Empirical Evaluation of Cooperative Awareness in Vehicular Communications

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***Abstract*—Vehicular networks will enable a number of active safety and traffic efficiency applications. At the core of many of those applications is cooperative awareness: the ability to detect location, speed, and heading of surrounding vehicles. We empirically analyze three key metrics that shed light on the communication performance available to applications: 1) Packet Delivery Ratio: link quality in terms of the proportion of received messages over distance; 2) Neighborhood Awareness Ratio: the proportion of detected neighbors within a given distance, which serves as an indicator of the effectiveness of cooperative awareness message exchange; and 3) Neighborhood Interference Ratio: the proportion of neighbors above the desired range of interest, which can provide insight into the interference levels of fully deployed systems. By analyzing the measurement data collected within the scope of the DRIVE-C2X project, we conclude that the link layer delivery and neighborhood awareness criterion can be fulfilled for safety applications: in the analyzed datasets, the cooperative awareness ratio is close to 100% up to 100 meters. Depending on the desired region of interest, the interference from far-away vehicles can be considerable, thus requiring effective congestion control to balance between neighborhood awareness and interference.**

***Index Terms*—Cooperative Awareness, Empirical Evaluation, Vehicular Networks, Intelligent Transportation Systems, Interference.**

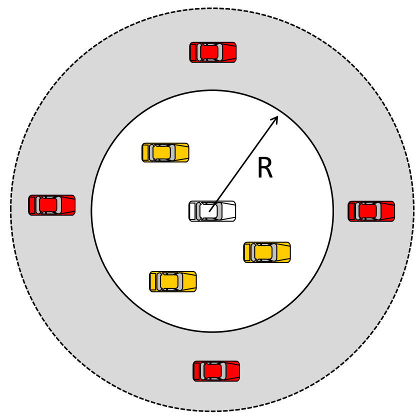


Fig. 1. Neighborhood awareness is based on the broadcast of periodic messages and allows gathering relevant information on the evolving neighborhood (white awareness zone with radius R). However, increased awareness can also result in interference from distant vehicles (grey interference zone) that are less relevant than the nearby vehicles.

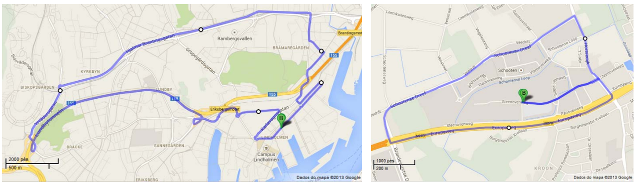
I. Introduction

Cooperative awareness is the basis for a number of safety and traffic efficiency Intelligent Transportation Systems (ITS) applications [1]. More specifically, applications such as Overtaking Systems [2], Virtual Traffic Lights (VTL) [3] or Cooperative Adaptive Cruise Control (CACC) [4] rely on the exchange of cooperative awareness messages between vehicles. The main premise is that, by knowing their neighborhood, vehicles (in coordination with their drivers) are better equipped for decision-making in hazardous situations (e.g., emergency braking) and more adept at finding better routes to their destination (e.g., by avoiding congested roads).

The exchange of local dynamic information (e.g. direction, position, speed) allows creating a precise picture of the evolving neighborhood and the dynamics of surrounding vehicles. Thus, in order to have up-to-date neighbor information, vehicles periodically send single-hop broadcast messages containing awareness information. To enable this service, the European Telecommunications Standards Institute (ETSI) and other standardization bodies have introduced Cooperative Awareness Message (CAM) for periodical update of vehicles' location, speed, and other salient information. However, improved awareness level comes at the cost of higher channel load and the associated packet collisions. Eenennaam et al. [4] studied the solution space of single-hop beaconing and concluded that the number of nodes, the beacon frequency and size, and the transmit power impact the beacon reception rate considerably. Adaptive power/rate beaconing [5] or selective beacon forwarding [6] can improve network conditions, especially in high load situations.

In this paper, we focus on the effectiveness of CAM message exchange. Specifically, we study the performance of cooperative awareness under realistic conditions and configurations by using measurements collected during large-scale Field Operational Tests (FOTs) of the DRIVE-C2X project[1]. Our main goal is to determine the feasibility and performance of periodic beaconing and to assess the awareness level provided to applications. With this aim, we analyze link quality in terms of Packet Delivery Ratio (PDR) and cooperative awareness efficacy in terms of Neighborhood Awareness Ratio (NAR). We study how these metrics are affected by the surrounding environment and node separation. While CAM messages increase the awareness, at the same time they have a negative impact on interference. Therefore, to gauge the level

[1] http://www.drive-c2x.eu/project



(a) Gothenburg. (b) Helmond.

