Removing Blind Spots

Infrastructure-assisted Collective Perception

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Abstract
Road traffic has increased tremendously over the past decades, confronting politics and industry with considerable road safety and efficiency challenges. Vehicle-to-vehicle (V2V) communication is generally regarded as one of the main emerging technologies to address these challenges by allowing vehicles to exchange information, about themselves (cooperative awareness) or other detected objects (collective perception) by video, radar or lidar systems. The latter, however, is not only interesting for the V2V link, but can further be used by sensor-equipped infrastructure to support vehicular perception over the infrastructure-to-vehicle (I2V) link, opening a whole new range of possibilities. In this paper we first introduce a demonstrator we developed in the scope of the German project 5G NetMobil and prove the high added value of road infrastructure-assisted collective perception for vulnerable road user (VRU) protection. Subsequently, we extend the findings to large-scale scenarios by investigating the performance on highways with different traffic densities in terms of reliability and link type. A key finding is that, in high-density scenarios, the reliability of the I2V link is reduced by the V2V transmissions, so that a more efficient resource allocation scheme maximizing the value of transmitted information is needed to optimize the wireless channel usage.

Introduction
Mobility is one of the essential drivers of modern times. A world without vehicles is unconceivable for most people nowadays. While the number of vehicles registered worldwide merely exploded in the first one hundred years since Karl Benz’s famous patent in 1886 [1], reaching as much as 440 million units in 1990 [2], that number has more than doubled in the past 30 years [3]. And the global traffic density is expected to increase even further, as (i) the number of vehicles per 1000 inhabitants in less developed countries is still far behind that of their developed peers, and (ii) the world population is expected to continue growing at a rate
of roughly 1% per year in the midterm [4]. This vertiginous development of the traffic density confronts the politics and industry with tremendous challenges when keeping high levels of traffic efficiency and comfort while trying to guarantee road safety. The two probably most promising cutting-edge technologies are traffic automation and vehicle-to-everything (V2X) communication. While they are clearly distinct from each other, the synergies are evident. Inter-vehicle communication can, e.g., greatly enhance the environmental perception of automated vehicles to strengthen their decision basis, with very positive effects on the mentioned road safety, efficiency, and comfort [5, 6]. Different V2X services have been proposed to extend a vehicle’s perception beyond the perception range of its sensor systems. Cooperative awareness [7] enables road users to share information about their current and past states. It is thus generally very reliable and accurate; however, it lacks sufficient availability until complete V2X market penetration [8]. Collective perception [9] in turn allows road users equipped with object-tracking sensors to share detected objects. While this service does generally not require full V2X market penetration to ensure a complete environmental perception, hence presenting a high availability [10], its reliability and accuracy may be compromised by the environment-dependent quality of their detections [11]. Not only weather conditions [12] but also occlusion by other traffic participants [10] and a limited sensor accuracy [11, 13] may negatively impact the performance of the service. Another service, introduced only recently, is starting to gain attention in the V2X community: collaborative localization [14]. Enabled vehicles can share GNSS and range measurements in order to enhance the localization accuracy and availability of all connected vehicles in the environment as compared to cooperative awareness. However, the availability is still limited to the perception of connected vehicles. Another challenge of deploying V2X services is that their efficient operation depends on the communication performance. Signal attenuation and interference may cause packet losses, compromising the performance of the system [15, 16]. The performance is further sensitively dependent on the absolute positioning capabilities of the connected stations, as shared position data generally needs to be converted to absolute coordinates by the transmitter and back to relative coordinates in the receiver [17]. Infrastructure-assisted connected driving has considerable potential to deal with most of these challenges: (i) road side units (RSUs) can be stationed at strategical positions (sensor height, angle, distributed arrangement) to guarantee high detection availabilities and accuracies, (ii) these RSU locations may further consider the V2X signal propagation within the area of interest, increasing the communication reliability, and (iii) being static, the RSUs’ absolute positions are well defined, reducing the introduced transformation errors.
In this work we present the following two studies on infrastructure-assisted collective perception:

1. Use case of V2X-based collision avoidance with pedestrians: A roadside infrastructure is equipped with a camera which detect pedestrians crossing the street. These detections are transmitted to oncoming vehicles, which then calculate the collision probability and, if needed, perform an automated braking manoeuvre. This function has been recently demonstrated as a proof-of-concept.

