss L_{static} as follows. For each signal transmission between a pair of vehicles, we consider the direct line of sight a between both. Given the set of line segments $B = \{b_1, b_2, \dots\}$ that make up 2D building outlines, we calculate the set of intersection points $P = \{p_1, p_2, \dots\}$ of a and B, ordered along a, as illustrated in Fig. 1a. We consider the number of intersections, $n = |P|$, and the sum of distances between every second pair of intersection points, $d_m = \sum_{i=1}^{n/2} \|p_{2i} - p_{2i-1}\|$.

Power loss is then estimated as $L_{\text{static}} = \beta n + \gamma d_m$, with $\beta = 9.6\,\text{dB}$ per wall and $\gamma = 0.45\,\text{dBm}^{-1}$ being empirically determined factors that gave good agreement between measurements and the model [12].

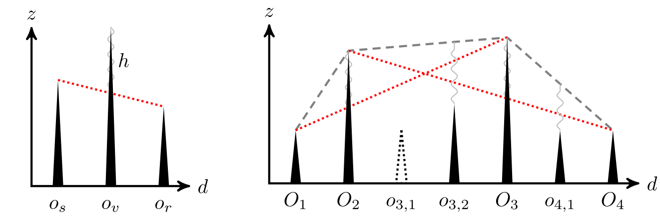
Of these calculations, finding the intersections between all lines of sight and all buildings is the most expensive step. Using binary space partitioning or treating this problem as a *red and blue line segments* intersection problem, however, can allow solving this step in $\mathcal{O}(n^2 \log n)$ [23]—with promising extensions to $\mathcal{O}(n \log n)$ [24] time, respectively. Intelligent caching of computed results can further reduce the effort for repeated transmissions, such as retries within the channel coherence time.

3.2 Moving Vehicles

For the calculation of the impact of moving vehicles on power loss L_{moving}, we employ a technique similar to that presented in [14].

For every signal transmission between a pair of vehicles o_s and o_r, we identify the set of vehicles that intersect their direct line of sight. As illustrated in Fig. 1b, we store all points where this line of sight enters the bounding box of a vehicle as $\{o_1, o_2, \dots\}$. Similar to the problem of finding obstructing buildings, this problem can be cast as a *red blue intersection* problem, drastically reducing its computational complexity below that of a brute force search.

For calculating the signal power loss by an individual obstacle in-between sender and receiver, a *single knife edge* approximation according to ITU-R recommendations [25] is employed. This method uses a geometrical parameter v to determine how much of the first Fresnel zone is obstructed by the obstacle. As illustrated in Fig. 2a, this takes into account the relative height h of the obstacle above ($h > 0$) or below ($h < 0$) the straight line joining sender and receiver. Given the distances d_1 and d_2 to



(a) Single knife edge (b) Multiple knife edge approximation

Fig. 2. Approximation of signal power loss by moving vehicles.

both, as well as the wavelength λ, the geometrical parameter is then calculated as

$$v = h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)}. \quad (1)$$

In the implemented model, power loss is assumed to only occur for a geometrical parameter of $v > -0.7$ (a better fit than the ITU-R recommended empirical value of $v > -0.78$). In these cases, the loss is calculated in dependence of sender o_s, obstructing vehicle o_v, and receiver o_r as

$$L_{o_s,o_v,o_r}[dB] = 6.9 + 20\log_{10}\left(\sqrt{(v-0.1)^2+1}+v-0.1\right). \quad (2)$$

This single knife edge method is then generalized to a multiple knife edge method using a variant of the Epstein-Peterson method with an applied correction term. First, *major* obstacles $M = \{O_1, O_2, \dots\}$ (those touching a virtual rope stretched from the sender, over all obstacles, and to the receiver) are identified and ordered by their distance from the transmitter, as illustrated in Fig. 2b. The transmitter and receiver constitute the first and last members of M, respectively. Obstacles in-between major obstacles O_{i-1} and O_i are stored as *minor* obstacles $M'_i = \{o_{i,1}, o_{i,2}, \dots\}$.

Obstacles in-between each pair of major obstacles that will cause the most obstruction are then stored as $o_{i,\max}$ to calculate the power loss due to major obstacles L_M as well as the power loss $L_{M'}$ due to minor obstacles for each adjacent pair of major obstacles as follows:

$$L_M[dB] = \sum_{i=3}^{|M|} L_{O_{i-2},O_{i-1},O_i}[dB], \quad (3)$$

$$L_{M'}[dB] = \sum_{i=2}^{|M|} L_{O_{i-1},o_{i,\max},O_i}[dB], \quad \text{with} \quad (4)$$

$$o_{i,\max} = \underset{o_{i,j}\in M'_i}{\arg\max}\, L_{O_{i-1},o_{i,j},O_i}[dB]. \quad (5)$$

A correction term which takes into account the pairwise distances $S = \{s_1, s_2, \dots\}$ in-between major obstacles is needed and calculated as

$$L_c[dB] = -10\log_{10}\frac{\left(\prod_{i=1}^{|S|} s_i\right)\left(\sum_{i=1}^{|S|} s_i\right)}{\left(\prod_{i=2}^{|S|} s_{i-1}+s_i\right) s_1\, s_{|S|}}. \quad (6)$$

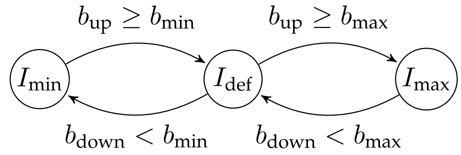


Fig. 3. State machine of the TRC algorithm.

