Modern WLAN for V2X Applications: Exploiting Beamforming for Platooning

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***Abstract*—A key challenge in the domain of Inter-Vehicle Communication (IVC) is to make the best use of limited channel capacity to achieve a continuous exchange of information. In this work, we propose the use of directional radio transmission and reception (known from modern WLAN standards, but following the IEEE 802.11p specifications) to lower the channel utilization. In this work, we use platooning as an example application, since this application offers a well-defined communication topology. Using extensive simulations, we show that directional communication can substantially lower the channel busy ratio to less then half for platoon vehicles and down to less than 1 % for non-platoon vehicles. If care is not taken, however, it can drastically increase the probability for packet collisions.**

I. Introduction

Vehicular Ad-Hoc Networks (VANETs) are an essential building block for modern Intelligent Transportation Systems (ITSs) and can help to increase road safety, to reduce congestion, and to reduce environmental pollution. To enable various applications for cooperative actions between cars, a continuous exchange of information is necessary.

VANETs are relying on IEEE 802.11p as a basis for Vehicle to everything (V2X) communication and thus employ the listen-before-talk scheme CSMA/CA for medium access. This means that, while two nodes are communicating using a channel, the MAC protocol requires nearby other nodes to stay silent to avoid collisions. Moreover, the more busy the channel becomes the more often it suffers from interference [1].

This problem used to be addressable by multi-channel designs. Indeed, in 1999 the Federal Communications Commission (FCC) allocated 75 MHz to Dedicated Short Range Communication (DSRC), the frequency band for VANETs. In 2020, however, the FCC proposed reallocating the spectrum [2], now reserving the lower 45 MHz for unlicensed devices and the middle 20 MHz for cellular V2X devices – leaving only a single channel of 10 MHz dedicated to DSRC.

A common solution, thus, is to reduce channel load by mandating sparser intervals for information transmission as the channel gets more crowded [3]. However, sparser intervals lead to lower update rates and, thus, to a lower quality of information. This is especially dangerous for safety-critical applications. It is thus crucial to better exploit the remaining resources to preserve – or even to improve – the performance of modern ITS solutions.

In this work, we therefore propose to, instead, exploit the capabilities of modern WLAN standards for vehicular networks. In particular, we propose the use of beamforming, that is, directional communication, for selected broadcast transmissions by ITS applications. Using directional communication allows a larger set of vehicles to communicate simultaneously without interfering with each other, it mitigates the interference caused by other traffic participants, and it thus improves the reliability of communication.

On the flip side, however, directional communication can also be expected to decrease the performance of simple listen-before-talk schemes, requiring an in-depth study. Still, we posit that beamforming is an appropriate technique not just for unicast communication between exactly two participants, but for a plethora of use cases for which an intended group of receivers of information is more likely to be located in a certain sector (or less likely to be in another). This information might be known either explicitly (potential receivers known from neighbor tables [4]) or implicitly such as in intersection collision avoidance (potential receivers unlikely to be behind the ego vehicle), virtual induction loops (potential receivers likely to be in front of the ego vehicle), or merge assistance applications (potential receivers likely to be behind the ego vehicle and in the direction of planned merge).

In this work, we use platooning as an example application for V2X communication to show the benefits of directional communication. Platooning is an application for forming groups of vehicles where the first one is driving (leading) the platoon and others are cooperatively following, governed by Cooperative Adaptive Cruise Control (CACC). Vehicles in a platoon use wireless communication to propagate information about the current vehicle state, but also information concerning future actions like the desired acceleration. This data is used by the CACC to maintain gaps of only a few meters between vehicles at freeway speed.

A platoon is thus a good example use case which has a well-defined physical and communication topology that can be exploited for directional communication without needing time-intensive beam sweeping or incurring added signaling overhead.

In brief, the key contributions of this paper are:

- Based on a small field trial, we confirm the low impact of a typical car roof on directional communication capabilities.

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- Based on extensive computer simulations, we investigate trade-offs of using directional communication for information dissemination in VANETs, focusing on platooning as a use case.
- We show that directional communication lowers the interference for other road users and can have an additional positive effect on characteristics of a platoon.
- We show that directional communication can have a strong negative impact on application performance if the transmit power is not carefully chosen, e.g., set too high.

