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A Spatio-Temporal Metric for the Evaluation of Cooperative Awareness*

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Upcoming field trials for cooperative systems provide unique opportunities to evaluate research results in real world experiments. Amongst these research results, there are many approaches for efficient use of available communication resources. It is crucial to establish a metric for performance evaluation, in order to identify the most suitable approaches. This metric should be usable in both, field trial experiments and preparative simulations.

In this paper, we propose such a metric. It measures the quality of the ultimate goal of cooperative systems, the quality of cooperative awareness. We discuss the implementation of the metric in a simulation environment, and provide results of a simulation study on the system performance under high load. Furthermore, we provide essential hints in order to obtain comparable results via large-scale field trials using the proposed metric.

1. Introduction

Advanced driver assistance systems using vehicular ad-hoc networks (VANETs) are supposed to enhance drivers' horizon and hence to avoid traffic accidents. This is achieved by frequently exchanging status information between the vehicles, by means of so called Cooperative Awareness Messages (CAMs)[1], also referred to as beacons, heartbeats, or Basic Safety Messages (BSMs).

CAMs are exchanged using a communication technology according to IEEE 802.11p. Simplified, they contain a vehicle ID, position, time, and heading of the sending vehicle (see **Fig. 1**). Vehicles store received information from beacon messages in their neighbor table. Having received the information in particular about surrounding vehicles in the vicinity, this constitutes the major feature of cooperative systems, the cooperative awareness.

Due to high relative movement of vehicles, CAMs have to be sent with a high frequency to ensure the availability of up-to-date information. However, frequent sending of CAMs leads to a high channel load and results in packet collisions and significantly increased medium access delay. The communication channel is getting congested. In the end, this results in information loss, especially in situations where a large number of vehicles access the communication channel with high frequency. In these situations, communication and thus cooperative awareness suffer from increased packet loss. In[2], we identified that the overload of the channel causes packet loss occurring at larger distances between sender and receiver. At shorter distances, we observed a certain area of very low packet loss, nearly independent of the channel load, i.e. the communication range under interference. Furthermore, spatio-temporal packet loss occurs due to significant shadowing by stationary and non-stationary obstacles like buildings or heavy trucks, a known problem of communication in non-line-of-sight (NLOS)[3], between transmitter and receiver.

Various approaches to solve the issue of network congestion in VANETs have been proposed. An overview on and an integration of these approaches into a generic congestion mitigation architecture can be found in[4].

In this paper, we establish a metric to measure cooperative awareness. It is supposed to allow assessing the awareness quality of different resource saving mechanisms, in both field trial experiments and simulations.

Vehicle ID	Position	Time	Heading

Fig. 1　Simplified CAM format

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2. Related Work

The evaluation of safety-related communication in VANETs has to be based on suitable metrics. Simply measuring throughput, end-to-end delay and packet error rate do not provide meaningful answers on how well active safety applications may operate. Therefore, some metrics have been defined in the literature.

Kloiber et al.[5] apply a metric called *Update-Delay* for the evaluation of the up-to-dateness of the information on surrounding vehicles. They use a complementary cumulative distribution to highlight the occurrences of higher update delays. In this metric, aspects like packet loss and latencies are implicitly included. The simulation study compares CAM rates of 1, 2, 4, and 8 Hz in a highway scenario with 6 lanes per direction. As an outcome, Kloiber et al. identify based on the metric, which reliability boundaries can be met in which road traffic scenario.

In[6], Mittag et al. define the *Probability of Awareness* to evaluate forwarding strategies in multi-hop communication. Depending on the distance to the reference node and a receiving node, the metric provides the probability if the reference node is known to the receiver. That is, the reference node is known if at least one CAM has been properly received within one second out of the 5 CAMs sent per second. A simulation study shows that the probability of awareness drops below 90% at distance of 600 meters. This value can be compared with forwarding strategies where the transmit power has been decreased in order to maintain roughly the same channel load.

In our work in[7], we introduced the metric Awareness Quantile which focuses more on application requirements. For a given percentage of the needed awareness for a certain distance, the metric provides the percentage of how many vehicles fulfill this requirement at certain point in time. On the one hand, this metric can be used at critical points in time when an accident is imminent, targeting pre-crash applications. On the other hand, the metric can measured periodically and may then provide an evaluation of the awareness for a certain time span. In the following section, we will review the metric and will refine it with spatio-temporal aspects to implicitly consider different awareness requirements in one metric.