2. Simulation results extend the investigation to large-scale scenarios, proving the benefit of infrastructure-assisted collective perception for elevated numbers of connected stations. The investigation analyses key performance indicators such as reliability and latency in a highway scenario where a roadside unit supports the vehicles' environmental perception by detecting nearby vehicles and transmitting its data using collective perception.

Finally, the next steps to further enhance automated driving using V2X communication, such as a data-quality dependent channel resource allocation are described.

**Infrastructure-assisted Collective Perception**

Collective perception allows vehicles and RSUs to inform nearby vehicles of objects (e.g. pedestrians, motorcycles, or other vehicles) detected by their on-board sensors [18]. This enables receiving vehicles to extend their own environmental model beyond their own sensors range by looking through the “eyes” of others. The object data received through V2X communication are then incorporated into the vehicle’s environmental model, eventually combining the object data with that obtained from the on-board sensors by means of data fusion [19, 20]. This approach increases the redundancy of the detected object data [21], leading to a higher reliability.

The exchange of object data is done by means of Collective Perception Messages (CPM)s, currently in standardization by the European Telecommunications Standards Institute (ETSI) [9] in order to ensure its interoperability among all equipped vehicles.

The term “Infrastructure-assisted Collective Perception (ICP)” refers to the case when the object detection is performed by an RSU, which transmits the object data to nearby vehicles in CPMs [22]. ICP has been the focus of several research projects. The EU-funded TransAID project [23] performed a demonstration of ICP with infrastructure equipped with a video camera using the ETSI CPM. The considered use cases are a blocked road assistant and cooperative
lane merge. The German projects KoMo:Dnext [24] and LUKAS [25] explore the use of ICP to support automated driving at an urban intersection. For this purpose, data for a high-resolution multimodal environment detection are aggregated on the infrastructure side and made available to the surrounding traffic. Equipped road users serve as mobile sensor, transmitter and receiver units and form a multi-sensor network together with the infrastructure. This network generates data to determine the position and dimension of dynamic objects (motorized vehicles, pedestrians, and cyclists) in the observed traffic space in terms of time. These data are transmitted in CPMs and integrated in the vehicles' Local Dynamic Map (LDM). Fig. 1 shows a sample scenario where ICP allows increasing the traffic safety.

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Fig. 1: Infrastructure-assisted Collective Perception in an intersection. Vehicle A detects vehicle B with its on-board sensors and transmits the corresponding detected object in a CPM. The RSU receives the CPM, identifies that the message is relevant for vehicle D and that vehicles A and D are not in communication range, since their line-of-sight is blocked by a building. Furthermore, the RSU detects vehicle C with its own sensors and realizes that it is also relevant for vehicle D. Therefore, the RSU retransmits a CPM containing information about vehicles B and C towards vehicle D, which then adapts its maneuver to prevent a collision risk with them.
Demonstrator: Vulnerable Road User (VRU) Protection

In scope of the German public founded project 5G NetMobil [26], sensor-equipped infrastructure was used to inform approaching vehicles of pedestrians and other VRUs by infrastructure-to-vehicle (I2V) communication. This use case is especially relevant in scenarios with reduced visibility, where vehicle sensors have difficulties perceiving parts of their environment, e.g., due to vision-occluding obstacles. The perception data provided by the RSU is aimed at making nearby vehicles aware of potentially undetected VRUs. The warned vehicle can then perform an Automatic Emergency Braking (AEB) despite not having detected the VRU with its own sensors early enough, thereby avoiding a collision (see schematic in Fig. 2). The safety-critical nature of this use case sets stringent requirements to the reliability and latency of the data transmission over the I2V link that must be investigated.

Fig. 2: Schematic representation of the investigated VRU protection scenario relying on infrastructure-assisted collective perception.

To investigate the described scenario in the real world, a demonstrator vehicle (left part of Fig. 3) and infrastructure system were built up. To cope with the identified high communication requirements, the project developed the so-called “NetMobilBox” (right part in Fig. 3). It features a hybrid communication approach implementing both state-of-the-art direct vehicular communication technologies C-V2X [27, 28] and ITS-G5 [29, 30] and extending them with cellular connectivity (4G/5G), allowing a comparison of the different approaches.
Fig. 3: Demonstrator vehicle (left) equipped with multiple radio technologies brought together in the “NetMobilBox” (right) developed in the scope of the project 5G NetMobil.

The infrastructure setup is depicted in Fig. 4. It consists of another NetMobilBox extended by a local processing unit connected to a Bosch IP camera [31] as sensor. The camera was attached to the local processing unit via power and ethernet cable. The camera’s integrated intelligent video analytics [32] was used for the video-based VRU detection and situation analysis.