Finally, the compound power loss by moving obstacles is the sum of all terms:

$$L_{\text{moving}}[dB] = L_M[dB] + L_{M'}[dB] + L_c[dB]. \quad (7)$$

4 Dynamic Beaconing

Beacons support cooperative awareness, so they should be sent at an interval ensuring the delivery to all interested receivers within a proper deadline. The correct interval depends on network conditions and propagation scenario, as in congested or bad networking conditions it is preferable to have a larger interval, rather than risking 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 TRC mechanism [11] to adapt I based on a simple state machine as depicted in Fig. 3. 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 $b_{\text{up}} = \min\{b_{t-T_{\text{up}}}, \dots, b_t\}$ and $b_{\text{down}} = \max\{b_{t-T_{\text{down}}}, \dots, b_t\}$; they are compared against threshold values $b_{\min}$ and $b_{\max}$. Table 1 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 $\{I_{\min}, I_{\text{def}}, I_{\max}\}$, as shown in Fig. 3.

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 [10]. Moreover, in highly dynamic scenarios (cf. Section 5) we show that the algorithm can also lead to the opposite: a pronounced over-load of the channel and, thus, packet loss.

TABLE 1
Parameters of the Implemented Algorithms

Method	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

The DCC TRC mechanism shows weak performance due to 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 Dynamic Beaconing (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}.

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

$$I = I_{\mathrm{des}}(1 + rN). \tag{8}$$

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 $l = 512\,\mathrm{bit}$ at $18\,\mathrm{Mbits}^{-1}$ according to the operation of the PLME-TXTIME.*confirm* primitive described in [26, Section 17.4.3]:

$$t_{\mathrm{busy}} = T_{\mathrm{preamble}} + T_{\mathrm{signal}} + T_{\mathrm{sym}} \left\lceil \frac{16 + l + 6}{N_{\mathrm{DBPS}}} \right\rceil. \tag{9}$$

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

For a packet transmitted on the Control Channel (CCH) with an application layer priority that maps to AC_VO, default parameters according to [3, Section 7.3.2.29] dictate a Transmission Opportunity TXOP limit of one frame, resulting in a minimum idle time of one Arbitration Interframe Space (AIFS), $t_{\mathrm{aifs}} = T_{\mathrm{sifs}} + \mathrm{AIFSN} \times \mathrm{T_{slot}}$. With default values of $\mathrm{AIFSN} = 2$, $T_{\mathrm{sifs}} = 32\,\mu\mathrm{s}$, and $T_{\mathrm{slot}} = 13\,\mu\mathrm{s}$, we obtain $t_{\mathrm{aifs}} = 58\,\mu\,\mathrm{s}$. Providing for a true channel idle time t_{idle}, one can then obtain

$$b_t = \frac{t_{\mathrm{busy}}}{t_{\mathrm{busy}} + t_{\mathrm{aifs}} + t_{\mathrm{idle}}}. \tag{10}$$

For $t_{\mathrm{idle}} = 0$ (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 $t_{\mathrm{idle}} = 1.5 \times 13\,\mu\mathrm{s} = 20.5\,\mu\mathrm{s}$ ($CW_{\min} = 3$) 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 $p_{\mathrm{coll}} \leq 0.05$. 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 (CW). Easy combinatorics (not reported here for the sake of brevity) leads to a desired channel busy ratio of $b_{\mathrm{des}} = 0.25$ for values of N compatible with vehicular networks.

5 Evaluation

We investigate the effects of beaconing approaches in an extensive set of simulations, studying challenges and opportunities of radio signal shadowing. We first present the simulation setup including the used models and scenarios, before investigating the beaconing based approaches.

5.1 Simulation Setup

We are using Veins [27], which integrates the OMNeT++ network simulator with the SUMO road traffic simulator. Veins builds on the MiXiM framework physical layer model, which allows the implementation in the simulator of the building and vehicle shadowing models discussed in Section 3. We run 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.

5.1.1 Physical and MAC Layer Models

The packet error and Medium Access Control (MAC) layer models adopted are based on the IEEE802.11p model presented in [28], using a rate of $18\,\mathrm{Mbits}^{-1}$, a transmission power of $20\,\mathrm{mW}$, and a receiver sensitivity of $-94\,\mathrm{dBm}$. For eliminating effects caused by channel switching between the 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 they will be replaced with new information when available. In addition, all beacons use the same Access Category (AC) AC_VO, which results in the Contention Window and AIFSN parameters mentioned in Table 2. This table also summarizes all other communication related parameters.

5.1.2 Scenario Description

In order to study realistic vehicle-caused radio shadowing, we used a typical mix of different vehicles (90 percent cars and 10 percent trucks), listed in the SUMO documentation. Table 3 gives the parameters (length, width, height, and max speed) and their distribution. The length and max speed variables have been normally distributed by SUMO

TABLE 2
PHY and MAC Parameters

Parameter	Value
Channel	Channel 178, 5.89 GHz
Bandwidth	10 MHz
Bitrate	$18\,\text{Mbits}^{-1}$
Transmission power	20 mW
Sensitivity	-94 dBm
CW_{min}, CW_{max}	3, 7
AIFSN	2

TABLE 3
Percentage (P) of Vehicle Types Together with Their Length (L), Width (W), Height (H), and Max Speed ($S_{\max}$)

