Technical Evaluation of GLOSA Systems and Results From the Field

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***Abstract*—The goal of Green Light Optimal Speed Advisory (GLOSA) systems is to lower CO_2 emissions and to avoid unnecessary stopping in intersection approach scenarios by giving speed advices to drivers based on current and future traffic light signal phase timings. These systems have been widely evaluated by means of simulation and, while most research focuses on the impact assessment of GLOSA along with environmental influences, minor attention was drawn to the holistic technical evaluation of included sub-modules and implementations.**

In this paper we address this problem with a novel and holistic concept for the technical evaluation of IEEE 802.11p based GLOSA systems. We introduce metrics to cover the whole spectrum of GLOSA operations and identify important factors that are usually not considered in simulations, yet, strongly influencing the results. We demonstrate how this concept is used to evaluate the real-world GLOSA system tested in the European Commission co-funded field trial DRIVE C2X. Results derived from Field Operational Test (FOT) data show that our metrics are well-suited to assess the performance of the GLOSA system, but also to identify sources of potential problems or bottlenecks. Based on our findings, we argue that most simulation studies are too optimistic and that further considerations are required to deploy real-world GLOSA systems.

***Index Terms*—GLOSA, DRIVE C2X, Field Trial, Evaluation**

I. Introduction

In the last years several large-scale Field Operational Tests (FOTs) were performed to support the deployment of Cooperative Intelligent Transport Systems (C-ITS) by investigating benefits and limitations of Car-to-X (C2X) communication technology. Research projects such as sim^{TD} [1] and DRIVE C2X [2] supported the development of both cooperative safety and traffic efficiency applications. The tested applications were mainly realized using wireless communication technology based on the ITS-G5 and IEEE 802.11p standards.

Green Light Optimal Speed Advisory (GLOSA) systems were among these applications. They are believed to be capable of introducing environmental benefits through lowering CO_2 emissions and fuel consumption in intersection approach scenarios [3], [4], [5]. To this end, information about traffic light signal phases is broadcast to approaching vehicles in the vicinity of the intersection by means of Map Data Messages (MAP) and Signal Phase and Timing Messages (SPAT)[6]. Speed recommendations are then calculated by the vehicle to pass the traffic light during green phase to avoid unnecessary stops and acceleration maneuvers, when possible.

In order to ensure proper functionality of the system under investigation within a FOT, technical evaluation is performed, that is functions and components are quantitatively measured. This assessment of technologies is carried out to help ensure and improve the technical functionality of the implemented system. Moreover, data from field tests allows for the creation of empiric models and often helps to identify previously unconsidered characteristics of the real-world scenario. They thereby contribute to improving simulations and analytical models [7]. Unfortunately, this has not yet sufficiently happened for GLOSA simulations owing to the lack of a holistic technical evaluation concept and results for real-world GLOSA systems, leading to overly optimistic simulation results.

We address this shortcoming by presenting such a technical evaluation concept, taking into account all related modules in the On-Board Unit (OBU) as well as the Roadside Unit (RSU). This creates the possibility for a holistic performance evaluation of components across different layers of the ITS architecture. Our main contributions include:

- we introduce the IEEE 802.11p-based GLOSA application as it was realized for field operational testing within the pan-European FOT DRIVE C2X.
- we define metrics for the technical evaluation of GLOSA systems providing information about communication performance, positioning accuracy, infrastructure related precision, and system latencies for fast and correct presentation of speed advices.
- we show the technical concept for data acquisition that enables calculation of introduced metrics.
- we present results of technical evaluation for the deployed GLOSA system within DRIVE C2X on the test site in Gothenburg, Sweden.

The remainder of this paper is structured as follows: In Section II we present an overview of related work, Section III introduces the DRIVE C2X GLOSA application with related metrics and concepts for the technical evaluation. In Section IV data acquisition, the experimental design and its results are reported. Finally, Section V concludes our work and provides an outlook on future activities that may be conducted based on our technical evaluation concept.

