

Enabling Situation Awareness at Intersections for IVC Congestion Control Mechanisms

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Abstract—An Intersection Assistance System aim to assist road users in avoiding collisions at intersections, either by warning the driver or by triggering automated actions. Such a system can be realized based on passive scanning only (e.g., using LiDAR) or supported by active Inter-Vehicle Communication (IVC). The main reason to use Inter-Vehicle Communication (IVC) is its ability to provide situation awareness even when a possible crash candidate is not yet in visual range. The IVC research community has identified beaconing, i.e., one-hop broadcast, as the primary communication primitive for vehicular safety applications. Recently, adaptive beaconing approaches have been studied and different congestion control mechanisms have been proposed to cope with the diverse demands of vehicular networks. In this paper, we show that current state-of-the-art congestion control mechanisms are not able to support IAS adequately. Specifically, current approaches fail due to their inherent fairness postulation, i.e., they lack fine grained prioritization. We propose a solution that extends congestion control mechanisms by allowing temporary exceptions for vehicles in dangerous situations, that is, situation-based rate adaptation. We show the applicability for two state-of-the-art congestion control mechanisms, namely Transmit Rate Control (TRC) and Dynamic Beaconing (DynB), in two different vehicular environments, rural and downtown.

Index Terms—Inter-Vehicle Communication, Vehicular Ad Hoc Network, Intersection Assistance System, Congestion Control

1 INTRODUCTION

IN the past decade, many applications have been envisioned in the field of Intelligent Transportation System (ITS). A strong focus has been put on vehicular safety applications, as the number of fatalities in everyday road traffic is still alarming, even though current cars come with more safety features than in the past [2]. Intersection Assistance Systems (IAS) are safety systems whose goal is preventing crashes at intersections by either warning the driver—such systems are referred to as Intersection Collision Warning Systems (ICWS) in the literature—or triggering automated actions (like braking, accelerating, and swerving) to circumvent fatal collisions. Two driving simulator studies [3], [4] have independently shown that IAS are able to substantially

reduce reaction times of drivers. For automated intersection collision avoidance systems the feasibility has been demonstrated by a prototype implementation which was able to prevent crashes [5].

To enable IAS, different strategies have been investigated, ranging from processing stereo cameras videos, to LiDAR scanning, to cooperation through Inter-Vehicle Communication (IVC). However, by relying on on-board sensing only, critical situations under non line of sight conditions cannot be recognized. Moreover, placing sensing infrastructure at every intersection would be a costly approach. Decentralized Vehicular Ad Hoc Network (VANET) that are built upon IVC do not rely on infrastructure and hence overcome these problems. It has been shown that IAS based on IVC only are feasible if they are able to provide a minimum update lag of 100 ms [6], a widely accepted threshold [7]. For that reason, the research focus of the IVC community has now shifted to higher layer protocols that might be realized on top of this standard, i.e., investigations of various vehicular traffic applications (safety, efficiency, and comfort) and their communication needs [8]. Since the topology in vehicular networks changes so quickly, beaconing solutions, i.e., one-hop broadcasting, based on IEEE 802.11p [9] have been identified as the best possibility to exchange information timely for vehicular safety applications [10], [11]. It has been shown that rate adaptation is the most feasible congestion control mechanism for most vehicular network environments [12]. Current congestion control mechanisms include Transmit Rate Control (Transmit Rate Control (TRC)) (which is part of the ETSI ITS G5 Decentralized Congestion Control (DCC) [13]) and Dynamic Beaconing (DynB), a more reactive congestion control mechanism [11], [14]. Both congestion

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Manuscript received 5 Oct. 2014; revised 3 Aug. 2015; accepted 23 Aug. 2015. Date of publication 28 Aug. 2015; date of current version 1 June 2016. 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.2015.2474370

control mechanisms try to provide an equal fair share of communication opportunities to all vehicles and hence do not take the difference of road traffic situations of individual vehicles into account. Therefore, both congestion control mechanisms can fail to provide more frequent channel access opportunities to selected vehicles for safety applications.

Recently, we proposed the use of a *situation-based rate adaptation* algorithm to overcome the limitations of proposed congestion control mechanisms [1]. It allows vehicles in dangerous situations at intersections to get a temporary exception of congestion control mechanisms and hence to communicate with possible collision candidates more frequently. In this paper, we go one step beyond and investigate the behavior of current congestion control mechanisms at intersections when shadowing effects by buildings separate the present vehicles into two almost distinct interference domains.

Our main contributions can be summarized as follows:

- We propose an application-aware beacon rate adaptation algorithm, *situation-based rate adaptation*, which prevents critical communication outages for vehicles in dangerous situations (Section 4).
- We first evaluate the situation-based rate adaptation using state-of-the-art simulation models for both the network and the road traffic dynamics in synthetic worst case scenarios, showing its functionality even when the situation is unrealistically bad (Sections 6.2 and 6.3).
- We discuss the viability of the proposal for a dynamic scenario with realistic additional road traffic, highlighting the necessity of situation-based rate adaptation even in normal, everyday road traffic situations (Section 6.4).

2 RELATED WORK

IAS have opened up a wide range of challenges in different research fields, such as control theory, wireless communication, accurate vehicle localization, and transportation science. Here, we review related work only for wireless communication related research. First, we concentrate on studies that investigated communication aspects of IAS. Second, we review IVC related research with a focus on congestion control mechanisms in vehicular networks.

2.1 Intersection Assistance Studies

Le et al. investigated the busy time fraction of early IEEE 802.11p systems for IAS [15]. Since they were using a simplified radio propagation model which uses only a fixed unit-disk communication range, open questions regarding channel utilization remain. A detailed study on communication requirements for crash avoidance applications (intersection as well as pileup collision avoidance) has been published in [16]. The authors changed collision-free vehicle traces by artificially forcing collisions to happen between pairs of cars with a given relative speed, and evaluated their protocol for crash mitigation as a function of the relative speed of the collisions. However, simplifying assumptions like idealistic radio signal propagation and not considering low speed collisions (< 7 m/s) limit the applicability for intersection

safety applications. In our work, we are primarily concerned about the last 3 seconds of the intersection approach. Thus, pileups and related issues, even though very interesting, are not in the main scope of the paper.

Similarly, we observe that most of the studies investigating intersection safety applications do not consider realistic radio signal propagation (e.g., shadowing effects of buildings). Yet, several measurement campaigns considering non line of sight radio propagation [17], [18], [19] highlighted that such effects are of the utmost importance for intersection safety applications. In [20], we investigated safety metrics for IAS considering such shadowing effects, comparing the usefulness of static beaconing approaches and showing the necessity for high beacon rates (> 2 Hz).

In [5], this finding was confirmed: the authors implemented an automated intersection collision avoidance system which is able to prevent crashes at intersections if the update frequency of 2 Hz is maintained. Moreover, the authors provide a model for assessing the criticality of situations. Recently, substantial effort has been put into modelling intersection collision probability. For example, in [21] the collision risk is assessed by comparing intention and expectation of the driver behavior. Ward et al. model the vehicle collision probability considering uncertainty arising from sensor inaccuracy as well as communication delays [22]. In [23], we proposed a model for calculating the intersection collision probability which is suitable from a vehicular networking perspective.