Vehicle class	P (%)	L (m)	$E[W]$ (m)	$E[H]$ (m)	$Smax$ (ms^{-1})
Short Truck	3	$\sim N(8.05, 1.25)$	2.20	3.0	$\sim N(23.8, 2.25)$
Semitrailer	3	$\sim N(16.50, 1.00)$	2.40	4.0	$\sim N(23.6, 2.25)$
Trailer	4	$\sim N(18.75, 1.25)$	2.40	4.0	$\sim N(23.2, 2.25)$
Car 1	75	$\sim N(4.00, 0.09)$	1.75	1.5	$\sim N(33.8, 12.25)$
Car 2	15	$\sim N(4.70, 0.25)$	1.75	1.5	$\sim N(33.1, 6.25)$

TABLE 4
Scenario Configurations

Freeway	Inter-Vehicle Arrival Rate (s^{-1})	Inter-Vehicle Spacing (m)
Sparse	$\sim exp(0.7276)$	$\sim exp(0.0039)$
Dense	$\sim exp(0.1192)$	$\sim exp(0.0238)$
Traffic Jam	min()	min()
Suburban	**Total Number of Vehicles**	**Avg. Density (per k^2m)**
Sparse	1,500	76.2
Medium	2,000	98.8
Dense	4,000	171.5

with the specified standard deviation, because these two values also affect the behavior of the vehicles. The width and height parameters have been normally distributed by OMNeT++ with standard deviations of $\sigma_{\text{w}}^2 = \sigma_{\text{h}}^2 = 7.056\,\text{mm}$. All vehicles are moving according to the SUMO standard *Krauss* driver model.

In the *freeway scenario*, we simulated 10 km of a straight freeway with two lanes in each direction, where trucks are only allowed to drive on the rightmost lane. Table 4 summarizes the distribution of inter-vehicle arrival rate and spacing for different vehicle densities based on the results shown in [1], [29]. We calibrated the inter-vehicle spacings of our simulations to match these theoretical distributions (cf. Fig. 4). It can be seen that we are able to match the intended inter-vehicle spacing distribution well. 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 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 of the city of Ingolstadt, Germany from the OpenStreetMap project. We imported street (road geodata, speed limits,

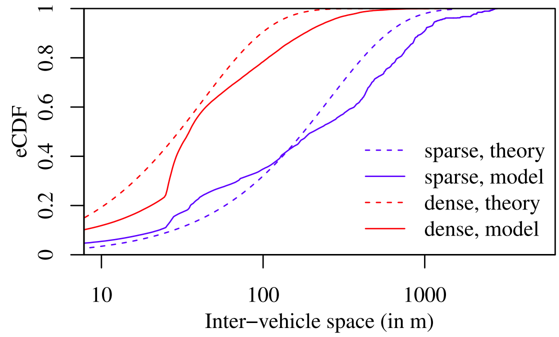


Fig. 4. Freeway vehicle densities.

Fig. 5. Suburban scenario: the city of Ingolstadt, Germany. Highlighted are the Regions of Interest for network communication and statistics collection.

right-of-way, etc.) and building information (exact outlines of the buildings) into SUMO and simulated traffic according to real world measurements. Table 4 gives an overview of the traffic parameters; a complete description can be found in [28]. We restricted the simulation of network communication to only that region of the scenario where high quality building geometry information was freely available (marked by a solid black rectangle in Fig. 5). To reduce border effects, statistics were only collected in the ROI marked by a dashed rectangle.

5.1.3 Metrics

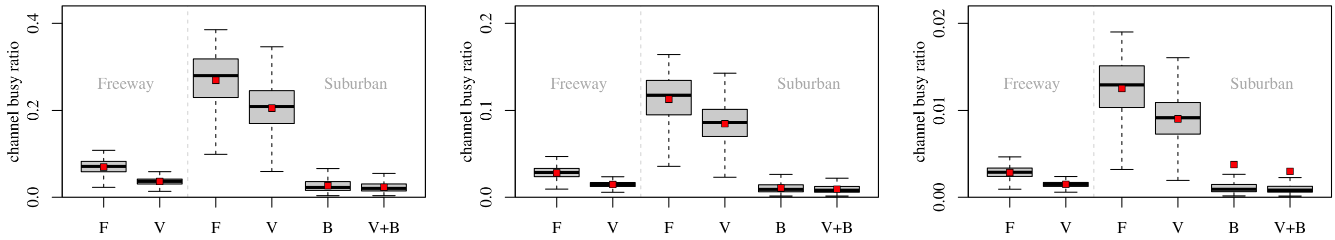
We rely on five metrics for evaluating the different beaconing approaches: the channel busy ratio, the number of received beacons, the beacon interval, the number of observed collisions, and the number of neighbors. These metrics are sufficient to assess the load of the wireless channel and the expected message latency.

The *channel busy ratio* measures the fraction of time that the physical layer observes the channel busy. As outlined in Section 4, it is expected to be below 0.57 even for high contention ratios.

We further count the *number of received beacons* during the whole simulation time. Combined with the channel busy ratio, this shows the efficiency of the beaconing approach.

The *beacon interval* reveals the behavior of adaptive beaconing approaches. This metric translates into responsiveness of the algorithm and latency to be expected by applications.

A table is used for the *number of one-hop neighbors* to track other vehicles in the local vicinity. An entry is added or updated when a beacon is received. Neighbors that were not updated for 390 ms, or 3.9 times the beaconing interval for static beaconing, are not counted in this metric.



(a) beacon interval 0.04 s (b) beacon interval 0.1 s (c) beacon interval 1.0 s

Fig. 6. Beacon performance (channel busy ratio) of static beaconing for the different radio shadowing scenarios.