II. RELATED WORK

Applying a range of different simulation frameworks, positive effects of GLOSA on environment and traffic were shown. Using microscopic traffic simulation as well as perfect and fuzzy communication models for IEEE 802.11p, Tielert et al. showed that fuel consumption can be reduced by up to 22% for a single vehicle simulation approach and around 8% in case of more vehicles in the road network [3]. They introduce the information distance which is the distance between vehicle and traffic light where information about traffic light program is received for the first time during an approach. For information distances higher than 500m to 600m positive impacts to fuel consumption mostly vanish. We take this as valuable input for the technical evaluation of GLOSA.

Katsaros et al. simulated the effects of GLOSA systems with a simulation platform based on IEEE 802.11p where traffic light information was integrated in Cooperative Awareness Messages (CAMs) and broadcast to approaching vehicles [8]. Their findings state that up to 7% reduction in average fuel consumption can be achieved with a GLOSA system. According to their work, the optimal distance between vehicle and traffic light for an activation of GLOSA is approx. 300m.

The negative impact of higher traffic densities for the reduction of CO_2 emissions of GLOSA systems is investigated by Eckhoff et al [5]. According their simulations, up to 11,5% of CO_2 emissions can be saved in low density scenarios. However, higher traffic densities lead to a reduction of these benefits. Based on our concept for technical evaluation, we will show in this paper how a GLOSA system performs in field tests compared to idealized environments in simulations.

Closing the gap between GLOSA simulations and real world prototypes, Xia et al. [4] conducted controlled testing with a 4G LTE based GLOSA prototype system in Berkeley, CA. In their findings they present measured fuel consumption reduction of 13,6% in real world compared to 14% in their simulation framework. Further pre-series development activities of GLOSA systems are shown in [9] and [10]. The project TRAVOLUTION demonstrated an IEEE 802.11 based speed advice and remaining red phase application in the city of Ingolstadt, Germany. In Verona, Italy and two other German cities, a GLOSA system based on cellular communication was established using standardized SPAT and MAP messages. However, no details about metrics and results from technical evaluation of these systems are given in the three aforementioned papers.

Brief insights about a GLOSA prototype system and its technical evaluation are given by Iglesias et al. [11]. Based on IEEE 802.11a, traffic light information is transmitted to a test vehicle. The vehicle's Human-Machine Interface (HMI) displays vehicle speed, distance to traffic light, and the predicted state of traffic light for the point in time when the vehicle is about to cross the stopping line. On a 500m test track with Line-of-Sight (LOS) conditions they reached average information distances between 95m (approach with 80km/h) and up to 420m (approach with 30km/h). Information on the number of measurements and introduced metrics is, however, missing.

Within the project ElisaTM in Munich, Germany, Schweiger et al. [12] developed an IEEE 802.11p-based GLOSA prototype system. The measured average communication range of received SPAT messages in vehicles reaches from 300m up to 500m with a decrease in received messages. Problems occurred in side roads and challenges with the prediction of adaptive traffic light programs are mentioned.