Fig. 2. Measurement routes.

of interference that both CAMs and other messages generate, we analyze the proportion of neighbors above a certain range from which a given vehicle receives messages. This metric is of interest for understanding the side-effects of higher level of distributed/local information and in combination with the previous metrics can be useful in the design of congestion control algorithms.

The remainder of this paper is organized as follows. In Section II, we present the work related to evaluating cooperative awareness. Section III provides an overview of the experimental evaluation platform, including assessment methodology, evaluation metrics, and experimental scenarios. Section IV details and discusses the results of communication performance and its impact on the application-level performance. Section V concludes the paper.

II. Related Work

Extensive research has been conducted to study communication performance as well as application performance in Vehicular Ad Hoc Networks (VANETs), with most studies resorting to analytical models or simulations. Mittag et al. [7] compared single and multi-hop broadcast performance using simulations. They concluded that a limited benefit is achieved when using multi-hop communication instead of single-hop for cooperative awareness. Van Eenennaam et al. [4] showed how different beaconing configurations support Cooperative Adaptive Cruise Control (CACC). Noori et al. [8] performed simulations to study the probability of beacon delivery in an urban scenario and showed how the delivery is impacted by increasing vehicle density and different road types.

Regarding empirical evaluation of communication and application performance in VANETs, Martelli et al. [9] analyzed the packet inter-reception time (PIR). Their results showed that PIR follows a power-law distribution (i.e., long-lasting outages occur with certain periodicity). Furthermore, PIR is strongly affected by line of sight (LOS) conditions, with up to five-fold performance drop in case of LOS obstruction by vehicles. Bai et al. [10] performed an extensive study on the impact of controllable parameters (transmit power, modulation scheme) and uncontrollable factors (distance, environment, velocity) on the performance of IEEE 802.11p [11] radios. The authors solely use PDR as the metric for the performance assessment. Vlavianos et al. [12] performed a measurement-based study to assess the link quality in IEEE 802.11 networks. The authors concluded that different evaluation metrics reveal relevant aspects of the link quality. Boban et al. [13] demonstrated the importance of accurate channel model selection for correctly simulating the application-level performance in terms of throughput, packet delivery, and latency.

Apart from analyzing the conventional communication performance (e.g. throughput, delay), several studies proposed using information-centric metrics (e.g., awareness quality [7], [14], update delay [15], and PIR [5]). These metrics allow for a better understanding of the impact of the underlying vehicular communication system on application-level performance.

TABLE I
Description of Experiment Locations and Parameters

Location	**Gothenburg** (Fig. 2(a))	**Helmond** (Fig. 2(b))
Scenarios	Suburban (57.710316,11.94238)	Suburban (51.472803, 5.622418)
	Urban highway (57.718424,11.918331)	Open road (51.477243,5.620085)
Number of Vehicles	6	7
Route Length	11 km	5.5 km
Vehicle Type	Personal	Personal
Antenna Type	Omni-directional	Omni-directional
Antenna Location	Rooftop	Rooftop
Antenna Height	approx. 1.55 m	approx. 1.44 - 1.66 m

III. Experimental Evaluation Of Communication Performance

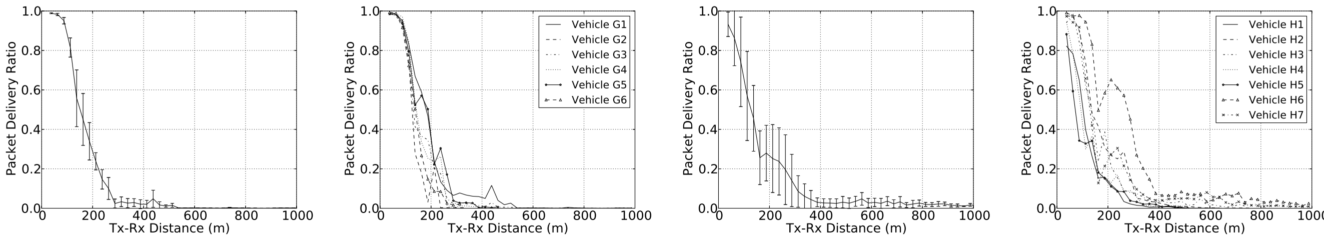
A. Experimental platform

DRIVE-C2X project designed and evaluated a set of applications enabled by Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication in test sites throughout Europe. In our study, we are concerned with V2V communication only.