Other works in the scope of IAS include the investigation of the impact of privacy preserving strategies [24] or studies on the suitability of virtual traffic lights [25] for IAS.

All the presented findings for improving situation awareness at intersections strongly depend on the accuracy of vehicle localization and distance measurements. GPS accuracy is particularly in downtown areas an issue due to high building shadowing. We ourselves experimented with different types of GPS sensors in urban environments. Depending on the software capabilities, the error will easily be in the order of up to 20 meters, thus, massively influencing our metric. Surely, such a system would be insufficient. However, recent proposals for future systems investigating differential and cooperative positioning approaches are claiming centimeter accuracy [26], [27]—much better than is required for intersection assistance systems including our proposed approach.

2.2 Inter-Vehicle Communication

Two different protocol stacks are envisioned in the U.S. and Europe, both of which operate on top of the IEEE 802.11p standard [9]: The U.S. are currently standardizing the vehicular networking stack in the IEEE 1609 WAVE standard suite. In Europe, the ETSI standards define a similar protocol stack. However, ETSI standardizes not only general networking services but also defines DCC mechanisms which adapt their behavior by monitoring current channel conditions [13]. Both standards share a common concept, the periodic exchange of awareness messages, named *beacons*, for safety, albeit under different names: Basic Safety Message (BSM) and Cooperative Awareness Message (CAM).

Static beaconing approaches, as used in the current IEEE 1609 standards, might congest the channel and hence vehicular networks demand channel congestion control mechanisms which make use of adaptive beaconing approaches [10], [28]. Recent studies have proposed and investigated different mechanisms (e.g., [12], [14], [29]). In general, there are three possibilities to regulate the channel and maintain efficiency: change the transmit power, modify the encoding (bit rate), and reduce the information dissemination rate (beacon rate).

The current ETSI ITS G5 standard DCC uses all three possibilities [13]. However, it has been shown that even in not rapidly changing environments it is advantageous to use a fixed transmit power level which is dependent on the vehicle density [12]. Since intersection assistance applications have to deal with a very challenging and rapidly changing wireless channel, the vehicle density is hard to predict. Therefore, we assume for the rest of the paper that the highest allowed transmission power and a robust encoding (i.e., transmit power of 33 dBm and a bitrate of 6 Mbit/s) are used. The only remaining possibility is then to adapt the beacon interval. The rate adaptation part of the ETSI ITS G5 standard DCC [13] is called TRC. In [11], [14], a very reactive protocol called DynB and TRC have been compared in detail. Older congestion control approaches are summarized in [30].

Indeed, all proposed protocols succeed when it comes to their main goal: maintaining a reasonable channel load and hence keeping collisions in the air at a low rate, and provide equal fair shares to all vehicles. When we think about information dissemination for safety applications one problem becomes visible: The equal shared channel might result in situations where vehicles in critical situations are not allowed to exchange sufficient information for their safety applications. A follow-up ETSI standard [31] tries to address this problem by providing the DCC profile DP0 which can be used to send emergency messages at a higher rate, but still they are subject to congestion control restrictions and all share the same class.

In [32], the authors investigated a context aware congestion control mechanism for highway overtaking assistance. This approach is in many ways an opposite to the one we propose: it allows vehicles to omit transmissions of Cooperative Awareness Message (CAM) when no benefit is expected for overtaking assistance.

In contrast to related works, we propose in this work a situation-based rate adaptation algorithm that allows vehicles in dangerous situations at intersections to flexibly use more than the equal fair share of the communication channel. Our approach improves communication for vehicles in danger by selectively increasing the message rate, independent of how many other vehicles are willing to lower their transmit rate voluntarily.

3 BACKGROUND

In the following, we briefly outline the two congestion control mechanisms we relied on in our investigations: TRC and DynB. We also introduce the *Intersection Collision Probability* metric [23], which assesses the criticality of situations for individual vehicles during intersection approaches.

3.1 Transmit Rate Control

ETSI ITS-G5 standardized the DCC TRC mechanism [13] to adapt the maximum message intervals I using three different states: relaxed, active and restrictive. Basically state transitions are triggered when the channel busy ratio exceeds some pre-defined thresholds b_{\min} or b_{\max} . The busy ratio b_t is calculated based on a sampling interval T_m : b_t is the fraction of time the channel has been sensed busy when being probed between t and $t - T_m$.

State transitions may occur after each inter-decision interval T_{DCC} using two additional times T_{up} and T_{down} that are integer multiples of T_m to filter b_t and avoid oscillations. These two times are used to calculate the decision variables $b_{\text{up}} = \min\{b_{t-T_{\text{up}}}, b_{t-T_{\text{up}}-T_m}, \dots, b_t\}$ and $b_{\text{down}} = \max\{b_{t-T_{\text{down}}}, b_{t-T_{\text{down}}+T_m}, \dots, b_t\}$, which are compared against the thresholds b_{\min} and b_{\max} .

3.2 Dynamic Beaconing

DynB [14] tries to maintain the channel load at a fixed, pre-defined ratio. The idea is to keep the channel load within a reasonable range (around the so-called desired busy ratio b_{des}), so that the number of collisions is small and hence only few messages get lost. In particular DynB observes the channel busy ratio and adapts its current beacon interval based on this ratio and the number of neighbors. If the busy ratio is higher than desired, the beacon interval is increased; otherwise it is reduced, until it reaches a configurable minimum value I_{des} . To formally define the computation of the next beacon interval I , we need the number of neighbors N , which is available by keeping track of beacons from other vehicles, and the channel busy ratio b_t :

$$I = I_{\text{des}}(1 + rN), \quad (1)$$

where $r = b_t/b_{\text{des}} - 1$, clipped in the interval $[0, 1]$. Since the beacon interval gets adapted each time a beacon is sent or was scheduled to be sent, DynB is able to keep the channel busy ratio very close to the desired value [14], and it adapts more aggressively to the current channel conditions than TRC.

3.3 Intersection Collision Probability

A suitable metric to decide whether an intersection approaching vehicle is in a dangerous situation is needed for our approach. In this paper, we rely on the *Intersection Collision Probability* \mathcal{P}_C proposed and validated in [23]. A vehicle can calculate \mathcal{P}_C using its own position, heading, and speed whenever it receives a CAM of another vehicle as follows.