Finally, we measured the *number of collisions*. We perform the stochastic decision process of whether a packet can be decoded twice, once based on the Signal to Interference plus Noise Ratio (SINR) and once based on the Signal to Noise Ratio (SNR) only, using the same pseudo random seed. If the two processes disagree, we attribute the frame drop to a collision with interfering transmissions, i.e., a collision.

5.2 Influence of Signal Shadowing on Beaconing Performance

In a first set of experiments, we evaluated the performance of static beaconing as was originally suggested by ETSI for cooperative awareness applications. The basic idea of such applications is to periodically send CAM messages describing the speed, heading, position, mass, etc. of a vehicle. Proposed intervals for such messages are commonly in the range of 0.1 s to 1 s. In our experiments, we simulated static beaconing with four different beacon intervals of 0.04 s, 0.1 s, 0.5 s, and 1.0 s, thus covering this interval range as well as the short interval allowed by the $I_{\min} = 0.04\,\mathrm{s}$ minimum beacon interval of TRC.

The key results of these simulations are shown in Fig. 6. We plot the channel busy ratio for static beacon intervals in both the suburban and the freeway scenarios for medium vehicle density. Each graph shows the results 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 individual boxplots show the channel busy ratio for radio shadowing models of different fidelity: freespace only ‘F’, vehicle shadowing ‘V’, shadowing caused by buildings ‘B’, and shadowing by buildings and vehicles ‘V+B’.

As can be seen (and as can be expected), there is a substantial impact of the radio signal shadowing model on the suggested performance of the beaconing protocols. The channel busy ratio clearly drops if the radio signal is heavily obstructed. This effect is already visible for shadowing by other vehicles and even more pronounced if buildings are considered. These effects are fully independent of the beacon interval. Similar results have been obtained for other vehicle densities (data not shown).

Table 5 lists selected statistics for the neighbor count and the number of collisions metrics. Each table gives the median values, along with the 5 and 95 percent quantiles, for both scenarios and all four shadowing model fidelities. Studying these numbers, we can clearly identify disadvantages but also advantages of the additional shadowing.

Starting with the neighbor count, we can see that the amount of vehicles that is able to receive beacons is substantially affected by radio signal shadowing. For the suburban scenario, it goes down from 162 (freespace only) to 129 (vehicle shadowing) and even to 11 or 10 if buildings are considered.

This trend is even more evident for the freeway results. 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 see that their number is reduced from 1131 to 940 or even to 0 in the suburban scenario, and from 64 to 41 in the highway scenario.

Even though positive and negative effects can be observed, the presented results also indicate that no specific beacon interval is clearly appropriate for all the scenarios.

In conclusion, 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 [5], [8], [11].

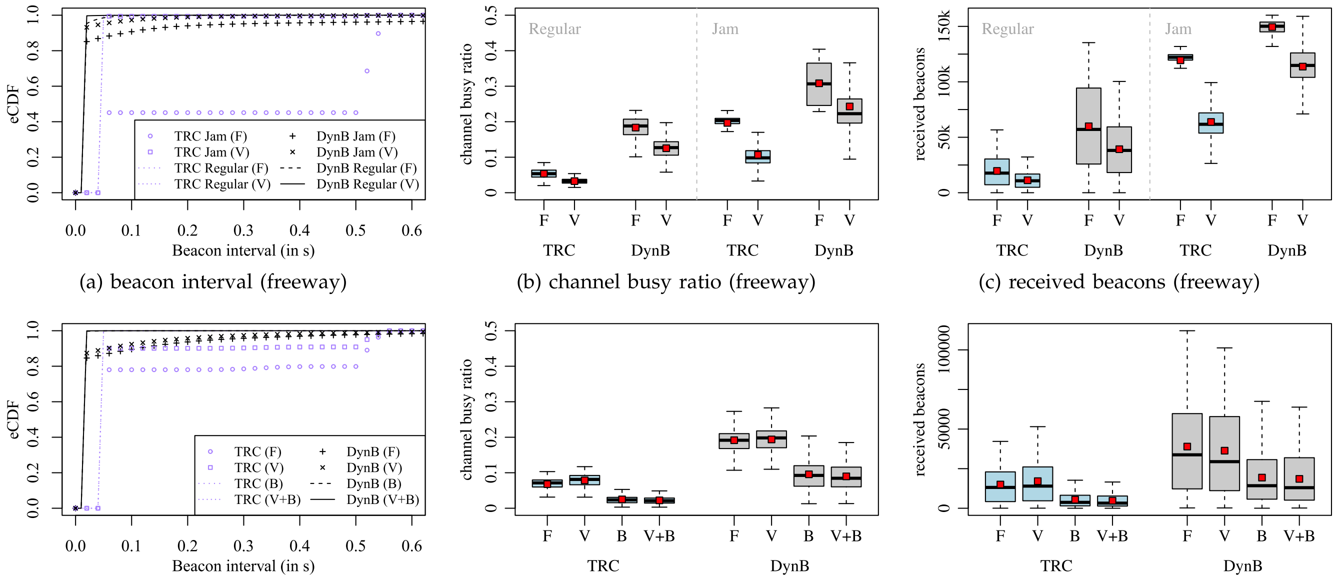
5.3 Benefits of Dynamic Beaconing

In a second step, we investigate the performance of dynamic beaconing approaches. We implemented simulation models of both the TRC and the DynB algorithm (cf. Section 4) and examine the same scenarios we presented in Section 5.2, replacing the static algorithm of the broadcast protocol with either TRC or DynB.