Fig. 4: Demonstrator infrastructure setup using the extended NetMobilBox (left) and a Bosch infrastructure camera (right).

The system architecture is depicted in Fig. 5. The camera provides the metadata computed by its integrated intelligent video analytics to a Robot Operating System (ROS) based system. The processing unit within the extended NetMobilBox then generates a CPM message based on the detected and classified objects obtained over the ROS interface. The format of the CPM and the carried perceived object list complies with the current version of the ETSI specifications.
[9]. The generated CPM is then transmitted via the hybrid communication approach using the three links: (i) cellular connectivity using a Multi-access Edge Cloud (MEC) with geocast to address the correct vehicles in the proximity, (ii) C-V2X, and (iii) ITS-G5, the two latter being direct, broadcast-based communication technologies.

The data is received and decoded by the vehicle’s NetMobilBox and ROS-based vehicle system. After this step, a collision probability is calculated using the predicted trajectories of the VRUs and the vehicle itself. The collision probability is estimated by an overlap analysis of the trajectories for all relevant future points in time. If a certain threshold is exceeded, a warning message will be shown to warn the driver, and an AEB is triggered if needed. The vehicle’s own onboard sensors can be used to double check the incoming data and avoid unwanted braking manoeuvres. In this demonstrator, the vehicle sensors were not used, as the data received from the RSU was trusted to be confident and accurate. This assumption allowed to better determine the performance of merely infrastructure-assisted collective perception.

![System architecture of the VRU protection use case](https://example.com/system_diagram.png)

**Fig. 5:** System architecture of the VRU protection use case, detailing the three communication paths of the implemented hybrid communication approach.

In order to guarantee a safe demonstration of the scenario with activated AEB, a pedestrian dummy was used as VRU, similar to the one used in the official NCAP crash tests [33], featuring moving legs to ensure a high level of realism. In the recreated scenario, the dummy was set to emerge from behind a transporter, representing a typical safety-critical road situation where vehicle and driver only have very limited time to react. During the performed testing, the V2X-triggered AEB in the vehicle was highly reliable and robust, triggering the emergency braking before the on-board sensors could detect the pedestrian dummy. This demonstration proved the high safety benefit of infrastructure-assisted collective perception for VRU protection. An impressive demonstration video of the system is offered in [26].
Simulation: I2V Performance Analysis

While the potential of vehicular communication to improve road safety and traffic efficiency for next-generation vehicular traffic system has been well investigated and proved [6, 34], the benefit of I2V communication to support automated driving has received considerably less attention [35]. After having investigated infrastructure-based collective perception with only two connected stations in the previous section, we evaluate next the effects of road traffic conditions as well as mobile shadowing on the I2V communication performance in a highway scenario based on a profound simulation campaign. For this purpose, we consider a distance-based evaluation of packet reception ratios with respect to sender and receiver positions.

As simulation environment, we use Veins [36], a hybrid simulation platform composed of the well-known simulation tools SUMO [37], which provides road traffic simulation, and OMNeT++ [38], which provides the basis for our network simulation. For a more realistic investigation of the performance of I2V communication, we extended the Veins framework by adding a radio propagation model designed to reflect radio propagation characteristics on highway environments [39].

The simulation scenario consists of a highway section with two lanes per direction. Although the total length of the section is 6 km, only a centre segment of 4 km length is used for statistical evaluation, in order to eliminate boundary effects. Vehicles enter the scenario following a Poisson process with an average speed of 120 km/h. We examine different road vehicle densities by using the so-called Level of Service (LoS), which quantifies the aggregated number of vehicles per kilometre for all highway lanes and both directions, resulting in different network loads categorized in LoS A, B and C. While LoS A, the lowest road traffic condition used, corresponds to free-flow traffic of 650 vehicles per hour per lane with an average inter-vehicle-distance of 77 m per lane, the intermediate traffic condition, LoS C, represents stable
traffic flow of 1550 vehicles per hour per lane with roads remaining safely below but efficiently close to the highway section's capacity and an average distance of 29 m (further details for all LoS are found in [40]). A single RSU located at the scenario's centre is responsible for the transmission of information from the deployed fixed infrastructure sensors including camera, radar and lidar on the downlink I2V communication path, while vehicles broadcast periodic status messages. A summary of the simulation system parameters is presented in Table 1.