Let two vehicles A and B have distances to their potential collision point of d_A and d_B as well as speeds v_A and v_B . Further assume that, without loss of generality, the vehicles have identical maximum deceleration a_{\min} and maximum acceleration a_{\max} . Assuming that the trajectory of a vehicle depends on its longitudinal acceleration only, the collision probability \mathcal{P}_C can then be calculated by considering all possible future trajectories of both vehicles via integrating over the interval $[a_{\min}, a_{\max}]$, yielding

$$\mathcal{P}_C = \int_{a_{\min}}^{a_{\max}} p(a_B) \int_{a_{\min}}^{a_{\max}} p(a_A) \text{coll} \left(\begin{bmatrix} a_A \\ v_A \\ d_A \end{bmatrix}, \begin{bmatrix} a_B \\ v_B \\ d_B \end{bmatrix} \right) da_A da_B. \quad (2)$$

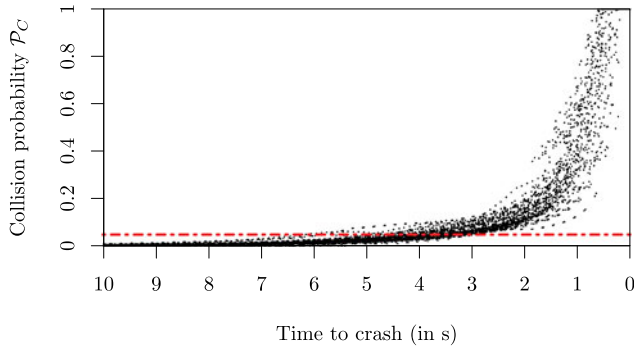


Fig. 1. Evolution of the intersection collision probability \mathcal{P}_C for various intersection approaches which resulted in a vehicle collision. The dotted line shows the threshold \mathcal{P}_{th} of 5 percent.

The key element of this calculation is the function $\text{coll}()$ which determines based on the input (distance, speed and acceleration of vehicles A and B) whether the two supplied trajectories will result in crash or not; returning 0 for no crash and 1 for crash. By summing up and weighting by the likelihood of single trajectories using $p(a_A)$ and $p(a_B)$ the overall collision probability can be calculated.

In [23], two different types of distributions for $p(a)$ have been proposed and validated: a *uniform* distribution for validation and a *triangular* distribution resembling more realistic driver and vehicle behavior, where the current acceleration is the most likely to be maintained. In this work, we use the triangular distribution, because it better reflects a realistic behavior of drivers. It is based on acceleration limits (a_{\min} and a_{\max}) and the current acceleration of the vehicle (a_{cur}). Using a_{\min} as lower limit, a_{cur} as mode and a_{\max} as upper limit, the probability of any acceleration between a_{\min} and a_{\max} can be calculated.

4 SITUATION-BASED RATE ADAPTATION

We propose a *situation-based rate adaptation* to prevent blackout periods in critical situations at intersections. This rate adaptation makes use of the described intersection collision probability and can be added to congestion control mechanisms for beaconing based IVC (we show this for ETSI ITS-G5 DCC and DynB).

4.1 Concept

Fig. 1 depicts the evolution of the collision probability depending on the *time to crash* for intersection approaches that finally resulted in a vehicle collision. After a crash has happened, the time to crash has been post-calculated for previously received CAM. For intersection assistance applications it is of the utmost importance to have reliable and continuous communication for a certain time before a potential crash would happen. Since this time frame heavily depends on the situation in which the vehicles are and it is not known a priori, we introduce a threshold \mathcal{P}_{th} for collision probability below which situations are not yet dangerous enough to trigger warnings or actions. We decided to use 5 percent as threshold \mathcal{P}_{th} for the situation-based rate adaptation based on \mathcal{P}_C , since most of the approaches did not exceed this threshold earlier than 5 s before the crash (as illustrated in Fig. 1 by the dashed line), and IAS do not need

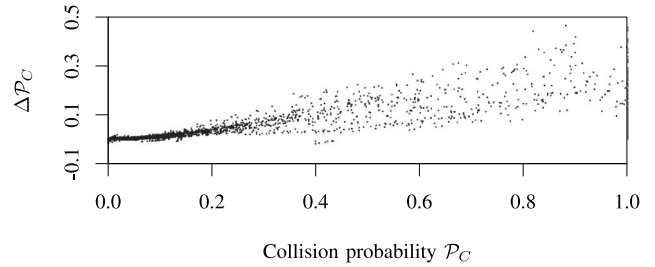


Fig. 2. Variation $\Delta\mathcal{P}_C$ of the intersection collision probability with respect to \mathcal{P}_C computed at the preceding CAM (y -axis) versus the collision probability (x -axis) plotted for a constant beacon rate of 5 Hz for approaches actually resulting in a vehicle collision.

to trigger actions earlier. Note that for different criticality metrics this threshold will likely be different.

Moreover, it can be seen that the collision probability during intersection approach rises non-linearly in time, however from Fig. 1 it is difficult to assess the evolution and distribution of the increments of the intersection collision probability \mathcal{P}_C . To further investigate these increments, let $\Delta\mathcal{P}_C$ be the difference between two successive evaluations of \mathcal{P}_C . Fig. 2 plots $\Delta\mathcal{P}_C$ for a fixed beacon rate of 5 Hz as a function of \mathcal{P}_C showing that $\Delta\mathcal{P}_C$ increases as the estimated collision probability \mathcal{P}_C rises.

Fig. 3 shows the eCDF of the increments ($\Delta\mathcal{P}_C$) for CAM which result in an intersection collision probability above the threshold \mathcal{P}_{th} , because this allows to assess the distribution of changes in dangerous situations. When looking at the eCDF of baseline, i.e., no adaptation, results, it can be seen that more than 20 percent of CAM yield changes of the intersection collision probability of more than 10 percent (the figure also shows data for the adaptation strategies described in Section 4.3). Based on these findings we propose to use a situation-based rate adaptation, which uses the intersection collision probability as control metric.

4.2 Adaptation Algorithm

Algorithm 1 outlines the operation of the situation-based rate adaptation. When a vehicle receives a CAM the procedure `RECEIVEDCAM` (line 1) is triggered, which calculates the intersection collision probability \mathcal{P}_C based on current position and speed information and the data contained in the received CAM. This probability is used to immediately adapt the beacon rate by calling `ADAPTBEACONRATE` (line 6).

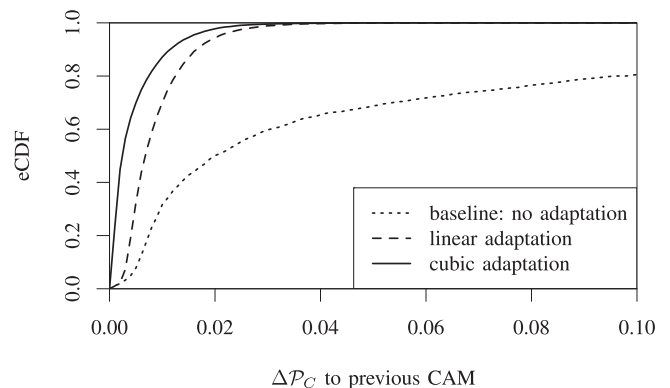


Fig. 3. eCDF of the $\Delta\mathcal{P}_C$ for a constant beacon rate of 5 Hz (w/o adaptation) and linear as well as cubic situation-based rate adaptation.