II. Related Work

Typical communication systems for VANETs are relying on omnidirectional radiation patterns. Because it makes no assumptions on physical topology, this kind of communication is suitable for almost all applications. However, this radiation pattern also introduces unnecessary interference and makes noise cancellation or signal source location more difficult. A promising alternative is directional communication using techniques like beamforming to focus the signal on a specific receiver or to a specific region. Recent studies [5], [6] investigate beamforming for millimeter-wave frequencies, but there are only few studies available that consider beamforming for DSRC frequencies.

A physical alternative to beamforming, Kornek et al. [7] used a multi-antenna system to improve the knowledge of a vehicle about certain channel characteristics. For this, the authors place three antennas with different characteristics on a vehicle and evaluated different configurations for a cooperative awareness scenario using ray-optical simulations. The goal of this work was to measure the distinction between the different positions and a corresponding isotropic configuration. Using simulations, the authors investigated the link robustness and showed that switching between multiple antennas can substantially increase system performance. However, experiments were only performed using two vehicles in an urban scenario, thus the performance gain at scale is unknown. Effects on higher density scenarios with realistic channel load are not considered.

Kang et al. [8] used beamforming to generate individual radiation patterns and deliver information only to relevant cars. In doing so, the authors followed the specifications of the IEEE 802.11p standard and thus used beamforming on 5.9 GHz. Utilizing simulations, the authors showed that beamforming results in a higher number of packet collisions, but also in a larger number of vehicles being reached. To compensate for the high number of collisions, the authors used retransmissions for all packets. Thus, the approach transmits double the number of packets and the channel might become unusable very fast in bigger scenarios. Although the interference is reduced because of the used beamforming compared to omnidirectional radiation, the authors did not investigate the additional load caused by retransmissions. The additional traffic due to retransmissions and the therefore caused communication latencies might not be beneficial when scaling the approach to larger scenarios.

Kalogeiton et al. [9] equip vehicles with multiple directional antennas to limit the dissemination area of packets and thus to reduce the usage of network resources. The suggested approach rotates all antennas to enable a node to transmit in any direction the application requires. The evaluation is done by counting transmitted packets, received packets, and by measuring the latency at the application layer. However, important metrics characterizing the channel quality, e.g., the channel load, have not been investigated.

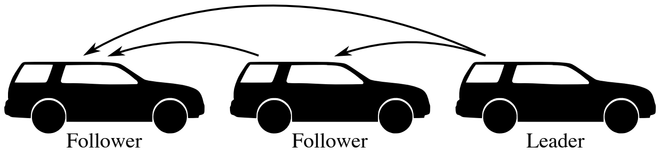


Figure 1. CACC PATH Communication Topology. Each vehicle in the platoon requires information from the preceding and leading vehicle.

Eckhoff et al. [10] investigated the impact of different antenna radiation patterns on VANET performance. Using a collision avoidance approach for intersections as an example application, the authors showed that the used antenna pattern can have a strong impact on application performance. Through simulations, the authors showed a strong difference in terms of received frames regarding the used antenna pattern. The authors did not, however, focus on potential positive impacts, i.e., how to exploit antenna directionality for improving performance.

In summary, many publications are investigating the use of directional antennas or different antenna patterns for VANETs. However, exploiting directional communication for reducing channel load of IEEE 802.11p based networks and improving the performance of applications has not been their focus. Important properties like the channel load of the wireless channel are not considered in great detail.

In this paper, we close this gap by taking platooning as a use case for directional communication, using detailed computer simulation modules for wireless communication and road traffic mobility. In particular, we have a detailed look at important metrics characterizing wireless communication performance in highly dynamic scenarios.

III. Directional Communication for Platoons

The concept of platooning is to form road trains where only the first (the leading) vehicle is driven by either Adaptive Cruise Control (ACC) or a human driver; all other vehicles are operated by CACC and can thus follow each other at a constant, small distance. This is achieved by exchanging data through wireless broadcasts called platoon *beacons*. These beacons contain information like the speed, position, or the desired acceleration, all of which is used as an input for the CACC. Literature reports different controllers for CACCs that differ in the required input data or the communication topology. Some examples like the consensus controller by Santini et al. [11] can dynamically reconfigure the topology at runtime. The most common controllers like the PATH controller [12] and the Ploeg et al. [13] controller, however, require a well-defined communication topology, e.g., the PATH controller requires data from the preceding vehicle and the leading vehicle only.

In other words, the PATH communication topology, illustrated in Figure 1, implies that a platoon member only requires communication directed to the rear of a vehicle.