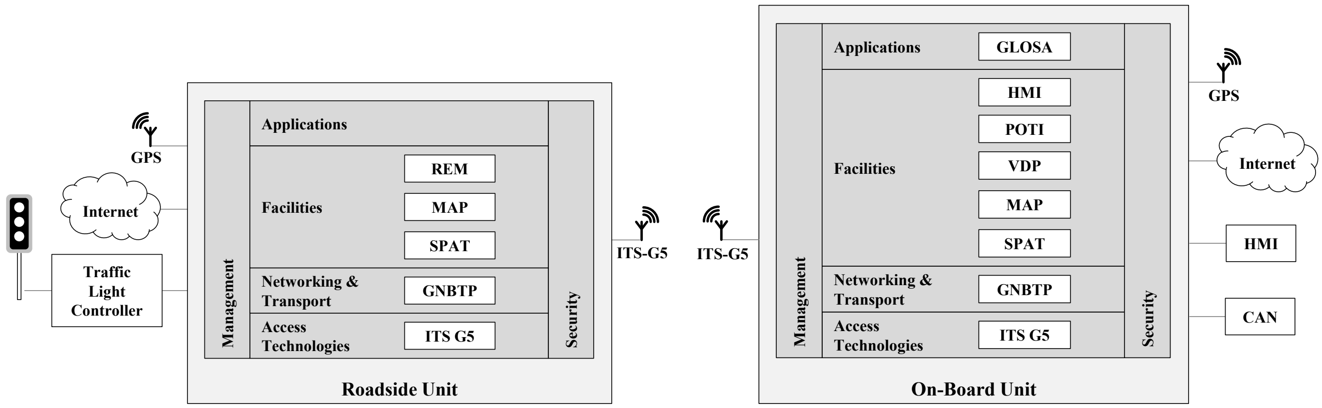
In their approach Bernais et al. [13] developed a hybrid communication system for their GLOSA application in the German cities of Braunschweig, Düsseldorf and Kassel as part of the UR:BAN project. It uses wireless communication as well as cellular communication technologies. SPAT and MAP messages are transmitted to approaching vehicles in a system that applies ITS-G5/ IEEE 802.11p standards. Wireless communication reached distances of up to 300m in their tests. Ranges vary based on configuration and environmental influences. However, no deeper technical evaluation was defined and hence not performed.

An approach to overcome challenges for GLOSA systems caused by semi-adaptive and fully adaptive traffic light programs is introduced by Bodenheimer et al [14]. Unexpected changes in remaining phase times due to non-static traffic light programs lead to drastic changes in given speed advices showing the importance of an accurate forecasting. Their algorithm based on graph transformation predicts signal changes 15s before they appear with an accuracy of 80%. We therefore consider the infrastructural impacts to the GLOSA system for our technical evaluation concept.

Several effects from the technical evaluation of C-ITS were observed by Netten et al. [15] on a test site in Helmond, The Netherlands. For the validation of the DRIVE C2X system, vehicles from different manufacturers and the RSU infrastructure were tested regarding positioning accuracy and time synchronization. Additionally, communication performance was investigated in terms of packet-delivery-ratio (PDR) and received signal strength indicator (RSSI) measurements. Results show large variations in overall performance. Authors argue for an integration of performance criteria from technical evaluation in standardization activities and documents.

On a motorway test site close to Trento, Italy, Visintainer et al. [16] carried out an empirical study for an assessment of communication coverage. End-to-end delay (E2ED) measurements of message transmission between RSU and OBU with over 3600 messages resulted in an average latency of 40ms. However, the achieved communication range of the two measured RSUs was different caused by geographical and environmental influences. One RSU showed a communication range of more than 1000m in a LOS scenario whereas the range of the other RSU was below 400m.

In this paper we contribute to the state of the art by developing a technical evaluation concept for GLOSA systems based on wireless communication technologies and by presenting results from the in-vehicle components of the DRIVE C2X field trial.



(a) Roadside Unit (RSU)

(b) On-Board Unit (OBU)

Fig. 1. Simplified DRIVE C2X system specification and protocol stack derived from [2] with relevant GLOSA software and hardware components.

III. Concept

We present the specifications of the GLOSA application within the DRIVE C2X framework and the definition of proposed metrics for the technical evaluation of GLOSA.