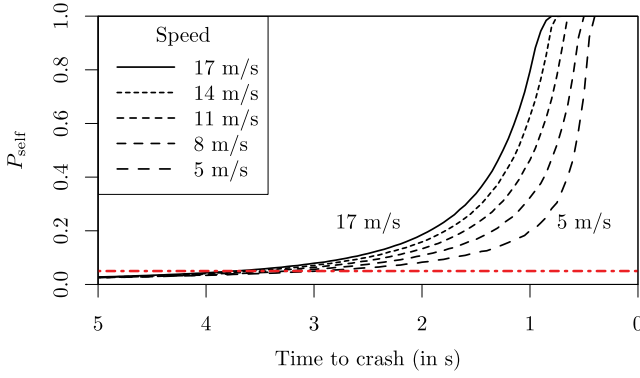


Fig. 4. Evolution of $\mathcal{P}_{\text{self}}$ computed assuming that there is a car in the exact same situation approaching the crossroad from the other road computed for several different approaching speeds and no acceleration.

The situation-based rate adaptation itself is performed in multiple steps. By default, it keeps the rate r at r_{default} , the rate chosen by the congestion control algorithm. Rate adaptation is performed based on the current collision probability \mathcal{P}_C if a CAM was received recently (defined by a timeout t_{out}). If no received CAM is available for computing \mathcal{P}_C , a default probability $\mathcal{P}_{\text{self}}$ is calculated, assuming a worst case scenario where another car is approaching the crossroad from the other road at exactly the same distance from the crossroad and traveling exactly with the same speed and acceleration. Fig. 4 shows the evolution of $\mathcal{P}_{\text{self}}$ for different constant speeds.

Algorithm 1. Situation-Based Rate Adaptation

```

1: procedure RECEIVEDCAM
2:   calculate  $\mathcal{P}_C$  ▷ see Eq. (2)
3:   call ADAPTBEACONRATE
4: end procedure
5:
6: procedure ADAPTBEACONRATE
7:    $r \leftarrow r_{\text{default}}$ 
8:    $p \leftarrow \mathcal{P}_C$ 
9:   if no CAMs received for at least  $t_{\text{out}}$  then
10:     $p \leftarrow \mathcal{P}_{\text{self}}$ 
11:   end if
12:   if  $p > \mathcal{P}_{\text{th}}$  then
13:    calculate  $r$  ▷ see Eqs. (3), and (4)
14:   end if
15:   (re-)schedule calls of SENDCAM with rate  $r$ 
16: end procedure
17:
18: procedure SENDCAM
19:   flush MAC queue
20:   enqueue CAM
21:   call ADAPTBEACONRATE
22: end procedure

```

Independent of whether \mathcal{P}_C is available or $\mathcal{P}_{\text{self}}$ is used, the adaptation overrides the information dissemination rate of the congestion control mechanism only if the intersection collision probability p exceeds the threshold \mathcal{P}_{th} . The adapted rate r is set to the maximum between the current dissemination rate and the situation-based adapted rate.

This rate is then used for sending CAM by calling SENDCAM (line 18). It ensures that the most recent CAM gets transmitted by flushing CAM from the MAC queue before

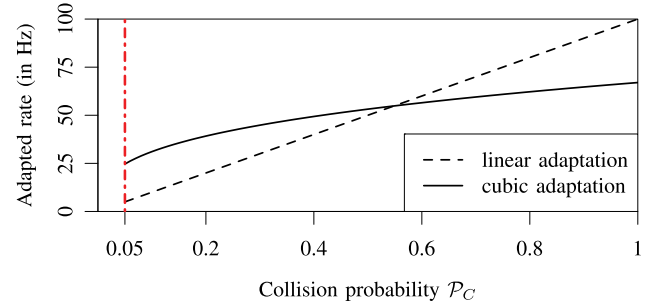


Fig. 5. Comparison of the adapted rate of the *linear* and *cubic* situation-based rate adaptation for different intersection collision probabilities.

queuing the current CAM for transmission, then again checks if the beacon rate needs to be adapted.

4.3 Adaptation Strategy

To adapt the CAM transmission rate we need to estimate the vehicles' collision probability at the intersection with Eq. (2), as this estimation is the base for the adaptation algorithm. Next we need an adaptation strategy. In our preliminary work [1], we considered a linear adaptation when $\mathcal{P}_C > 5\%$ as depicted in Fig. 5, assuming a maximum beacon rate of 100 Hz. In this paper, we also study a non-linear, cubic adaptation, which increases the rate faster for low intersection collision probabilities. However, to make a correct comparison of the two strategies, we need to impose that the additional channel load is the same, otherwise it is clear that the more a strategy is aggressive the more benefits it shows, but it would also congest the channel more, which in some situation can be very detrimental (e.g., in presence of many cars). To equalize the average channel load, we leave the maximum beacon rate for the cubic adaptation as a free variable r_{cubic} . Then we compute the average channel load for both adaptation strategies by integrating the adaptation function on the surface defined computing the intersection collision probability in the interval $[0.05, 1.0]$, and finally impose that the two results are equal, which yields a value $r_{\text{cubic}} = 67.76$ Hz.

The adaptation strategy for the linear adaptation is calculated as follows

$$r = \max(r_{\text{default}}, p \times r_{\text{linear}}), \quad (3)$$

where r_{linear} is the maximum dissemination rate for the linear case. In contrast, the more aggressive cubic adaptation uses

$$r = \max(r_{\text{default}}, p^{1/3} \times r_{\text{cubic}}). \quad (4)$$

When looking at the distribution of $\Delta\mathcal{P}_C$ in Fig. 3, it can be seen that both the linear as well as the cubic adaptation have no larger increments than 5.9 percent. A small difference between the two adaptation functions can be seen by looking at the 99th percentile: For the linear adaptation 99 percent of the increases are smaller than 3.2 percent and for the cubic adaptation the increases are even smaller with 2.5 percent. Fig. 3 shows that the cubic adaptation yields to smaller steps of the intersection collision probability, although it uses a lower maximum information dissemination rate. However, this initial analysis does not show yet that the cubic adaptation is also advantageous in a crowded

TABLE 1
Network and Congestion Control Protocol Parameters

	Parameter	Value
PHY & MAC	Path loss model	Free space ($\alpha = 2.0$)
	Shadowing model	Simple Obstacle Shadowing [18]
	Attenuation per wall [18]	$\beta = 9.0$ dB
	Attenuation per m [18]	$\gamma = 0.4$ dB
	PHY model	IEEE 802.11p
	MAC model	IEEE 1609.4 single channel (CCH)
	Frequency	5.89 GHz
	Bitrate	6 Mbit/s (QPSK $R = 1/2$)
	Access category	AC_VO
	MSDU size	193 B
Transmit power	33 dBm	
TRC	$I_{\min}, I_{\text{def}}, I_{\max}$	0.04 s, 0.5 s, 1 s
	b_{\min}, b_{\max}	0.15, 0.40
	$T_M, T_{\text{DCC}}, T_{\text{up}}, T_{\text{down}}$	1 s, 1 s, 1 s, 5 s
DynB	I_{des}	0.04 s
	b_{des}	0.25
Adaptation	Threshold \mathcal{P}_{th}	5%
	Min. rate r_{\min}	5 Hz
	Max. rate linear r_{linear}	100 Hz
	Max. rate cubic r_{cubic}	67.76 Hz
Timeout t_{out}	1 s	

communication scenario, but this will be investigated in Section 6.