We select this PATH controller as the basis for our work, both because it being a very common controller in recent literature [14], [15] and because it enables vehicles to drive with a constant inter-vehicle gap independent from the driving speed. Without loss of generality, however, our results can be generalized to many other platooning systems.

Many publications [16]–[18] relying on the PATH controller assume omnidirectional radiation of all information. In this work, in contrast, we propose the usage of directional communication to exchange platoon beacons for the CACC input.

Even though such directional communication can be expected to negatively impact the quality of listen-before-talk schemes, it can also be expected to improve spatial reuse, thus having the potential to realize a net performance benefit. In this work, we therefore set out to explore the performance impact in detail.

IV. Experimental Validation

Literature such as work by Kwoczek et al. [19] and Aguiar et al. [20] routinely points out the substantial impact that different vehicle roof configurations can have on antenna patterns.

We therefore prefix our simulative study by a short field trial that seeks to validate assumptions about the quality of beamforming that can be expected by an antenna mounted on an actual vehicle. For this, we perform a set of experiments using an antenna with (physical) directionality characteristics specifically built for operation in the 5.9 GHz band. This allows us to circumvent any uncertainties that might result from (electrical) beamforming, limitations of the hardware, or firmware limitations. In particular, we have chosen the HG3-TP-S30 horn antenna because of its symmetrical beam radiation pattern. We expressly note that the use of an antenna with (physical) directionality characteristics only serves as an ideal model of (electrical) beamforming – it is not what we are proposing to be used in an actual implementation.

In more detail, we performed two experiments for investigating the impact of the car roof on the radiation pattern of a directional antenna:

1) with the directional antenna mounted on an aerial mast instead of a car and
2) with the directional antenna mounted on a car roof.

We placed the horn antenna at a fixed position on an unoccupied parking lot of approx. 180 m x 180 m. The sender was transmitting with a fixed transmit power of 5 dBm.

To perform the measurements, we created a circle with a radius of 30 m around the antenna and performed measurements for every 4°, i.e., at 90 measurement points around the circle. For the omnidirectional antenna, we use a Mobile Mark ECOM9-5900 model which has an antenna gain of 9 dBi and is built for the 5.9 GHz band. This type of antenna was already used in various field tests because of its close approximation of an omnidirectional radiation pattern. We mounted this antenna

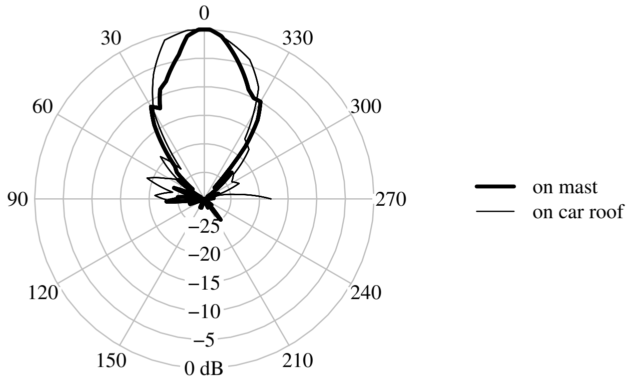


Figure 2. Measured radiation pattern (as seen from top) with the antenna mounted on either a mast or on a car roof. Values between recorded samples are linearly interpolated.

on a versatile dolly (taking care to align both antennas in height) and moved around the horn antenna.

To evaluate the impact of the directional pattern of the horn antenna on the communication performance, we chose three prime metrics: The Received Signal Strength (RSS), the goodput, and the communication delay. For our measurements we build upon the FOT-Box Toolkit [21].

In a first experiment, we measured the antenna pattern. For this, we mounted the horn antenna on an aerial mast at a height of 2 m. The antenna periodically transmitted beacons at an interval of 5 ms and we measured the RSS at the receiver by using the omnidirectional antenna. We collected samples at every measuring position for 20 s and calculated the median of their respective RSS.

Figure 2 (thick line) shows the results of this experiment. Since we are interested in only directionality characteristics, we normalize the shown values to the maximum observed RSS and display a measurement range of 30 dB (the difference between gain to the front and to the back). We can observe that, overall, the recorded antenna pattern follows that from the data sheet. Crucially, when the receiver is placed within the main lobe, we observe the expected increase of approx. 30 dB compared to the back of the antenna.