The overall behavior of both algorithms 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

TABLE 5
Selected Results for a Static Beacon Interval of 0.1 s

	Suburban				Freeway	
	F	V	B	V+B	F	V
	Number of neighbors					
5%	117	86	2	2	25	12
median	162	129	11	10	42	21
95%	192	157	34	28	57	32
	Number of collisions					
5%	7.4	8.0	0.0	0.0	0.0	0.0
median	1131.0	940.0	0.0	0.0	64.0	41.0
95%	4738.8	3782.6	106.2	111.6	509.0	292.4



(a) beacon interval (freeway) (b) channel busy ratio (freeway) (c) received beacons (freeway)

(d) beacon interval (suburban) (e) channel busy ratio (suburban) (f) received beacons (suburban)

Fig. 7. Comparison of TRC and DynB in both the suburban and the freeway scenario.

the nature of the algorithms this distribution is highly irregular.

Again, the comparatively low density of vehicles in all regular freeway scenarios (plotted as lines in Fig. 7a) allows TRC to always send at its lowest configured interval ($I_{\min} = 40\,\mathrm{ms}$). Similarly, even DynB can almost always pick its shortest configured interval ($I_{\mathrm{des}} = 10\,\mathrm{ms}$). 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 percent of recorded observations).

The benefit of these shadowing effects is even more evident in jammed freeway scenarios (plotted as dots in Fig. 7a). 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 $0.5\,\mathrm{s}$ interval (note that, for TRC, we randomize beacon intervals in a range of 10 percent to avoid the synchronized oscillation effects mentioned in Section 4). The benefit of these shadowing effects is also very pronounced in suburban scenarios (cf. Fig. 7d). Again, simulations ignoring shadowing by vehicles and/or shadowing by buildings would suggest that up to 20 percent of beacons need to be delayed—in the case of TRC by up to $0.5\,\mathrm{s}$.

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 ($I_{\min} = 40\,\mathrm{ms}$ and $I_{\mathrm{des}} = 10\,\mathrm{ms}$, respectively).

The channel load that results from these choices is illustrated in Figs. 7b and 7e. The aggressive channel use of DynB is shown to lead to a channel busy ratio much closer to the value of $b_{\mathrm{des}} = 0.25$ derived in Section 4, 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. It thus follows that the more aggressive channel use is made possible, to a large extent, because of radio shadowing by both vehicles and buildings.

How this affects IVC applications is illustrated in Figs. 7c and 7f, in which we plot the number of beacons that could be delivered to the application layer. In all three of the realistic simulation scenarios (highway, jam, and suburban environment) the more aggressive use of channel capacity 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 $500\,\mathrm{ms}$ even on a single message can be unacceptable.

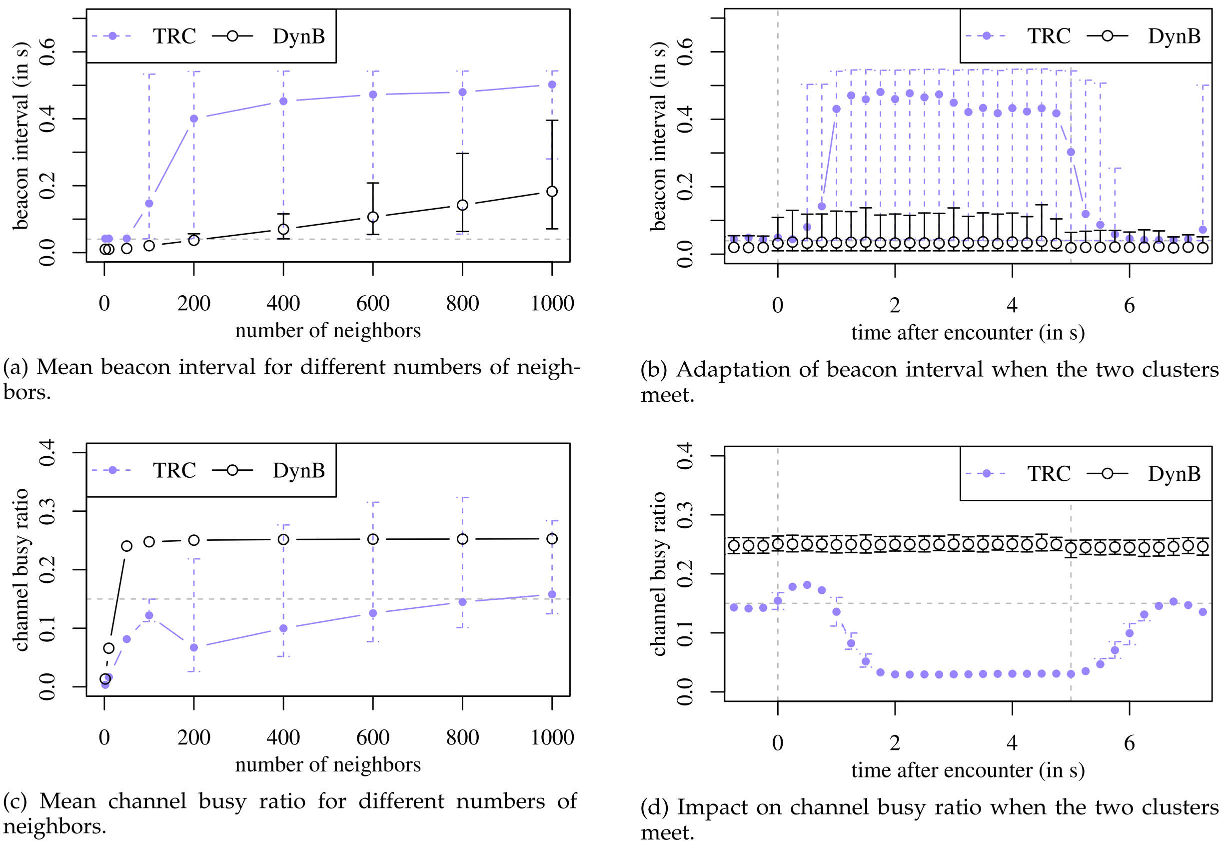
5.4 Behavior in Highly Dynamic Scenarios

DynB was theoretically derived in Section 4 to be stable under heavy network congestion, and to be able to quickly react to density changes. To validate the theoretical results, we simulate two artificial sets of scenarios.