5 SIMULATION MODELS AND SCENARIOS

To analyze the effectiveness of the situation-based rate adaptation we use the Veins simulation framework [33], which bidirectionally couples the road traffic simulator SUMO and the network simulator OMNeT++, and provides a rich set of models for vehicular network simulations. Table 1 summarizes the parameters for physical and MAC layer models, as well as for DynB, TRC, and the situation-based rate adaptation.

5.1 Modeling Intersection Approaches

In previous work [20], [23], we simulated intersection crashes by randomly selecting vehicles that disregard traffic rules or traffic lights at intersections. This simulation technique however resulted only in a few vehicle collisions (less than 5 percent of all situations), and in high speed collisions due to the fact that both vehicles cross the intersection with their right-of-way speed, which is usually quite high. To evaluate IAS in a more realistic manner, we implement an intersection approach model that is parameterized by the aggressiveness and discipline of the driver, as proposed in [34]. This allows to simulate arbitrary intersection approaches and vehicle collisions with different speeds and acceleration/deceleration behavior when right-of-way rules are disabled in SUMO. In addition, the simulated arbitrary intersection approaches represent possible driver behavior for all different regulation types at intersections: uncontrolled, yield-controlled, stop-controlled and signal-controlled. The only assumption is that no other vehicle is driving in front of the two vehicles under analysis and hence

TABLE 2
Road Traffic Simulation Parameters

Parameter	Value
Road traffic simulator time step	10 ms
Safety boundary for near crash	0.4 m
Vehicle length	5.0 m
Vehicle width	1.75 m
Maximum speed v_{\max} [4, Tab. IV]	$\sim N(13.89, 2.92)$ m/s
Maximum acceleration a_{\max}	2.1 m/s ²
Desired deceleration a_{des} [4, Tab. IV]	$\sim N(3.47, 2.76)$ m/s ²
Maximum deceleration a_{\min} [37]	9.55 m/s ²
Starting speed v_0	$\sim U(0, v_{\max})$ m/s
Crossing speed v_{cross}	$\sim U(3, 12)$ m/s
Driver Aggression potential	$\sim U(10, 90)\%$
Driver Discipline	$\sim U(10, 90)\%$

the drivers could make mistakes such as: inadequate surveillance, internal and external distraction from driving, misjudgment of situation, or turning with obstructed view [35].

With this technique a wider range of intersection collision situations can be simulated; moreover, the possibility to select driver behaviors precisely guarantees that every “run” of the simulation results either in a vehicle collision or an interesting (from the perspective of IAS) situation. This is very important, because simulations, especially when there are many vehicles crowding the communication channel, are computationally intensive and it is important to use the simulation time as efficient as possible. The vehicles approach the intersection and cross it without turning. The parameters for simulating the vehicle movements are summarized in Table 2. More details on the distribution of the traffic parameters can be found in [36].

We performed collision detection of vehicles within the network simulator as described in [23]. After observing two vehicles crossing an intersection, we classify the result as one of the following: CRASH, NEAR CRASH, and NO CRASH. Here, NEAR CRASH refers to situations where the vehicles violated their safety boundary of 0.4 m, but did not crash into each other.

5.2 Scenario Description

We simulated the real-world intersection in Innsbruck, Austria depicted in Fig. 6, importing the geodata available from OpenStreetMap to integrate the road layout and outlines of buildings into our simulation framework. To analyze the



Fig. 6. Road map of the simulated intersection area in Innsbruck, Austria (N 47° 15' 50.0" E 11° 25' 2.5").

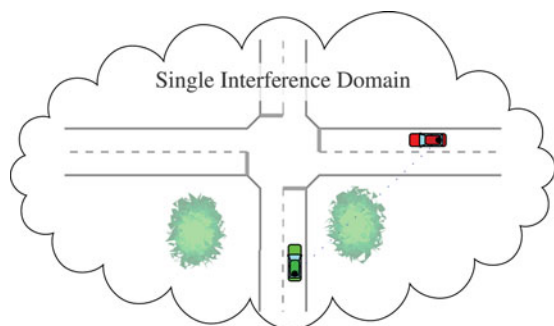


Fig. 7. Schematic overview of the *Rural Scenario* showing the approaching vehicles that do not see each other yet due to visual obstructions (e.g., bushes or trees). Vehicles causing background communication are not depicted.

communication performance at intersections, we added “ghost” vehicles which generate additional network traffic. These vehicles use the same communication strategies as the two vehicles under analysis. To ensure that these additional vehicles are not interacting with the two monitored vehicles from a road traffic point of view, the background communication vehicles are simulated only in the network simulator and not in SUMO. We use the layout of the intersection in Fig. 6, to simulate both a *Rural Scenario* and a *Downtown Scenario*, which are used to demonstrate the baseline behavior of the proposed situation-based rate adaptation. In addition we evaluate our approach with a realistic *Downtown Scenario with moving background traffic*, where interfering cars are simulated also in SUMO.

5.2.1 Rural Scenario

In this scenario all vehicles in the vicinity of the intersection hear, and hence interfere with, each other. In other words, they form a *single interference domain*, as depicted in Fig. 7. More precisely we do not simulate any building that would impair radio communication. This allows the analysis of a rural intersection where no buildings obstruct the line of sight of any two vehicles and hence no shadowing effects need to be considered. We employ this scenario to show the behavior of the situation-based adaptation in a rural environment where all interfering vehicles are very close to the intersection; hence the signal attenuation in this scenario is modeled using a simple Freespace path loss model. Even if there are no compact obstacles obstructing radio communications, from the drivers’ point of view the line of sight might be still obstructed by bushes or trees as shown in Fig. 7. The densities of 40, 60, and 80 vehicles have been achieved by placing 10, 15, and 20 “ghost” vehicles in each road segment at a distance of 50 m from the intersection.

5.2.2 Downtown Scenario

In this scenario we consider two almost distinct interference domains. As shown in Fig. 8, the two interference domains (red and green cloud) overlap in the intersection area. Therefore, the wireless communication of vehicles approaching the intersection is first influenced by vehicles on their own road only. However, when entering the critical area for intersection assistance systems they start to get influenced by both interference domains. This challenging communication scenario is caused by shadowing effects due to buildings

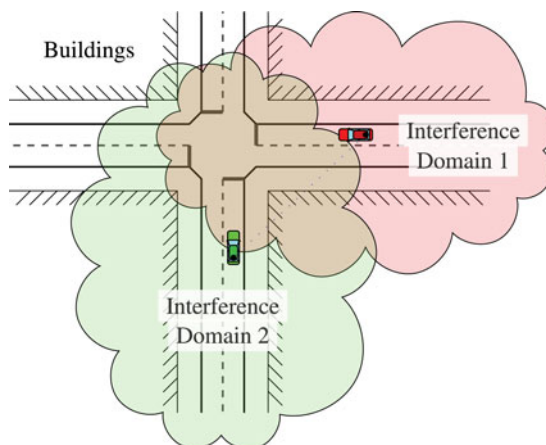


Fig. 8. Schematic overview of the *Downtown Scenario* showing two vehicles which are about to enter the intersection area where the two interference domains overlap (effect caused by shadowing due to buildings).

which are placed along each crossroad as depicted in Fig. 6. To get different kinds of shadowing effects, the approaching vehicles are alternating their starting place (i.e., NE, SE, SW, NW). The densities of 20, 28, and 40 background communication vehicles are obtained by placing “ghost” vehicles as described before.