To better understand the impact of potential physical effects on communication performance, we also evaluate the goodput (measured using iperf in TCP mode) and the one-way latency (measured using sockperf in UDP and TCP mode). These results depend on the chosen Modulation and Coding Scheme (MCS) at the transmitter, for which the Linux rate selection algorithm selects the *best* fitting MCS based on lost acknowledgments at the MAC. In our directional antenna setting, the achievable datarate gets more than doubled in the main-lobe compared to the back of the horn antenna (data not shown because of space constraints). We can also observe these results when looking at the communication delays: Low signal strengths at the back of the horn antenna and thus many lost acknowledgements leading to retransmissions at the MAC heavily increase the observed communication latency. This is especially evident

Figure 3. Antenna with (physical) directionality characteristics serving as an ideal model of (electrical) beamforming.

when using TCP as transport protocol because of additional retransmissions at the transport layer. Importantly, however, we observe stable communication performance in the main lobe.

In the second experiment, we mounted the horn antenna on the roof of the car, as shown in Figure 3. Again, we adjusted the height of the omnidirectional antenna for measuring the metrics to match the height of the horn antenna. We then sampled RSS values within 180° in 8° increments to measure main and side lobes.

Figure 2 (thin line) shows the results of this experiment. We do note additional small side lobes in regions of low gain, but (also because their asymmetry hints at them being, in part, attributable to measurement artifacts) we can conclude that introduction of a car roof does not negatively impact directionality characteristics of transmissions.

V. Simulative Evaluation

Having confirmed the practical applicability of directional communication even if an antenna were to be mounted on a car roof in a field trial, we continue to investigate the difference between pure directional communication and traditional omnidirectional communication purely through computer simulations. For this, we are using the OMNeT++ network simulator, Veins [22] for realistic modeling of wireless communication, Plexe [16] for platooning support, and Sumo for road traffic simulations as detailed in Table I along with simulation parameters. Specific configurations are explicitly mentioned in all subsections. Since we consider homogeneous platoon scenarios in this work, we assume identical heights for senders and receivers [10].

For all experiments, we consider a freeway with four lanes. We choose this scenario for its simplicity: it allows us to study the impact of different radiation patterns on the performance of the platooning application in a detailed and reproducible way while having a close look at channel-related aspects.

We realize communication within the platoon by following the static beaconing approach [1]: Beacons are periodically scheduled at a frequency of 10 Hz to ensure communication. To model processing delays and reduce simulation artifacts, we subtract a uniformly random time offset between 0 s and 0.001 s from each transmission interval. Channel access is coordinated following pure CSMA/CA as standardized by IEEE 802.11p WLAN. In particular, we are not using a dedicated MAC protocol for directional communication [23].

Table I
Parameters employed in the simulative evaluation

Parameter	Value
Road traffic simulator	Sumo 1.5
V2X simulation models	Veins 5
Platooning simulation model	Plexe 3.0a1
Sumo update interval	0.01 s
Car Following (CF) model	CACC
CACC implementation	California PATH controller [12]
Vehicle length	4 m
CACC desired gap d_d	5 m
CACC bandwidth ω_n	0.2 Hz
CACC damping ratio ξ	1
CACC weighting factor C_1	0.5
Emergency braking deceleration	8 m/s^2
Technology	IEEE 802.11p
Carrier Frequency	5.89 GHz
Bit rate	6 Mbit/s
Noise floor	−95 dBm
Path loss (Friis model)	$\alpha = 2$

We use two different vehicle configurations:

1) For the *omni* (omnidirectional) configuration, vehicles are modeled as being equipped with a simple non-ideal monopole antenna [7]. This is the default approach to information dissemination that is used in many publications.
2) For the *directional* configuration, vehicles are modeled as being equipped with facilities to employ an antenna pattern following the recorded idealistic pattern described in Section IV. Depending on whether a vehicle is sending or receiving, we assume this pattern for either communication towards the front or to the back of the platoon. Figure 4 illustrates the resulting setup.

We performed three different experiments to assess the impact of directional communication on platooning as an application, but also on prime metrics characterizing the

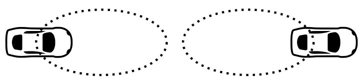


Figure 4. Each vehicle in a platoon is equipped with directional communication capabilities, selectively increasing gain to the front or to the back, e.g., by exploiting beamforming. This allows a vehicle to exploit the antenna gain for both transmission and reception.