The DRIVE-C2X system uses ITS-G5 compliant radios that operate in the 5.9 GHz frequency band. The devices have dual transceivers for multi-channel operation on the control and service channels. The default value for transmit power is set to 21 dBm. Omni-directional antennas are placed on the roof of personal vehicles with heights ranging from 1.44 meters to 1.66 meters. Vehicles had different antenna setups that created variations of the effective transmit power output. A GPS receiver is used for collecting vehicle position data. The radios transmit CAMs that are in line with the ETSI standard [16]. CAMs contain node information (e.g., position, speed, and sensor information) and are broadcast to one-hop neighbors over the control channel. Since different safety applications defined by ETSI require different beacon frequencies (e.g., vulnerable road user warning application requires 1 Hz frequency, while emergency electronic brake lights requires 10 Hz [1]), the default beacon frequency was set between 1 Hz and 10 Hz. The size of the beacon is 100 Bytes. Each vehicle collects and stores all CAMs that have been received and transmitted.

B. Metrics

To evaluate cooperative awareness in vehicular environments, we analyze the following three performance indicators.



(a) Overall results – Gothenburg. (b) Per-vehicle results – Gothenburg. (c) Overall results – Helmond. (d) Per-vehicle results – Helmond.

Fig. 3. Packet Delivery Ratio (PDR). Each distance bin is 25 meters, with the plotted data point centered in the middle of the distance bin. Error bars represent one standard deviation around the mean PDR of each vehicle. For statistical relevance, we consider solely bins with at least 40 data points.

1) *Packet Delivery Ratio (PDR)*: the ratio of the number of correctly received packets to the number of transmitted packets. Formally, for a vehicle i, the PDR is calculated as $PDR_i = \frac{PR_i}{PT_i}$, where PR_i is the number of packets sent by i that were correctly received by the surrounding vehicles and PT_i is the total number of packets sent by i.
2) *Neighborhood Awareness Ratio (NAR)*: the proportion of vehicles in a specific range from which a message was received in a defined time interval. Formally, for vehicle i, range r, and time interval t, $NAR_{i,r,t} = \frac{ND_{i,r,t}}{NT_{i,r,t}}$, where $ND_{i,r,t}$ is the number of vehicles within r around i from which i received a message in t and $NT_{i,r,t}$ is the total number of vehicles within r around i in t (we use t=1 second). Referring to Fig. 1, for the white vehicle in the center, NAR is the proportion of nodes in the inner (white) circle from which the observed vehicle received a message.
3) *Neighborhood Interference Ratio (NIR)*: for a vehicle i, range r, and time interval t, the ratio of neighbors that are above a certain distance from the observed vehicle is defined as $NIR_{i,r,t} = \frac{NA_{i,r,t}}{N_{i,t}}$, where $NA_{i,r,t}$ is the number of vehicles above r from which i received a message in t (again, we use t=1 second) and $N_{i,t}$ is the total number of vehicles from which i received a message in t (irrespective of r). Referring to Fig. 1, for the white vehicle in the center, NIR is the proportion of vehicles from which it received a message within the time interval and which are outside the inner (white) circle, divided by the total number of vehicles from which a message was received. This metric is important for interference analysis, as it sheds light on the proportion of nodes that are overheard, but are not necessarily relevant. It has to be noted that, since the generation rate of the messages was low and the frequency was the dedicated 5.9 GHz spectrum, the results shown in the paper can be considered virtually interference free, thus exhibiting the upper bound of performance for the system. Thus, the NIR metric is a reflection of the potential interference in future, fully deployed system, rather than the interference exhibited in the small-scale measurements.

C. Measurement scenarios

The datasets used in the analysis were collected over several days between 9 a.m. and 5 p.m. in Gothenburg, Sweden (in June, 2013), and in Helmond, Netherlands (in September, 2012).