5.2.3 Downtown Scenario with Moving Background Traffic

This scenario is similar to the *Downtown Scenario* (Fig. 8), the only difference being that instead of adding “ghost” vehicles, all vehicles are simulated in the road traffic simulator. In order to be able to investigate the communication performance of the two vehicles in dangerous situations, we paid attention that none of the other vehicles is influencing their road traffic behavior. In contrast to *Rural Scenario* and *Downtown Scenario*, where the vehicles have alternated their starting points, in this scenario all observed vehicles were starting from SE and NE. This was necessary due to the complexity of the scenario setup to ensure the non-interaction with other vehicles. Since this scenario uses an unregulated single lane intersection, we could not simulate a high density of background vehicles, and the injection of vehicles with different speeds in SUMO also results in a non-constant distribution of vehicles. On average 20 vehicles have been driving in the scenario.

6 EVALUATION

All our plots show only data points of intersection approaches that resulted in a CRASH. In total, we simulated 480 intersection approaches per scenario. In the *Rural Scenario* and the *Downtown Scenario*, 352 of them resulted in a CRASH, whereas in the *Downtown Scenario with moving background traffic* only 314 approaches resulted in a CRASH. Every intersection approach mimics a different driver behavior and hence we investigate a wide range of crash situations at an X-intersection. The experiments only record the behavior of the cars and communications without activating any countermeasure. Thus, the high number of CRASH is not indicating a failure of the proposal, but allows us to show the need for reliable communications to implement IAS.

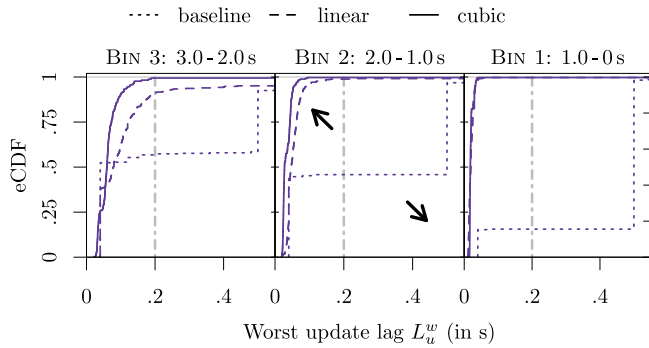


Fig. 9. eCDF showing the worst case update lag L_u^w for TRC and the different adaptation algorithms up to three seconds to intersection (BIN 3, BIN 2, and BIN 1).

6.1 Metrics and Validation

The main evaluation metric is the *update lag* L_u that measures the time between two consecutive CAM from an approaching vehicle, i.e., $L_{u_i} = t_{CAM_i} - t_{CAM_{i-1}}$. For investigating the impact of IVC protocols on road traffic safety, it is not sufficient to look at the average L_u [23], as it is the worst case that determines the most dangerous situation. Therefore, we carry out a *worst case analysis* by exploring the worst update lag L_u^w per approaching vehicle. To highlight the behavior of the different communication strategy we split the last three bins: BIN 3, BIN 2, and BIN 1. In all graphs, we highlighted the 200 ms threshold of the update lag that we aim to achieve.

We can observe two interesting trends: First, the results for the non-adaptive version of TRC get worse during the intersection approach. In BIN 1, only 15 percent of all communications are faster than the 200 ms threshold (in contrast to about 56 percent in BIN 3). This is due to the increasing congestion level on the wireless network causing TRC to back-off.

Second, the adaptation algorithm acts particularly well in the last two seconds to the intersection (BIN 2 and BIN 1), achieving more than 99 percent of all communications within the safety threshold. The more dangerous the situation gets—the closer the cars get to the crash—the more often cars do get an update of the situation, hence achieving situation awareness exactly when it is needed for intersection assistance systems. Thus, we will concentrate in the following particularly on BIN 3, which is also most critical when it comes to early notification of the driver.

By only investigating the distributions of L_u^w , it is not possible to assess how good or bad the communication during the whole intersection approach was for a specific vehicle. To highlight this fundamental measure, we define a vehicle to be in an unsafe state whenever it has not received an update for a specific *required update lag* L_{req} . Hence, for each vehicle, we can independently calculate the set of unsafe times $T_{unsafe} = \{t_{unsafe-0}, \dots, t_{unsafe-n}\}$ that it has spent in such an unsafe state. Summing all T_{unsafe} in a single measure t_{unsafe} , we assess the total amount of time the vehicle has not received sufficient information. For example if a vehicle gets an update after 680 ms and we consider a required update lag of 500 ms, the unsafe time for this vehicle was 180 ms.

In our evaluations, we assume two different update lags: For automated vehicles, we assume a required update lag of 500 ms, because, for example, the automated collision avoidance controller designed in [5] needs a reliable update frequency of 2 Hz. In the case of a non-automated system, e.g., an acoustic warning to a driver, the maximum lag requirement might be tighter because of human reaction times. For this reason, we also consider a required update lag of 200 ms.

We start with a validation of the proposed situation-based rate adaptation for intersection assistance applications. We have shown in Section 4 that the collision probability is rising non-linearly and proposed two adaptation

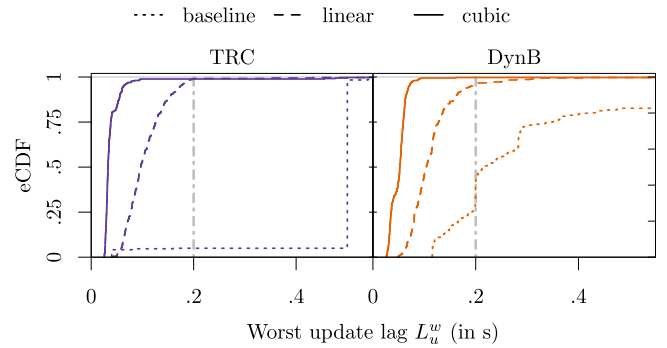


Fig. 10. eCDF comparing the worst case update lag L_u^w of DynB and TRC, for no adaptation (baseline), linear, and cubic adaptation in the *Rural Scenario* with 60 vehicles.

strategies for the information dissemination rate depending on the situation.

Fig. 9 shows the results of a selected experiment (*Down-town Scenario* with 20 vehicles) that we use to identify the most relevant measures (the particular experiment will be discussed later in detail). We plot eCDFs for all protocol adaptation strategies (baseline, i.e., no adaptation, linear adaptation, and cubic adaptation) using TRC as a beaconing protocol. As described before, we split the graph into three bins: BIN 3, BIN 2, and BIN 1. In all graphs, we highlighted the 200 ms threshold of the update lag that we aim to achieve.