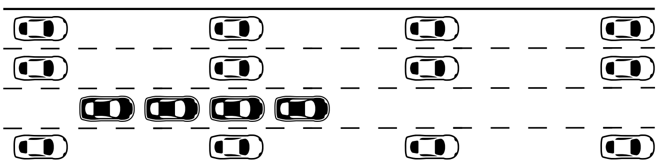
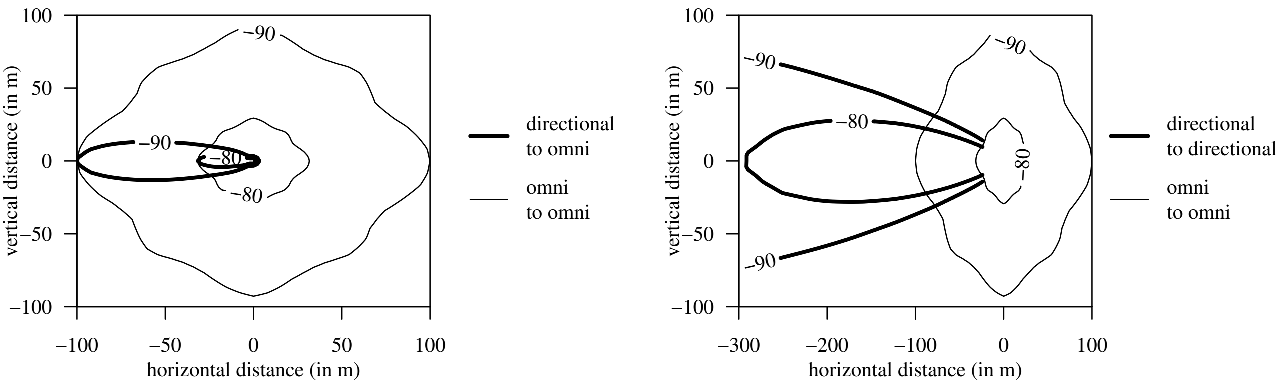


Figure 5. The scenario consists of a traffic jam, which has a length of 7500 to 30000 meters and 2000 vehicles on three lanes. The third lane from the top is free, where the platoon (dark vehicles) is driving and performing an emergency braking maneuver.



(a) both as recorded by a (non-ideal) omnidirectional antenna

(b) with directional communication recorded using a directional beam pointing at heading 270° (i.e., right)

Figure 6. Contour plot of radiation pattern, illustrated as Received Signal Strength (RSS) samples in dBm; shown for omnidirectional communication with a transmit power of 0 dBm and for a directional beam pointing at heading 90° (i.e., left); transmit power of directional communication is reduced by −19.68 dB, so that both have the same Effective Radiated Power (ERP).

wireless channel quality.

1) We analyze the average channel busy ratio for a single platoon, investigating both platoon and non-platoon vehicles on the freeway. For this, each vehicle measures the busy ratio of the channel as the fraction of the total experiment time that its Clear Channel Assessment (CCA) mechanism considered the channel to be *busy*.
2) As a core metric of platoon stability and safety, we investigate the *packet collision ratio*, the fraction of receivable transmissions lost due to interference: In more detail, for each transmission and considering each potential receiver, we determine whether it was received successfully taking into account all effects including interference; then, we repeat the exact same calculation (in particular, using the same pseudorandom numbers) but ignore interference. As a result, each transmission could either be (a) received, (b) not received but only due to interference, or (c) not received either way. The collision ratio, then, is the fraction of $b/(a+b)$.
3) We analyze the average channel busy ratio when multiple platoons are driving on the freeway at the same time, all potentially interfering with each other.

We perform ten independent repetitions for each experiment and compute confidence intervals of mean values we report; because their span is negligible compared to the effects we report, we omit them from plots.

A. Channel Busy Ratio

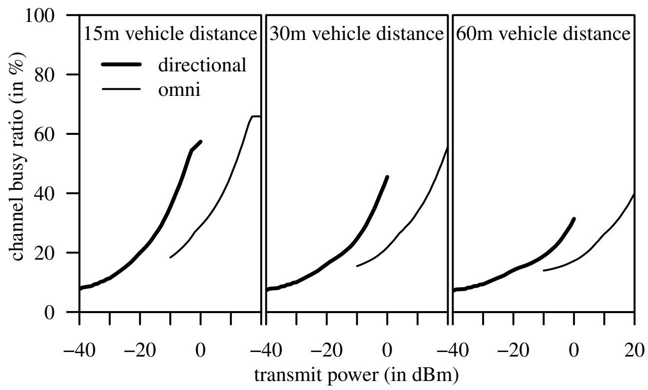
We first investigate the effect of omnidirectional and directional communication on the channel busy ratio of vehicles. We differentiate between vehicles that are part of the platoon and those that are not. For this, we insert a platoon consisting of 25 vehicles following the communication topology of the PATH controller [12] on a freeway. This platoon is driving at 100 km/h on a free lane as shown in Figure 5. After 15 s of simulation time, the platoon leader performs an emergency braking maneuver.