In the first set of scenarios, a fixed number of nodes, from 2 to 1000 was configured into a static, fully meshed IEEE 802.11p wireless network. In the second set, we conduct simulations for an extreme case of topology dynamics: two disconnected clusters of 100 nodes each, both fully meshed, meet for $5\,\mathrm{s}$.

The impact of each algorithm was then observed over the course of $30\,\mathrm{s}$. 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 $10\,\mathrm{s}$. For the remaining $30\,\mathrm{s}$, we calculate the mean value of the beacon interval and the channel busy ratio, as well as the $5\mathrm{th}$ and $95\mathrm{th}$ percentile.

We plot the simulation results in Fig. 8. Fig. 8a illustrates that both algorithms successfully choose the beacon interval according to different, but constant numbers of neighbors.



(a) Mean beacon interval for different numbers of neighbors.

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

(c) Mean channel busy ratio for different numbers of neighbors.

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

Fig. 8. Channel capacity management as performed by the TRC and DynB algorithms (mean, 5th, and 95th percentile).

It also shows the discrete nature of beacon interval adaptation in TRC and how, at medium to high densities, TRC can oscillate between states in its state machine: the plotted percentiles span the whole range from $I_{\min}$ to I_{def}. DynB succeeds at its goal of smoothly adapting the beacon interval to the number of neighbors, exhibiting a linear correlation, and keeping much lower beacon intervals.

Fig. 8b illustrates that both protocols can also dynamically react to changes in the number of neighbors. Further, DynB reaches its goal of reacting almost instantly to such changes and with only a minimal increase in the beacon interval.

Figs. 8c and 8d illustrate 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 underutilization 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 $b_t = 0.25$.

5.5 Dissemination Speed

Besides the capabilities of DynB to manage the resources of the wireless channel, i.e., the available channel capacity, in a fair and very adaptive manner, we were also interested in the dissemination speed of new messages in the network. In a final experiment, we therefore created a *magic* beacon that we can trace when the attached information travels through the vehicular network. We kept the load in the network constant, i.e., started our magic beacon only after an initial simulation period in which the employed protocols were able to adapt their parameters to the current situation.

Fig. 9 plots the maximum distance this magic beacon is able to travel by time. As can be seen, DynB is substantially faster when it comes to relayed beacons compared to TRC. The maximum distance of interest (we configured this to $800\,\text{m}$) can be reached already after about $20\,\text{ms}$ (most of the simulation runs reported even smaller dissemination times of about $10\,\text{ms}$). In contrast, TRC is only able to reach the maximum distance after $60\,\text{ms}$, which is 200 percent slower compared to DynB.

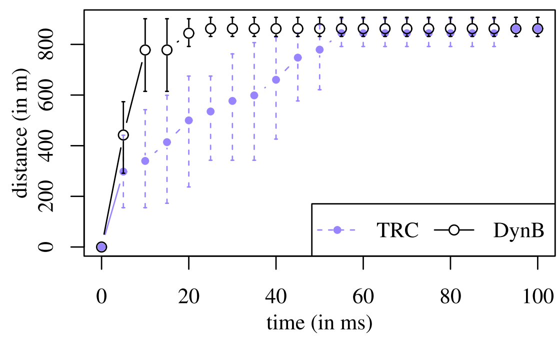


Fig. 9. Max. distance traveled by *magic* beacon vs. time.

6 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, we have come up with a new dynamic beaconing approach, Dynamic beaconing, which performs much better than the mechanisms adopted by ETSI, namely the Transmit Rate Control. The presented simulation results clearly substantiate our theoretical analysis.

In conclusion, it can be said that our approach, dynamic beaconing, paves the way for a new generation of dynamic beaconing solutions that react more aggressively to dynamics in the network—caused, for example, by time-varying signal shadowing effects.

Acknowledgments

The manuscript is based on earlier work on dynamic beaconing that was presented at IEEE INFOCOM 2013 [1].

References

[1] C. Sommer, S. Joerer, M. Segata, O. K. Tonguz, R. Lo Cigno, and F. Dressler, "How shadowing hurts vehicular communications and how dynamic beaconing can help," in *Proc. 32nd IEEE Conf. Comput. Commun. (INFOCOM 2013), Mini-Conf.*, Turin, Italy: IEEE, Apr. 2013, pp. 110–114.

[2] E. Schoch, F. Kargl, M. Weber, and T. Leinmüller, "Communication Patterns in VANETs," *IEEE Commun. Mag.*, vol. 46, no. 11, pp. 119–125, Nov. 2008.

[3] "Wireless access in vehicular environments," IEEE, Std 802.11p-2010, Jul. 2010.

[4] T. L. Willke, P. Tientrakool, and N. F. Maxemchuk, "A survey of inter-vehicle communication protocols and their applications," *IEEE Commun. Surv. and Tutorials*, vol. 11, no. 2, pp. 3–20, 2009.

[5] 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.