Table 1: Simulation parameters of the investigated highway scenario.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission power</td>
<td>23 dBm</td>
</tr>
<tr>
<td>Center carrier frequency</td>
<td>5.9 GHz</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>Channel model</td>
<td>Dual-slope highway propagation model [39]</td>
</tr>
<tr>
<td>Antenna height</td>
<td>Vehicle (V2I link) 5 m</td>
</tr>
<tr>
<td></td>
<td>RSU (I2V link) 5 m</td>
</tr>
<tr>
<td>Packet generation rate</td>
<td>10 Hz 15 Hz</td>
</tr>
<tr>
<td>Message payload size</td>
<td>500 Bytes 2000 Bytes</td>
</tr>
</tbody>
</table>

Fig. 7 illustrates the impact of the road traffic condition on the achievable communication performance by comparing the Packet Reception Ratio (PRR) resulting from simulation configurations under different LoS conditions. The PRR is defined for each node pair as the ratio of the number of successfully received messages to the total number of generated messages. This takes into account packet drops due to the waiting time in the Medium Access Control (MAC) queue as well as packet collisions due to the presence of hidden terminals or insufficient Signal-to-Interference-and-Noise Ratio (SINR) caused by interference or shadowing. We evaluated average PRR results for each communication link which are plotted against the distance between the vehicle and the RSU. To ensure statistical validity of the results, we performed at least 5 simulation runs per scenario. As expected, for all road conditions, the PRR decreases with increasing distance and increasing network load. For the I2V link, we observe that the PRR remains greater than 70% for \( d \leq 300 \) m, but decreases quickly for \( d \geq 400 \) m and only approximately 20% of the transmitted frames can be decoded for \( d = 800 \) m. Even less frequently, frames from greater distances can also be received successfully. Moreover, the PRR values of about 95% in the area around the RSU are particularly interesting. This indicates that vehicles located near the RSU are not able to efficiently exchange their status messages. This is due to packet collisions caused by a high
level of interference from all other vehicles around the target RSU. These results clearly illustrate the substantial impact of road traffic condition on the PRR and hence on the communication performance for the I2V-based application.

Fig. 7: Mean packet reception ratio for varying road traffic condition (LoS A, B and C) on the I2V link (left) and the V2I link (right).

To evaluate the impact of the radio shadowing, we have conducted additional simulation runs under the consideration of mobile radio shadowing caused by vehicles or trucks which might obstruct the communication path between stations. It is evident that vehicles located between communication paths attenuate or even fully block the radio propagation and result in undesirable shadowing effects. Fig. 8 depicts the PRR with (dotted lines) and without (solid lines) the shadowing effect for different road traffic conditions (LoS A and LoS B). We observe a significant degradation of communication performance when the radio propagation channel is obstructed by surrounding vehicles and/or trucks. We further note that even near the RSU an additional decrease of the PRR of more than 15% can be observed, which is more pronounced in the I2V communication path. Finally, it can be observed that the PRR increases at higher distances for LoS A in the obstructed I2V link. However, the treatment of this at first sight counterintuitive effect would go beyond the scope of this publication and will be subject of future work.

All these findings suggest the need for a more efficient resource allocation within the network, as the potentially highest-quality data disseminated over the I2V link is most affected. New intelligent congestion control or resource allocation mechanisms are required to mitigate this challenge and maximize the value of information disseminated within the vehicular networks. Some first interesting approaches have been proposed in [41, 42, 43].
Conclusions and Outlook

In this work, infrastructure-assisted collective perception, one of the most promising technologies to enhance future traffic safety, was analysed. For this purpose, a demonstrator was set up in the scope of the public funded project 5G NetMobil, tackling the use case of infrastructure-assisted VRU protection. It could be shown that the technology is well-suited for this safety-critical use case, even in challenging VRU-occlusion scenarios. It was further identified that the communication quality plays a crucial role for the usefulness of the technology. For this reason, a large-scale simulation was set up, shedding light on the impact of channel congestion on the technology’s performance. It could be determined that the performance of I2V communication notoriously suffers from high-density V2V networks, even though I2V links generally present a higher benefit in terms of data quality, also referred to as value of information. The investigation is especially relevant in view of the ongoing standardization of collective perception in Europe, as it makes clear that the standard should consider the value of information when allocating communication resources within the network to account for the higher added value provided, e.g., by RSUs. This could either be realised by prioritizing the I2V link over the V2V link under congested channel conditions, or by developing new intelligent data-quality aware resource allocation mechanisms.
References