3. Measuring Cooperative Awareness

Periodically exchanging CAMs establishes up-to-date awareness of all surrounding vehicles and their status. Awareness requirements depend on the active safety applications[8], and of course on the network load, i.e. the desired awareness under low and high load vary significantly. Under low load, the awareness should be equal or close to 100%. Under high load, there should be a suitable trade-off, where high awareness is only required for the safety-critical area. To quantify the achievement of these different requirements, a more fine-grained awareness metric is defined in the following. In the Awareness Quality (AQL) each vehicle reports the level of awareness as the exact fraction of aware vehicles based on a given validity which increases with the distance.

First of all, areas of different awareness requirements around receiving vehicles are defined. Simplified, these areas are rings. The most safety-relevant ones are the rings between 0 and 100 m, 100 and 200 m, and 200 and 300 m, as shown in **fig. 2** Safety areas A_k are assumed to be circular with a size of

$$A_k = \pi * (a_k^2 - a_{k-1}^2), k \in N$$

with k denoting the area identifier. For the sake of simplicity, the areas are assumed to have equidistant radiuses, i.e.

$$a_k = a_1 * k, k \in N$$

with the radius a_1 being 100 m in the previously described example.

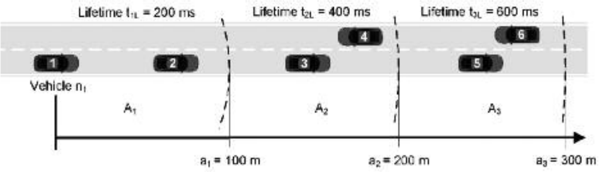

Fig. 2　Example for Awareness Quality for vehicle n_1.

Awareness in the road traffic context refers to the relation between knowledge of vehicles that *are* stored in a vehicle's neighbor table and the knowledge of vehicles that *should be* stored. In contrast to[6], the awareness metric is defined explicitly from the perspective of *each* vehicle. At time T and for a certain vehicle i, the awareness within area k is defined as

$$Awareness_k^T(i) = \frac{|\mathcal{N}_k^T(i) \cap \mathcal{V}_k^T(i)|}{|\mathcal{V}_k^T(i)|}$$

with $\mathcal{V}^{T;k}(i)$ denoting the set of vehicles being within area k and $\mathcal{N}^{T;k}(i)$ denoting the set of discovered neighbors within area k. Note that the intersection $\mathcal{N}_k^T(i) \cap \mathcal{V}_k^T(i)$ is required to filter out the vehicles that are still in the neighbor table stored but have moved out of the respective area. This ensures also that the fraction is always less or equal to one.

Vehicle j is a neighbor of i within area k at time T,

$$j \in \mathcal{N}_k^T(i) \Leftrightarrow a_{k-1} \leq d_{ij} < a_k$$

with $d_{ij} = distance(i,j)$ and the k-th safety area, where

$$T - T_{B-1} < \left\lceil \frac{d_{ij}}{a_1} \right\rceil t_{kL} + t_{MAC}$$

with $T - T_{B-1}$ the age of the previously received CAM for vehicle j located in the k_j-th safety area, determined by $\lceil d_{ij} a_1 \rceil$. t_{kL} denotes the respective validity of a CAM for vehicle in area k. In other words, the age of the previously received CAM must be lower than its *distance-dependent validity*, being valid for the safety area where the vehicle is currently located in.

There are various reasons why this ratio can be less than one. For example, a low penetration rate degrades this ratio significantly. However in this paper, it can be assumed that the penetration rate is close to 100%, otherwise high channel load may not be reached. Therefore, only communication-related issues are considered. First, shadowing of objects has a strong influence on the signal attenuation which may result in packet loss. Second, especially in high load situations, packet loss occurs due to interference. The packet loss may even occur at low distances between sender and receiver which would most likely prevent active safety applications from working properly.

In order to measure the awareness quality over time, the awareness is summed up over all vehicles and divided by the number of all vehicles for all time steps $t \in T$.

$$AQL(T,k) = \frac{\sum_{j=1}^{T} \sum_{i \in \mathcal{V}} Awareness_k^T(i)}{T * |\mathcal{V}|}.$$

For the sake of completeness, it is noted that the number of probes in the nominator is exactly the same as in the denominator. As these probes $Awareness_k^T(i) \in [0;1]$, the resulting value of the AQL is also in the interval [0;1].