The test site in Gothenburg is depicted in Fig. 2(a). This route was driven repeated times anti-clockwise by all vehicles. Vehicles were driven in normal traffic conditions with the presence of other vehicle types and respecting traffic rules. This test route was comprised of a mixture of suburban-like environment and an urban highway. The other test site, located in Helmond, Netherlands (Fig. 2(b)) is comprised of a suburban and open road environment with occasional buildings and foliage around the road. More details on the experimental setup are given in Table I.

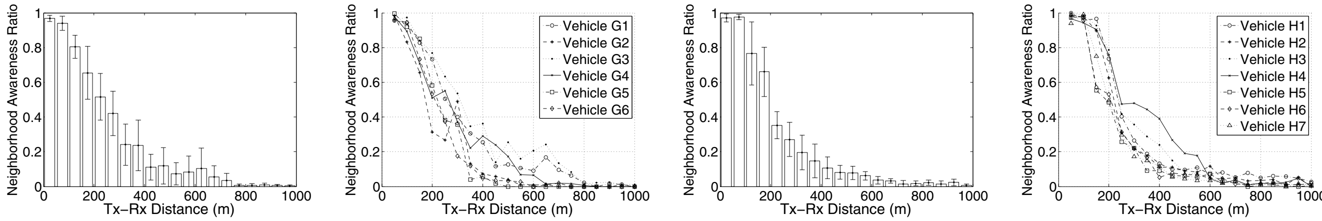
IV. Results

In this section we present and discuss the empirical results of Cooperative Awareness in Vehicular Communications.

A. Packet Delivery Rate

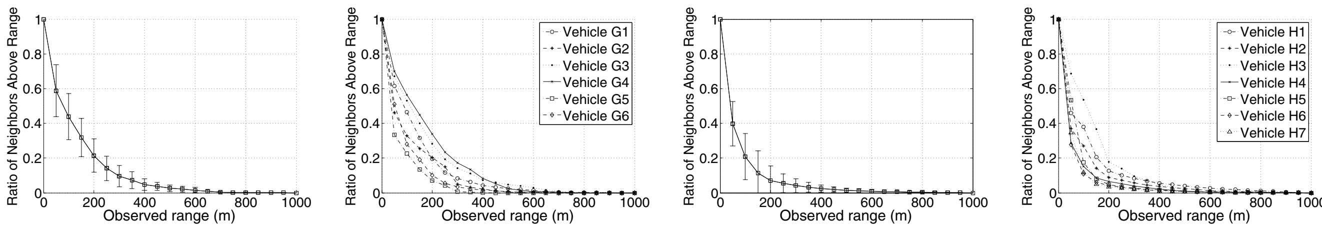
Fig. 3 shows the Packet Delivery Ratio (PDR) as a function of distance for V2V communications. As expected, PDR decreases as the node separation increases. In both scenarios, correct decoding of packets occurs predominantly at distances up to 500 meters, although occasionally communication is possible up to 1000 meters (e.g., in case of straight open road). The harsh propagation environment, including frequent Non Line of Sight (NLOS) conditions due to surrounding objects (e.g. other vehicles, buildings, and trees), and high vehicle mobility affect the link quality considerably. This results in fluctuations of PDR for a given distance. Furthermore, even for line of sight (LOS) channels, fluctuations over distance arise, mainly due to the dominating two-ray ground reflection model [13].

Our results are in line with the analytic results given by An et al. [14]. Under more favorable conditions, such as highway scenario and in case of V2I communications, the results presented by Visintainer et al. [17] show that high PDR is possible for communication ranges over 300 meters. Similarly, increased effective transmit power would result in higher PDR for a given distance.



(a) Overall results – Gothenburg. (b) Per-vehicle results – Gothenburg. (c) Overall results – Helmond. (d) Per-vehicle results – Helmond.

Fig. 4. Neighborhood Awareness Ratio (NAR). One second window was used for determining the reception of messages from direct neighbors. Each distance bin is 50 meters, with the plotted data point centered in the middle of the distance bin. Error bars represent one standard deviation around the mean ratio of detected neighbors for each vehicle. For statistical relevance, we consider solely bins with at least 40 data points.



(a) Overall results – Gothenburg. (b) Per-vehicle results – Gothenburg. (c) Overall results – Helmond. (d) Per-vehicle results – Helmond.

Fig. 5. Neighborhood Interference Ratio (NIR). One second window was used for determining the reception of messages from direct neighbors. Each distance bin is 50 meters, with the plotted data point placed at the end of the distance bin. Error bars represent one standard deviation around the mean ratio of detected neighbors for each vehicle. For statistical relevance, we consider solely bins with at least 40 data points.