Besides the platoon, there are another 2000 vehicles going in the same direction and distributed among three adjacent lanes of the freeway. These vehicles periodically transmit beacons at an interval of 1 s, each with a size of 238 Byte including vehicle and platooning status information. To investigate the impact on the channel busy ratio regarding different vehicle densities on the road, we simulate one configuration each for inter-vehicle distances between non-platoon vehicles of 60 m, 30 m, and 15 m.

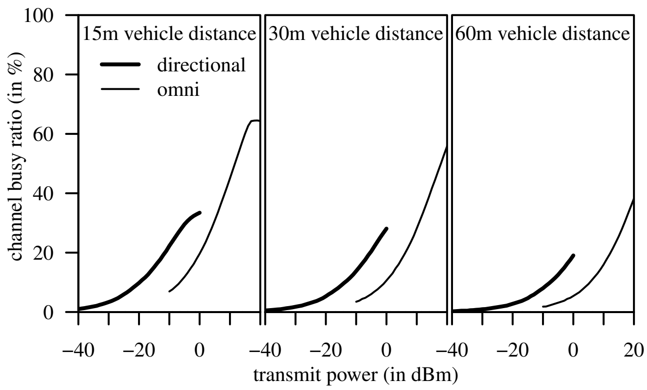
All vehicles in each experiment are using either the directional or omnidirectional radiation pattern. To empirically derive the impact of different transmit power levels, we reduce the transmit power of all vehicles from 20 dBm in steps of 1 dB. For directional communication, we reduce the transmit power by 19.68 dB so that the Effective Radiated Power (ERP) is the same as for omnidirectional communication, as illustrated in Figure 6a.

Figure 7a shows the channel busy ratio for platoon members as a function of transmit power for the case of directional and omnidirectional communication, omitting results for transmit powers below those where platoon stability was more than severely degraded (more than one third of braking maneuvers resulting in a vehicle collision; see below for a more detailed study of collisions).

We can observe that, in the scenario with small distances between the non-platoon vehicles (15 m distance), the channel is saturated (channel busy ratio of close to 65 %) for both omnidirectional and directional communication. In the omnidirectional case, however, the channel busy ratio is roughly 10 percentage points (% points) higher. We observed the first vehicle collision with a transmit power of approx. −10 dBm for omnidirectional communication. The channel load is approx. 20 % in this case. With directional communication, we can reduce the transmit power to approx. −40 dBm and the platoon

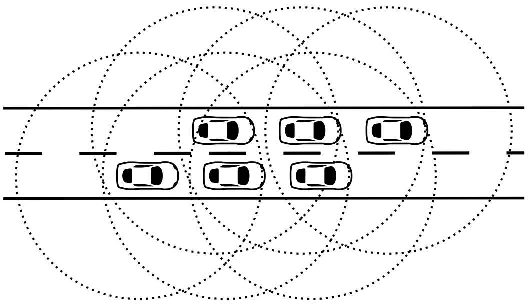


(a) channel busy ratio as observed by vehicles in platoon

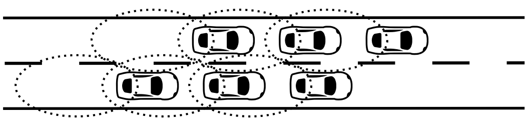


(b) channel busy ratio as observed by all other vehicles

Figure 7. Channel busy ratio of the channel depending on used transmit power. We show all values where less than one third of all simulation runs caused a vehicle crash. Using directional communication allows reducing the transmit power beyond what is possible using omnidirectional communication, resulting in a substantial fraction of channel capacity to be freed.



(a)



(b)

Figure 8. Using (a) omnidirectional communication introduces interference for vehicles in all directions, whereas (b) directional communication using the same Effective Radiated Power (ERP) heavily reduces interference to only a fraction of the available space.

is still performing the emergency braking maneuver without increasing vehicle collisions. Compared to the omnidirectional communication, the channel load for directional communication is reduced to only approx. 8 % and thus halved with respect to directional communication.