An example for the awareness for a single vehicle is depicted in **fig. 2.** Six vehicles $n_1, n_2, \ldots, n_6$ take part in this scene. Assuming n_6 just came into range of n_1 and no CAM has been received at the measurement time T=1 since the point in time $T-(t_{2L}+t_{MAC})$. There are three safety areas A_1, A_2, A_3 defined, equidistantly separated by a_1=100m and with a validity of a CAM for A_1 of t_{1L} = 200 ms.

$$(Awareness_1^1, \ldots, Awareness_3^1) = (1,1,0.5)$$

since

$$\left(|\mathcal{N}_1^1(n_1)|, \ldots, |\mathcal{N}_3^1(n_1)|\right) = (1,2,1), \quad \left(|\mathcal{V}_k^1(n_1)|, \ldots, |\mathcal{V}_3^1(n_1)|\right) = (1,2,2).$$

Note that the reason for not knowing vehicle n_6 could be also due to a packet collision or increased signal attenuation by the vehicles in-between.

4. Awareness Quality Measurement in Simulation

Following, we describe how we implement the metric into a simulation environment and discuss important implementation-specific details in order to obtain comparable results. In the second part, we apply the metric in a study of different CAM generation rates in two high-velocity scenarios.

4.1 Implementation Issues

Our implementation of the Awareness Quality metric is done in the network simulator Java in Simulation Time (JiST,[9]) in combination with the Scalable Wireless Ad-hoc Network Simulator (SWANS,[10]). Extensions from the Ulm University[11] include protocols for vehicular ad-hoc networks. Most important for the metric is storage of neighbor information and access to the actual movement of the simulated vehicles, i.e. to compute $\mathcal{N}$ and $\mathcal{V}$.

Determine actual neighbors $\mathcal{V}$ - In the simulation, it is relatively easy to compute $\mathcal{V}$ from each vehicle's perspective. The positions and movements of each vehicle are centrally stored in an array and modified by only one instance. For accurate results, it has to be ensured that the measurement of $\mathcal{V}$ is done at the same point in (simulated) time when $\mathcal{N}$ is computed.

Determine known neighbors $\mathcal{N}$ - As the extensions by Ulm University already provide an implementation of the neighbor table as well as the CAM generation and processing, one has to implement only the special conditions for valid neighbors according to the formula presented in the section before.

Sampling interval and MAC delay - For comparable results, we measure the Awareness Quality independent of the CAM generation rate. Therefore, we define a sampling interval depending on the lifetime of a CAM for A_1, i.e. $^{t_{lifetime}}/_{4}$, which is a reasonable trade-off in complexity and accuracy. We further set the tolerable medium access t_{MAC} to a strict requirement of 50 ms [12].

Performance issues - For performance reasons, we simply sum up the $|\mathcal{M}|$ for each vehicle separately without a cross-check with $|\mathcal{V}|$. In rare cases, this may lead to slightly differing results when a vehicle physically left a safety area. It may even occur that the awareness may become greater than 100%, if the lifetime of a CAM is not yet exceeded. However, cross-checking each vehicle to determine the correct values slows down the simulation significantly. Initial tests have shown that the difference is only within 1–3% depending on the vehicles' relative speeds.

4.2 Simulation results

Following, we show an example usage of this metric. A widely posed question is the appropriate rate of CAM generation. Therefore, we compare three CAM rates, being statically set to 2,5,10 Hz in order to satisfy three given lifetime requirements a_1=100,200,500 ms. We employ two highway scenarios with high velocities and two densities:

- Low density (Autobahn A92, 2 lanes - 106-124 vehicles/km^2)
- High density (Autobahn A92/A9, intersection of 2 lanes and 4 lanes - 262-272 vehicles/km^2)

Fig.3, **Fig.4**, and **Fig.5** compare the results for one of the given lifetime requirements in the two mobility scenarios. With the highest lifetime, shown in **Fig.3** the lowest CAM rate performs best. The higher rates pose too many packet collisions and increased medium access delay. Within the lowest safety area A_1=(0,100) meters, the CAM rates achieve 100% of the awareness quality. However, already in the consecutive safety area A_2=(100,200) meters, the awareness quality significantly drops for 10 Hz, to nearly 80%.

Fig. 4 shows the simulation results for a CAM lifetime of 200 ms. As the CAM generation rate is much lower than the lifetime, it is impossible to reach AQ=100% for A_1. However, as the channel load is relatively low compared to 5 and 10 Hz, the setup of 2 Hz provides a better awareness from area A_2 on and outperforms the other CAM rates. Looking at the high density underlines this observation.