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

[7] P. Muhlethaler, A. Laouiti, and Y. Toor, "Comparison of flooding techniques for safety applications in VANETs," in *7th Int. Conf. ITS Telecommunications (ITST'07)*, Jun. 2007, pp. 1–6.

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

[9] S.-Y. Ni, Y.-C. Tseng, Y.-S. Chen, and J.-P. Sheu, "The broadcast storm problem in a mobile Ad Hoc Network," in *5th ACM Int. Conf. Mobile Comput. Networking (MobiCom 1999)*, Seattle, WA, Aug. 1999, pp. 151–162.

[10] M. Werner, R. Lupoaie, S. Subramanian, and J. Jose, "MAC Layer performance of ITS G5 - Optimized DCC and advanced transmitter coordination," in *4th ETSI TC ITS Workshop*, Doha, Qatar, Feb. 2012.

[11] 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, Jul. 2011.

[12] C. Sommer, D. Eckhoff, R. German, and F. Dressler, "A Computationally inexpensive empirical model of ieee 802.11p radio shadowing in urban environments," in *8th IEEE/IFIP Conf. Wireless Demand Network Syst. Serv. (WONS 2011)*, Bardonecchia, Italy: IEEE, Jan. 2011, pp. 84–90.

[13] T. Mangel, F. Schweizer, T. Kosch, and H. Hartenstein, "Vehicular Safety Communication at intersections: Buildings, non-line-of-sight and representative scenarios," in *8th IEEE/IFIP Conf. Wireless Demand Network Syst. Serv. (WONS 2011)*, Bardonecchia, Italy: IEEE, Jan. 2011, pp. 35–41.

[14] M. Boban, R. Meireles, J. Barros, P. Steenkiste, and O. K. Tonguz, "TVR - Tall Vehicle Relaying in Vehicular Networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 5, pp. 1118–1131, May 2014.

[15] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed, Prentice Hall, 2009.

[16] H. Zhu, S. Chang, M. Li, K. Naik, and S. Shen, "Exploiting temporal dependency for opportunistic forwarding in urban vehicular networks," in *30th IEEE Conf. Comput. Commun. (INFOCOM 2011)*, Shanghai, China: IEEE, Apr. 2011, pp. 2192–2200.

[17] F. J. Ros, P. M. Ruiz, and I. Stojmenovic, "Reliable and Efficient Broadcasting in Vehicular Ad Hoc Networks," in *69th IEEE Vehicular Technol. Conf. (VTC2009-Spring)*, Barcelona, Spain: IEEE, Apr. 2009, pp. 1–5.

[18] E. Van de Velde and C. Blondia, "Adaptive REACT protocol for Emergency Applications in Vehicular Networks," in *32nd IEEE Conf. Local Comput. Networks (LCN 2007)*, Dublin, Ireland: IEEE, Oct. 2007, pp. 613–619.

[19] 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," ETSI, TS 102 636-4-1 V1.1.1, Jun. 2011.

[20] D. Borsetti and J. Gozalvez, "Infrastructure-assisted geo-routing for cooperative vehicular networks," in *2nd IEEE Vehicular Networking Conf. (VNC 2010)*, Jersey City, NJ: IEEE, Dec. 2010, pp. 255–262.

[21] M. Sepulcre, J. Mittag, P. Santi, H. Hartenstein, and J. Gozalvez, "Congestion and Awareness Control in Cooperative Vehicular Systems," *Proc. IEEE*, vol. 99, no. 7, pp. 1260–1279, Jul. 2011.

[22] G. Caizzone, P. Giacomazzi, L. Musumeci, and G. Verticale, "A power control algorithm with high channel availability for vehicular ad hoc networks," in *IEEE Int. Conf. Commun. (ICC 2005)*, Seoul, Korea: IEEE, May 2005, pp. 16–20.

[23] R. Nagel and S. Eichler, "Efficient and Realistic Mobility and Channel Modeling for VANET Scenarios Using OMNeT++ and INET-Framework," in *1st ACM/ICST Int. Conf. Simulation Tools and Techniques Commun., Networks and Syst. (SIMUTools 2008)*, Marseille, France: ICST, Mar. 2008, pp. 1–8.

[24] A. Mantler and J. Snoeyink, "Intersecting Red and Blue Line Segments in Optimal Time and Precision," in *Japanese Conf. Discrete Comput. Geometry (JCDCG 2000): Revised Papers*, Tokyo, Japan: Springer, Nov. 2000.

[25] "Propagation by diffraction," ITU-R, Rec. P.526-10, Feb. 2007.

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

[27] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," *IEEE Trans. Mobile Comput.*, vol. 10, no. 1, pp. 3–15, Jan. 2011.

[28] D. Eckhoff, C. Sommer, and F. Dressler, "On the necessity of accurate IEEE 802.11p Models for IVC protocol simulation," in *75th IEEE Vehicular Technol. Conf. (VTC2012-Spring)*, Yokohama, Japan: IEEE, May 2012, pp. 1–5.

[29] N. Wisitpongphan, F. Bai, P. Mudalige, and O. K. Tonguz, "On the Routing Problem in Disconnected Vehicular Ad-hoc Networks," in *26th IEEE Conf. Comput. Commun. (INFOCOM 2007)*, Anchorage, AK, May 2007, pp. 2291–2295.