The first reason for this observation is the directional radiation behavior, which radiates energy in one predominant direction. Because of this, the interference for preceding members in the platoon is substantially lower, although they are close by (CACC is configured to 5 m inter-vehicle distance). Figure 8 illustrates this phenomenon.

The second reason is the combination of directional transmission and directional reception, which thus exploits the directional gain twice. While Figure 6a shows the radiation pattern of the directional approach measured by an omnidirectional receiver, Figure 6b illustrates the directional radiation pattern as observed by a directional receiver. Due to this setup, a greater RSS is achieved at the receiver and packets can be successfully decoded even at low transmit power levels. However, our data also shows that too high transmit power levels can lead to vehicle collisions and higher packet loss. We are investigating this high packet loss in Section V-B.

Figure 7b shows the channel busy ratio for non-platoon members as a function of transmit power for the case of directional and omnidirectional communication. For the high density scenario (15 m distance) we observe a maximum channel busy ratio of approx. 65 % for omnidirectional communication, whereas in the case of directional communication the channel busy ratio is nearly halved. This is due to the fact that the transmission beaconing frequency of non-platoon vehicles is much lower and the distance between these vehicles is much larger. However, our data shows that even vehicles that are not part of a platoon benefit substantially from directional communication. This is again caused by the directional radiation pattern, which drastically reduces the interference for other road users.

Considering the minimum values for the transmit power, we can observe that in these cases, a relative reduction of the channel busy ratio to approx. one tenth compared to that of omnidirectional radiation is possible. In this case of the lowest possible transmit power the channel busy ratio for non-platoon members can be reduced below 1 % using directional communication.

B. Platoon Beacon Collisions

So far, we only studied the impact of transmit power reduction on high-level metrics (channel busy ratio and platoon cohesion); now we are also investigating the effect of this reduction on finer-grained quality metrics. To do so, we are using the scenario from Section V-A and measure the aforementioned *collision ratio* for platoon beacons while the platoon of 25 vehicles is driving on the freeway.

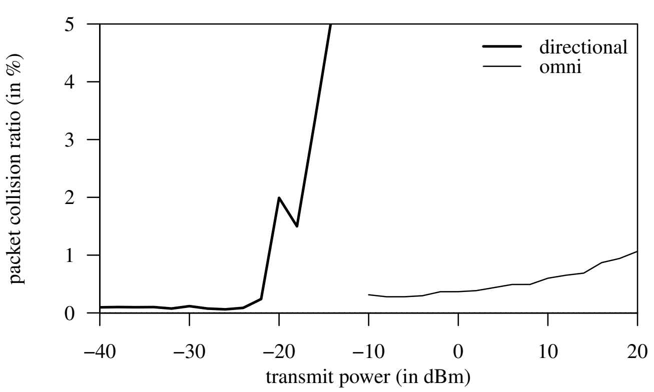


Figure 9. The figure shows the ratio of collisions for platoon beacons calculated as the fraction of collisions in the sum of collisions and decoded platoon beacons while the platoon of 25 vehicles is driving on the freeway. A high transmit power substantially increases the ratio of collisions for directional communication.

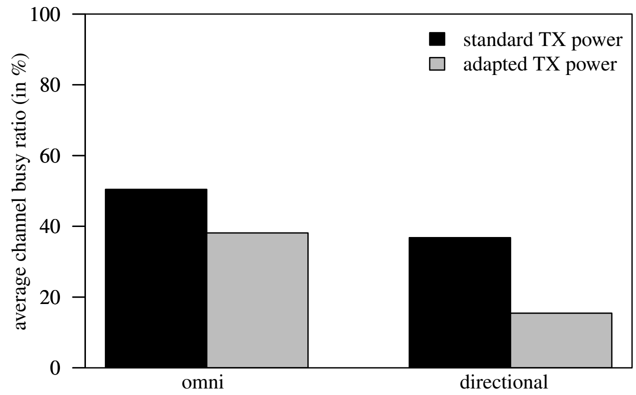


Figure 10. Bar plot showing the average channel busy ratio for directional and omnidirectional communication while three platoons with 25 vehicles each are driving on a freeway. With an adapted transmit power the channel busy ratio is approx. 23 % points lower for directional communication.