Fig. 5 presents a similar trend for the lowest lifetime 100 ms. The lowest CAM rate performs worst for the first area A_1. Interestingly, 5 Hz provides a better Awareness Quality throughout all areas compared to 10 Hz. 10 Hz is the only CAM rate that could theoretically achieve AQ=100%, however the high number of packet collisions and the increased medium access delay do not provide acceptable results for this strict requirement, neither in the high density scenario nor in the low density scenario. In the end, the lowest CAM rate outperforms again the higher CAM rates from A_3 and A_4 on, respectively.

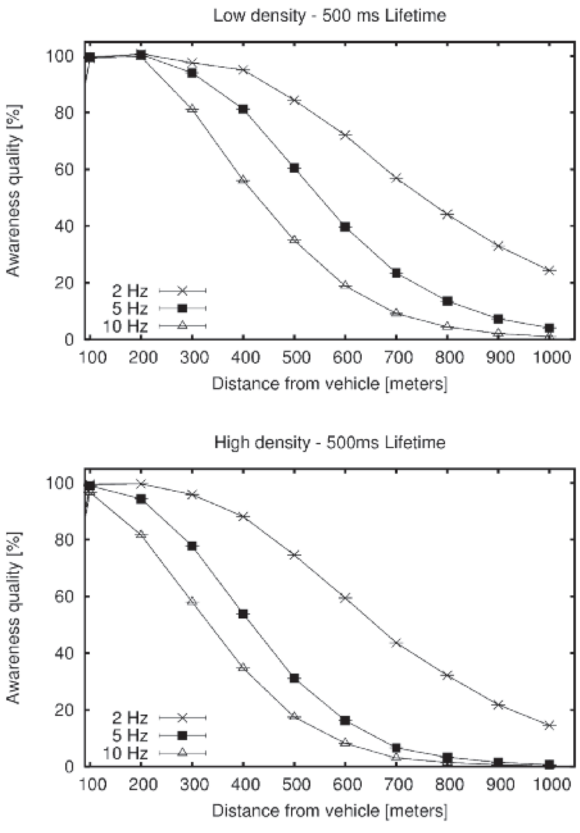

Fig. 3　Awareness Quality for given lifetime 500 ms

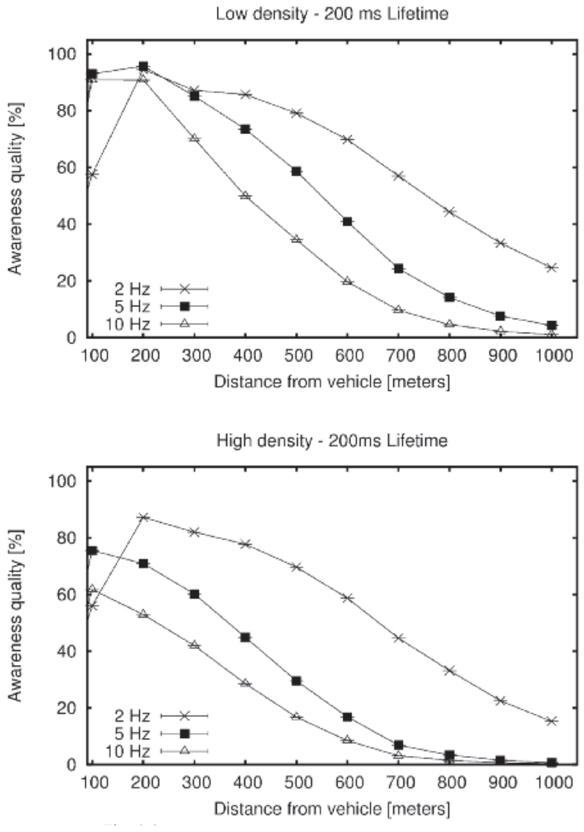

Fig. 4　Awareness Quality for given lifetime 200 ms

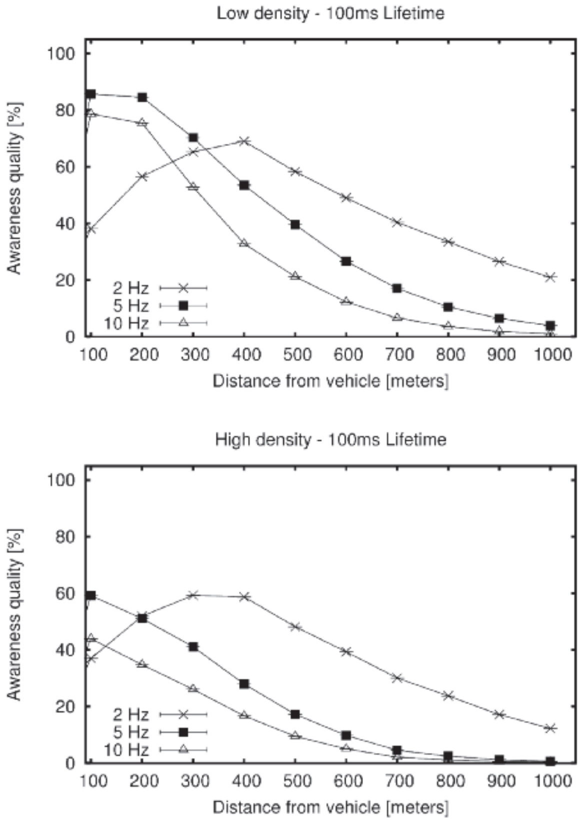

Fig. 5　Awareness Quality for given lifetime 100 ms

Summarizing, a clear trend can be observed that lower CAM rates provide higher awareness quality at higher distances. In the safety-critical area in particular, high CAM rates cannot guarantee awareness even for long lifetimes. Increased MAC delay and collisions prevent an adequate result for the awareness quality.

For further results, the reader may refer to other existing literature applying the metric. For example, in[13], several different approaches on different protocol layers have been evaluated based on the awareness quality, considering several traffic conditions with low and high channel load.

5.　Awareness Quality Measurement in Field Trials

Especially for actual deployment, real-world measurements have to be performed, covering various realistic traffic situations. It is a crucial part, to thoroughly define the target metrics and the data elements that have to be recorded by each vehicle. Thus, this section describes how the metric can be applied to cope with the decentralized data collection.

Obviously, the evaluation of the quality of cooperative awareness in field trials needs similar data as the simulations. It must enable for the tasks introduced in the previous section, i.e.

- Determine actual neighbors $\mathcal{V}$
- Determine known neighbors $\mathcal{N}$

with a sampling interval as introduced above. Consequently, every node has to store the following information with this sampling interval

- vehicle ID
- vehicle position
- vehicle timestamp (GPS)

to enable the determination of $\mathcal{V}$.

The determination of known neighbors $\mathcal{N}$ requires recording of a subset of information received from CAMs combined with the information about the current state of the receiver. Considering the information that is stored as mentioned above, it is sufficient to obtain

- sender ID
- sender timestamp (GPS)
- receiver timestamp (GPS)

The “sender ID” determines if the sending vehicle is in the neighbortable of a receiving vehicle. The two timestamps allow to calculate the age of and delay with which the CAM is received.