B. Neighborhood Awareness Ratio

Since the measurement locations were a combination of open road and (sub)urban environments, along the route there was considerable shadowing due to both buildings [18] and other vehicles [19]. This resulted in reduced average transmission range (as shown in Fig. 3), which affected the neighborhood awareness. As demonstrated by An et al. [14] and confirmed by Fig. 3 and Fig. 4, there is a strong correlation between neighborhood awareness and PDR. Fig. 4(a) and Fig. 4(c) show that the neighborhood awareness is above 90% for distances up to 100 m with a progressive decrease to 10% around 500 m. The comparatively complex propagation environment explains why the neighborhood awareness results are worse than the results obtained through simulation by Mittag et al. [7], where a two-ray ground reflection model was used to represent line of sight communication. Fig. 4(b) and Fig. 4(d) show the per-vehicle neighborhood awareness: while the trends are comparable, for a given distance bin there are differences exceeding 20% for different vehicles. Therefore, even in the same environment, different vehicles can have a significantly different perception of their surroundings, depending on their exact location and the performance of their communication systems.

C. Neighborhood Interference Ratio

With regards to the interference, Fig. 5 sheds some light on the effect that the distant neighbors can have in terms of interfering with contextually more relevant nearby neighbors. Fig. 5(a) and Fig. 5(c) show that the interference level from vehicles above approximately 300 meters is quite limited, with their proportion contained within 10%. Situation is somewhat more complex when the region of interest is 100 meters, since in that case the extraneous neighbors can comprise more than half of the total number of neighbors. Fig. 5(b) and Fig. 5(d) show that the per-vehicle variation can be considerable, with certain vehicles having more than 40 percentage points difference in NIR for a given distance.

D. Repercussions on interference supression and congestion control algorithm design

From the perspective of cooperative applications (e.g., Cooperative Collision Warning [1], [20]), the results shown in Fig. 4 indicate that the applications requiring above 90% of neighborhood awareness can function within 100 m. Increased awareness can be achieved by increasing the transmit power, at the expense of increased interference.

A more detailed analysis of the results has also shown that there are considerable variations in local awareness and interference levels between vehicles in similar environments. This could have significant repercussions on the design of congestion control algorithms. Specifically, most existing studies that analyzed congestion control were based on simulation studies where the large-scale shadowing effects – in particular, the transition between LOS and NLOS – were neglected (e.g., the authors of a recent study provide a discussion on this [5]). Therefore, the impact of the neighborhood awareness variation should be accounted for in the design and performance evaluation of the congestion control algorithms.

Furthermore, the results shown in Fig. 5 indicate that a distance based rate/power control schemes might not be directly applicable for all regions of interest, since in certain cases the distance to a neighbor does not necessarily signify the level of the interference on a link. This emphasizes the importance of proper network configuration and power and rate control in V2V communication.

V. Conclusions

The broadcast of CAM creates awareness between vehicles in close proximity. Safety and traffic efficiency applications use the local awareness information to improve their performance or to enable their functioning. In this study, we empirically studied the performance of single-hop beaconing using large-scale experiments performed in two locations encompassing a wide variety of environments, including open roads, urban highways, and suburban-like roads.

The results demonstrate that cooperative awareness is strongly dependent on the transmitter-receiver separation and the propagation conditions. Furthermore, we show that application-specific requirements can be met even in harsh propagation environments: in both test sites, the neighborhood awareness was above 90% within 100 meters. Using the neighborhood interference ratio as a metric, we show that the far-away neighbors can cause considerable interference; for example, in the Gothenburg test site, approximately 30% of the neighbors are more than 200 meters away. The per-vehicle results indicate that local awareness and interference levels can vary significantly between vehicles. Our results show that vehicles will need to employ carefully designed transmit power control mechanisms that will enable cooperative awareness, at the same time reducing the unnecessary interference.

As future work, we plan to analyze the behavior of PDR, NAR, and NIR in distinct V2V environments (e.g., urban, highway, suburban). Furthermore, we plan to investigate the same metrics in case of V2I links. The analyzed measurement datasets contained up to seven communicating vehicles. To investigate the behavior of the aforementioned metrics on a large network involving thousands of communicating vehicles, we plan to perform a large-scale simulation study using a realistic channel model (e.g., [21]).

Acknowledgments

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