We can observe two interesting trends: First, the results for the non-adaptive version of TRC get worse during the intersection approach. In BIN 1, only 15 percent of all communications are faster than the 200 ms threshold (in contrast to about 56 percent in BIN 3). This is due to the increasing congestion level on the wireless network causing TRC to back-off.

Second, the adaptation algorithm acts particularly well in the last two seconds to the intersection (BIN 2 and BIN 1), achieving more than 99 percent of all communications within the safety threshold. The more dangerous the situation gets—the closer the cars get to the crash—the more often cars do get an update of the situation, hence achieving situation awareness exactly when it is needed for intersection assistance systems. Thus, we will concentrate in the following particularly on BIN 3, which is also most critical when it comes to early notification of the driver.

6.2 Worst Case Update Lag

We start with the evaluation of L_u^w for the six different communication strategies DynB and TRC using the different adaptation strategies (baseline, i.e., no adaptation, linear, and cubic) for situation-based rated adaptation.

Fig. 10 presents the eCDFs of L_u^w for the *Rural Scenario* with 60 vehicles communicating in background. As can be seen, in some cases, the curve does not reach 1. This is due to lost CAM or long beacon intervals by congestion control mechanisms.

For DynB without adaptation it can be seen that L_u^w is for most of the vehicles above 200 ms (only 42 percent of the vehicles get the message within the threshold). In addition, we can notice that more than 15 percent of vehicles do not receive an update for the entire 1 s observation time. For TRC without adaptation the eCDF shows that only a small fraction of about 5 percent get the message within the

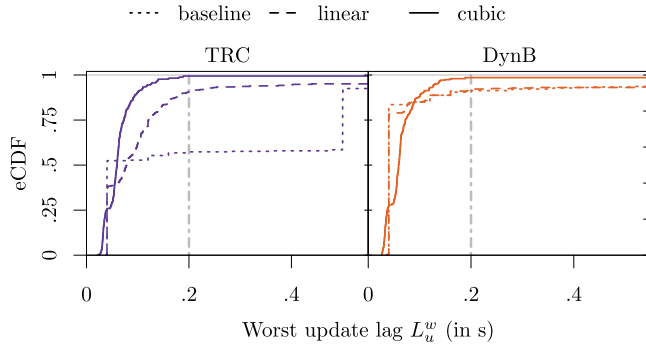


Fig. 11. eCDF comparing the worst case update lag L_u^w of DynB and TRC, for no adaptation (baseline), linear, and cubic adaptation in the *Downtown Scenario* with 20 vehicles.

200 ms threshold. However, almost all vehicles experience $L_u^w \geq 500$ ms.

When the situation-based rate adaptation is enabled, instead, Fig. 10 shows that L_u^w never exceeds 500 ms. In addition, 95-98 percent of all transmissions stay below 200 ms for the linear adaptation strategy and even close to 100 percent for the cubic adaptation strategy. This upper bound is also valid for the vehicle densities of 40 and 80 vehicles (results not shown for the sake of brevity). Interestingly, DynB and TRC with situation-based rate adaptation are both able to adapt the rate almost equally successful; only a minor deviation is visible.

Fig. 11 depicts L_u^w distribution for the *Downtown Scenario* and a vehicle density of 20 (10 vehicles in each of the intersecting roads). This plot shows that DynB and TRC without adaptation are highly sensitive to the additional channel load generated by the interfering vehicles on the crossroad. In fact, both seem to react faster than the adaptive version for a few fractions of a second but are clearly not able to meet the threshold of 200 ms: only in 56 and 90 percent of the cases the deadline is met for TRC and DynB, respectively.

This scenario also reveals problems of the linear adaptation strategy, which behaves almost similar as DynB without adaptation: only 91 percent of all transmissions meet the 200 ms deadline. The cubic adaptation, however, shows the advantage of the proposed adaptation algorithm and achieves again a successful communication within the time bound in more than 99 percent of all cases. Similar results have been obtained for higher vehicle densities (data not shown).

In summary, this initial analysis reveals that the situation-based rate adaptation is effectively keeping the update lags in a useful range for intersection assistance systems. For both investigated scenarios, the situation-based rate adaptation is able to provide frequent updates independent of the underlying congestion control mechanism.

6.3 Implications on Road Traffic Safety

In the previous section, we investigated the statistical behavior of the worst case update lag L_u^w . Its distribution, however, does not allow assessing communication performance for a single vehicle during the entire intersection approach. Therefore, we carry out an analysis of the accumulated *unsafe time* t_{unsafe} per vehicle for the last three seconds before the crash (cf. Section 6.1).

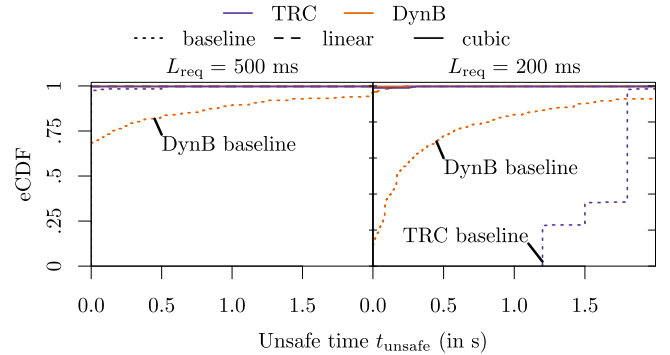


Fig. 12. eCDF showing the timespan that vehicles spent in an unsafe state during the last three seconds for the *Rural Scenario* with 60 vehicles.

In Fig. 12, we plot the eCDF of the timespan that individual vehicles have spent in t_{unsafe} for the two mentioned required update lags for the *Rural Scenario*. When looking on the left plot ($L_{\text{req}} = 500$ ms), it can be seen that DynB without adaptation would not be able to satisfy the firm update requirements of an automated collision avoidance controller. In particular, DynB without adaptation is not able to provide timely updates for more than 24 percent of vehicles in this medium dense road traffic situation. On the other hand TRC without adaptation is able to provide an update every 500 ms for more than 98 percent of vehicles if we neglect the short delays introduced by the MAC. This is possible because most vehicles have been in the “active” state where they are only allowed to send a CAM every 500 ms. Looking again at the results of situation-based rate adaptation, we can observe that both adaptation strategies independent of the underlying beaconing protocol fulfill the update lag requirement of 500 ms to almost 100 percent.

The right plot in Fig. 12 shows the eCDF for a required update lag of 200 ms. Obviously, the results are worse for both protocols without adaptation. Particularly TRC is not able to provide frequent updates due to the fact it stays most of the time in the state where it uses 500 ms as beacon interval. For this stricter update lag requirement the adaptation is again able to provide all updates in time in almost 100 percent of the cases.