Figure 9 shows the median ratio of collisions for platoon beacons for all vehicles in the platoon. The data is collected by the front beam for directional communication and without beamforming for omnidirectional communication. Due to space constraints, we only show data for the medium density scenario (30 m) representing a typical and realistic traffic scenario.

The collision ratio for omnidirectional communication remains largely constant for all feasible transmit power levels. Decreasing the transmit power level decreases the number of collisions due to a lower channel load and lower interference – until the platoon loses cohesion when the emergency braking maneuver is triggered.

When using directional communication, it becomes obvious that a corresponding reduction in transmit power is necessary: at too-high transmit power levels, vehicles experience a substantially higher collision ratio. The reason is, again, that our approach exploits the high gain of directional communication on both the transmitter and the receiver. As shown in Figure 6b, this design results in transmissions from more vehicles (including non-platoon vehicles) being received with a higher RSS. The high packet loss also leads to vehicle collisions. This phenomenon, however, requires further investigation and the identification of factors that may be caused by static beaconing.

The data also shows, however, that if the transmit power is reduced, interference from non-platoon vehicles is reduced as well. Thus, the collision ratio decreases strongly and quickly goes below the level of the omnidirectional setup at a transmit power of approx. −21 dBm.

C. Channel Busy Ratio for Multiple Platoons

To study the scalability of our directional communication approach for platooning applications, we set up a study of multiple platoons that are driving on a freeway at the same time. In more detail, we use a three-lane freeway where each lane hosts a platoon of 25 vehicles. All platoons are driving at a speed of 100 km/h and are performing an emergency braking maneuver. We compare both directional vs. omnidirectional communication as well as transmissions using two different power levels:

First, we use standard transmit power levels from related work, that is, approx. 13 dBm for omnidirectional communication and a power level reduced by 19.68 dB for directional communication, so that the ERP is the same as for omnidirectional communication. Second, we use the power levels found to be most beneficial in Section V-A, that is, −9 dBm for omnidirectional and −40 dBm for directional radiation.

Figure 10 shows the channel busy ratio for the standard and low transmit power as a bar plot showing the mean. Using an ERP of approx. 13 dBm, the standard value, we already observe a reduction of approx. 15 % points for directional communication. If, however, vehicles use the lowest workable transmit power, directional communication can effectively reduce the average channel busy ratio to less than one third – freeing up a substantial fraction of channel capacity.

Further experiments (data not shown due to space constraints) showed that especially the front vehicles, i.e., the leading vehicles, benefit most from the lower channel busy ratio. This is because, using the standard parameterization [12] of the PATH controller, the desired acceleration from the leader and the preceding vehicle are equally weighted, so each contributes equally to the output of the controller. This and the fact that the leader is the first vehicle to act, make the leader the most important vehicle in the platoon. Since CSMA/CA is used for channel access, the leader detects the channel less often as busy and can thus transmit more often compared to other vehicles.

VI. Conclusion

In this work we proposed to take advantage of the novel possibilities of current WLAN standards, in particular directional communication afforded by beamforming, and applied them to vehicle networks. Beyond what has been performed in state-of-art studies in this area, we investigated vehicular platooning using directional signal radiation from a realistic simulation perspective at scale and for both application and channel metrics, taking advantage of realistic models for communication and road traffic mobility. We used platooning as an exemplary application and showed that – if parametrized right – the benefits of directional communication far outweigh its drawbacks in terms of key performance indicators such as channel load and packet collision ratio – both in low density and in high density scenarios.

We further showed that a too-high transmit power for directional communication has strong negative effects on the channel in terms of packet collisions. Moreover, we were able to show, that the transmit power can be reduced by up to 40 dB for directional communication while still meeting safety requirements. This is also related to a substantially lower interference for other road users. In fact, we showed that the channel busy ratio for vehicles in a platoon can be reduced to less then half. This effect is even greater for non-platoon vehicles. Here, we showed a reduction of the channel busy ratio down to a channel busy ratio of less than 1 % for directional communication. Finally, our results also show that the most important vehicle in the platoon has the greatest advantages: the leading vehicle.

Since directional communication has proven to be very promising for platoons, there are several avenues of future work. First, a design using directional communication could be further improved by using one of several available dedicated MAC protocols [24] with directional communication capabilities. Second, an exploration of directional communication for platooning in urban areas could shed light on the interplay of directional communication with the drawbacks and benefits [25] of radio obstructions.

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