Even though the previous information is sufficient for the determination of the quality of cooperative awareness according to our metric, recording of additional data while sending and receiving CAMs is of importance. For example, to allow detailed analysis of situations with low quality of cooperative awareness. The straight-forward approach is to store both, sent and received CAMs plus “receiver position” and “receiver timestamp” upon reception of a CAM.

With this data available, the remaining challenge consists in the combination of data logged in different vehicles. Datasets have to be combined and neighboring vehicles have to be identified by calculating distances between all vehicles involved in the trial.

6. Conclusions

Field trials for advanced driver assistance systems are an important step to bring them into the market. In particular, cooperative safety systems like vehicular ad-hoc networks urgently demand convincing practical results on the system behavior under high load.

Cooperative awareness messages (CAMs) are exchanged among vehicles with high periodicity to meet requirements of active safety applications. The required information accuracy in terms of cooperative awareness should be achieved under all circumstances to properly run active safety applications thereupon.

In this paper, we presented a metric to measure the quality of cooperative awareness with strong consideration of the requirements of active safety applications. The metric introduces the aspect of different distance-dependent lifetimes for received information. The higher the distance to the transmitting vehicle, the higher the lifetime of this information. With this metric comparable results in simulations as well as field trials can be obtained.

We firstly discussed the implementation of this metric in a simulation environment with an appropriate parameter configuration. The metric was then applied in a simulation study to compare the achieved awareness quality depending on the transmit interval of the CAMs. As a result, a simple solution cannot be found for different road traffic scenarios. However, the determination of the CAM generation rate should be strictly guided by the application requirement on the lifetime for the safety-critical area. Higher CAM rates cause an even higher channel load and hence more packet loss. Lower CAM rates are not able to achieve 100% of awareness quality in the most safety-critical area.

Secondly, we discussed how the metric can be applied to field trials and which information must be gathered to get accurate results on the awareness quality. Data collected in the field trials that are going to be conducted within the coming years will enable testing and analysis of protocols for VANET based advanced driver assistance systems. Based on the results, protocols need to be refined and afterwards, tested again.

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