Fig. 13 shows the results for the *Downtown Scenario* with 20 vehicles. For the 500 ms threshold, even the non-adaptive protocols perform quite well, but they are not able to guarantee the update time in about 10 percent of the cases. Using

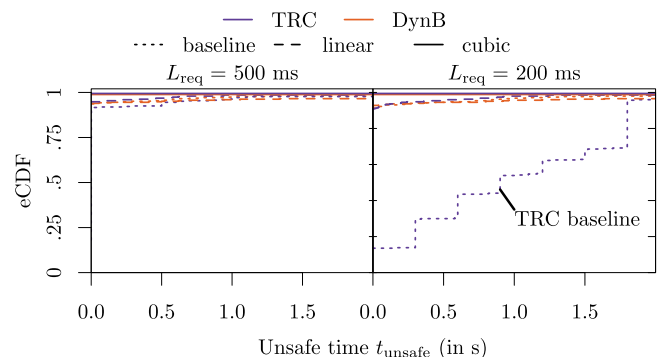


Fig. 13. eCDF showing the timespan that vehicles spent in an unsafe state during the last three seconds for the *Downtown Scenario* with 20 vehicles.

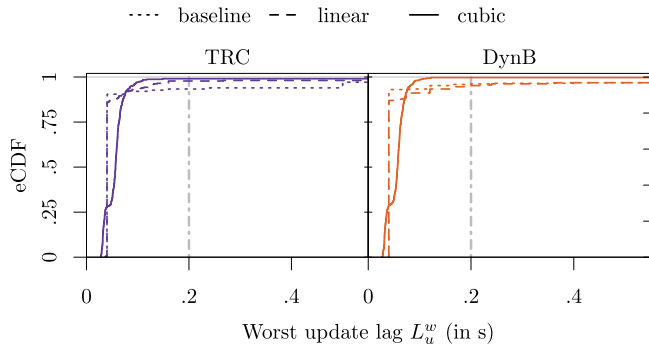


Fig. 14. eCDF comparing the worst case update lag L_u^w of DynB and TRC, for no adaptation (baseline), linear, and cubic adaptation in the *Downtown Scenario with moving background traffic*.

the linear adaptation strategy, the results improve to about 95 percent. Only the cubic adaptation strategy supports successful transmissions within the time bound in almost 100 percent of the cases.

When looking at the eCDF depicting the results for $L_{\text{req}} = 200$ ms on the right side in Fig. 13, it can be seen that TRC without adaptation is not able to provide the targeted update lag to almost any vehicle. DynB without adaptation is working better, but still is only able to provide frequent updates for 90 percent of vehicles. In contrast, the adaptation allows both protocols to provide timely updates for more than 95 percent of vehicles for the linear adaptation strategy and almost 100 percent for the cubic adaptation strategy.

6.4 Dynamic Downtown Scenario

So far we have studied results where the background communication nodes were static. This allows getting an in-depth understanding of the situation-based rate adaptation for two challenging scenarios and various vehicle densities. However, such a static environment does not reflect the reality in vehicular networks. Due to the mobility of all network nodes, vehicular networks are highly dynamic and change topology so frequently that only beacon-based solutions are able to support vehicular safety applications [2], [14]. Therefore, we simulated the *Downtown Scenario with moving background traffic* where all nodes are moving on the crossroads. The background communication nodes do not influence the two monitored vehicles from a road traffic point of view, but they participate in communication by using the same communication strategy as the two vehicles under supervision. Since also radio signal shadowing by buildings has been taken into account in this simulation, the reported results are comparable to the *Downtown Scenario* with a vehicle density of 20.

Fig. 14 plots the eCDF of L_u^w for the *Downtown Scenario with moving background traffic*. It can be seen that DynB and TRC without adaptation are performing better in this dynamic scenario compared to the *Downtown Scenario* with similar vehicle density (cf. Fig. 11). This can be explained by the fact that the two vehicles in question do not experience the additional channel load of the crossroad interference domain at once, but rather incrementally, due to the different positions of vehicles on the crossroad. Moreover, background vehicles close to the intersection are also aware of both interference domains and hence adapt their beacon

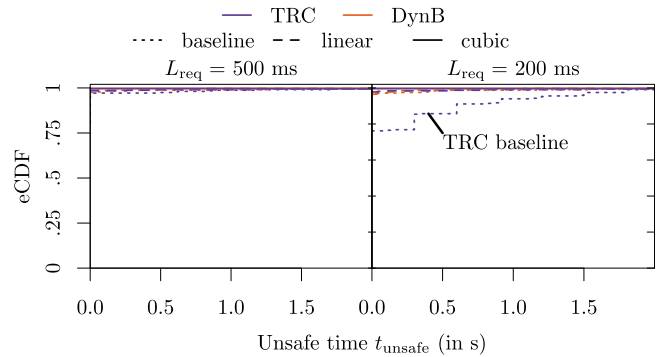


Fig. 15. eCDF showing the timespan that vehicles spent in an unsafe state during the last three seconds for the *Downtown Scenario with moving background traffic*.

rate accordingly. Still, both protocols support the 200 ms threshold only in about 95 percent of all transmissions.

When looking at the adaptation results, it can be noticed that the linear adaptation strategy only helps little in this scenario. The cubic strategy, however, improves the results so that more than 99 percent of the transmissions meet the time threshold.

To conclude the evaluation of the situation-based rate adaptation algorithm, Fig. 15 presents the impact of the investigated protocols on the situation-awareness of individual vehicles during the last three seconds before a crash. Focusing on the result of a required update lag of 500 ms on the left side in this figure, it can be seen that the adaptation is able to provide updates in time for almost all vehicles and the unsafe times are experienced early before the crash: 98 percent without adaptation to almost 100 percent using the cubic adaptation strategy.

On the right side in Fig. 15, the results for a required update lag of 200 ms show a similar behavior: TRC without adaptation is not able provide the needed update frequency for a substantial number of vehicles. DynB performs better but only the cubic adaptation strategy leads to almost 100 percent successful transmissions within the critical bound of 200 ms.

7 CONCLUSION

Current congestion control mechanisms are not able to provide frequent enough communication opportunities to satisfy the requirements of vehicular safety applications. We analyzed the case of IAS in three different intersection scenarios—*Rural Scenario*, *Downtown Scenario*, and *Downtown Scenario with moving background traffic*. In particular, these congestion control mechanisms neglect that vehicles might be in different situations and hence have diverse communication requirements. We addressed this problem by introducing the situation-based rate adaptation algorithm which is independent of the underlying congestion control mechanism. The situation-based rate adaptation is a good opportunity to make congestion control mechanisms (which are mainly built to achieve fairness) reconcilable with vehicular safety application requirements, which require biased channel access favoring vehicles in dangerous situations. Moreover, the situation-based rate adaptation algorithm might be used for other vehicular safety use cases which rely on frequent broadcast based updates.

Our work also reveals that beacon rates can be adapted to meet the demands of vehicular safety applications. Therefore, it can be seen as a starting point for decision controller designers of vehicular safety applications to specify their communication needs in more detail. Finally, the situation-based rate adaptation algorithm could become part of future congestion control mechanisms for vehicular networks and enable more frequent and reliable communication when required by applications.

ACKNOWLEDGMENTS

The manuscript is based on earlier work on intersection assistance systems that was presented at IEEE PIMRC 2014 [1].

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