Christoph Sommer is an Assistant Professor (AkadR a.Z.) at the University of Paderborn, where he joined the Distributed Embedded Systems Group in 2014. He received his Ph.D. degree in engineering (Dr.-Ing., with distinction) and his M.Sc. degree in computer science (Dipl.-Inf. Univ.) from the University of Erlangen in 2011 and 2006, respectively. In 2010, he was a visiting scholar with the research group of Ozan K. Tonguz in the Electrical and Computer Engineering Department at Carnegie Mellon University (CMU). In 2012, he was a visiting scholar with the research group of Mario Gerla in the Computer Science Department at the University of California, Los Angeles (UCLA). Until 2014, he was a Postdoctoral Research Fellow with the Computer and Communication Systems Group at the University of Innsbruck. Since 2011, he has been a member of the *ACM/Springer Wireless Networks (WINET)* editorial board. His research is focused on questions regarding traffic efficiency and safety, as well as on security aspects of Car-to-X communication in heterogeneous environments. He is a member of the IEEE.

Stefan Joerer received his BSc and MSc degrees in Computer Science from the University of Innsbruck, Austria, in 2009 and 2011, respectively. In 2011, he joined the Computer and Communication Systems group at the University of Innsbruck as a PhD Student. His research is focused on protocols and applications of inter-vehicle communication. He is a student member of the IEEE.

Michele Segata received his B.Sc. and M.Sc. degrees in Computer Science from the University of Trento, Italy, in 2009 and 2011, respectively. He is now pursuing a joint PhD degree at the Universities of Innsbruck (Austria), and Trento (Italy), under the supervision of Professors Falko Dressler and Renato Lo Cigno. His PhD grant is funded by the BIT School, a joint effort of the Bolzano, Innsbruck and Trento local governments. He is currently working on simulation models, network protocols, and management strategies for autonomous driving, with particular focus on platooning. He is a student member of the IEEE.

Ozan K. Tonguz is a tenured full professor in the Electrical and Computer Engineering Department at Carnegie Mellon University (CMU). He currently leads substantial research efforts at CMU in the broad areas of telecommunications and networking. He has published about 300 papers in IEEE journals and conference proceedings in the areas of wireless networking, optical communications, and computer networks. He is the author (with G. Ferrari) of the book *Ad Hoc Wireless Networks: A Communication-Theoretic Perspective* (Wiley, 2006). In December 2010, he founded the CMU startup known as Virtual Traffic Lights, LLC, which specializes in providing solutions to acute transportation problems using vehicle-to-vehicle and vehicle-to-infrastructure communications paradigms. His current research interests include vehicular ad hoc networks, wireless ad hoc and sensor networks, self-organizing networks, smart grid, bioinformatics, and security. He currently serves or has served as a consultant or expert for several companies, major law firms, and government agencies in the United States, Europe, and Asia. He is a member of the IEEE.

Renato Lo Cigno is an Associate Professor in the Department of Computer Science and Telecommunications (DISI) at the University of Trento, Italy, where he leads the Advanced Network Systems research group in computer and communication networks. He received a degree in Electronic Engineering with a specialization in Telecommunications from Politecnico di Torino in 1988, the same institution where he worked until 2002. In 1998/1989, he was with the CS Dept., UCLA, as a Visiting Scholar. Dr. Lo Cigno has been General Chair of the IEEE Int. Conf. on Peer-to-Peer Computing, and General Chair and TPC Chair of ACM WMASH and IEEE WONS in different years. He has served on many TPCs of IEEE and ACM conferences, including INFOCOM, GLOBECOM, ICC, MSWiM, VNC, and CoNext, and has been Area Editor for Computer Networks. His current research interests are in performance evaluation of wired and wireless networks, modeling and simulation techniques, congestion control, P2P networks and networked systems in general, with specific attention toward applications and sustainable solutions. Dr. Lo Cigno is a senior member of the IEEE and ACM and has co-authored more than 150 papers in international, peer reviewed journals, and conferences.

Falko Dressler is a Full Professor of Computer Science and head of the Distributed Embedded Systems Group in the Dept. of Computer Science, University of Paderborn. Before moving to Paderborn, he was a Full Professor in the Institute of Computer Science, University of Innsbruck, between 2011 and 2014, and an Assistant Professor in the Dept. of Computer Science, University of Erlangen. Dr. Dressler received his M.Sc. and Ph.D. degrees from the Dept. of Computer Science, University of Erlangen, in 1998 and 2003, respectively. He is an Editor for journals such as the *IEEE Trans. on Mobile Computing* and Elsevier's *Ad Hoc Networks*, *Computer Communications*, and *Nano Communication Networks* journals. He was Guest Editor of special issues on self-organization, autonomic networking, and bio-inspired communication for the *IEEE Journal on Selected Areas in Communications (JSAC)*, Elsevier *Ad Hoc Networks*, and others. Dr. Dressler was General Chair of IEEE/ACM BIONETICS 2007, IEEE/IFIP WONS 2011, and IEEE VNC 2014, TPC Co-Chair for IEEE VNC, IEEE VTC, IEEE GLOBECOM, and ACM MSWiM, Area TPC Chair for IEEE INFOCOM, and Poster/Demo Chair for ACM MobiCom. He regularly serves on the program committee of leading IEEE and ACM conferences. Dr. Dressler wrote the textbook *Self-Organization in Sensor and Actor Networks*, published by Wiley in 2007. Dr. Dressler has been an IEEE Distinguished Lecturer in the fields of inter-vehicular communication, self-organization, and bio-inspired and nano-networking. Dr. Dressler is a Senior Member of the IEEE as well as a Senior Member of ACM. He is actively participating in the IETF standardization. His research activities are focused on adaptive wireless networking and self-organization methods with applications in wireless ad hoc and sensor networks, vehicular networks, and nano-networking.