A. GLOSA in the DRIVE C2X Framework

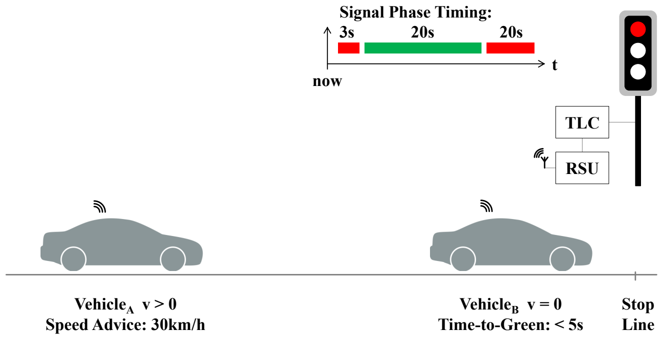
Before looking into the concept for technical evaluation it is necessary to understand the overall system architecture in which our GLOSA application is integrated. Figure 1 shows hardware interfaces, layer architecture, and software components of the RSU and OBU subsystems that establish ITS-G5 compliant C2X communication. As shown in Figure 1a there are several hardware components attached to the RSU. A GPS receiver provides positioning information and enables time synchronization. Connection to the traffic light controller allows to get information about current and upcoming traffic light phases from the traffic light. An ITS-G5 dual transceiver enables signal transmission and reception to and from other network nodes. Figure 1b depicts the OBU which additionally has an interface to the CAN bus system in order to access information such as velocity or turn signal status of the vehicle. An interface to the HMI, e.g., the instrument cluster display, allows to give information to the driver.

In general, GLOSA functionality is based on two message types: SPAT and MAP [6]. A Signal Phase and Timing Message (SPAT) informs about current state, current phase and next phase for each lane of an intersection, Map Data Messages (MAP) provide information about the topology of an intersection such as number of lanes and turning restrictions. Coding of these two message types in DRIVE C2X applies ASN.1 unaligned packed encoding rules. In order to give a speed recommendation or Time-to-Green (TTG) information to the driver, a vehicle must receive at least one message of every type and link them using the unique intersection ID included in the messages. When a message is received, the GLOSA application generates a geometry from the MAP message to match the vehicle's position and determines the corresponding lane number. Once the current lane is known, signal phases and timing data related to this lane number can be matched. SPAT and MAP messages are transmitted by single-hop broadcast.

The RSU and OBU subsystems are based on the ITS station protocol stack that consists of the layers, Management, Security, Access Technologies, Networking and Transport, Facilities and Applications. However, software components are different on the respective subsystem. Within the RSU in Figure 1a Roadside Equipment Management (REM) provides information from the traffic light controller interface to the RSU. SPAT and MAP components periodically encode respective messages. Once packets are received and verified on the OBU, valid messages are decoded by SPAT and MAP components. Needed information is made available for the GLOSA component. Before speed advice or TTG can be given to the HMI component, information from the Vehicle Data Provider (VDP) and Position and Time (POTI) are needed. VDP provides selected signals from vehicle's bus system and POTI delivers positioning information from the GPS system.

Two intersection scenarios are illustrated in Figure 2. The first scenario in Figure 2a depicts an intersection approach during a red traffic light phase; Figure 2b shows an approach scenario during a green traffic light phase. Indicated by red and green bars in the upper part of each figure is the duration and sequence of traffic light phases over time. For the red phase scenario, the remaining time of the current red light phase is 3s followed by a 20s green light phase which again is followed by a 20s red light phase. Vehicle$_A$ is approaching the traffic light and the GLOSA application determines (based on the vehicle's position, its indicator lights, and information included in the received MAP and SPAT messages) whether the vehicle can cross the signal in the upcoming green phase. Hence, a speed advice is shown on the HMI, which in this case is a recommendation of 30 km/h. The minimum speed advice was configured to be at least 50% of the speed limit.

Vehicle$_B$ is waiting at the stop line and a remaining Time-to-Green (TTG) of <5 s is displayed on the HMI. To avoid unnecessary distraction and to minimize the risk of premature



(a) Scenario 1: Current phase of traffic light program is red

(b) Scenario 2: Current phase of traffic light program is green

Fig. 2. Intersection approach scenarios

acceleration, exact values for the TTG are only displayed when it lies between 5 s and 30 s. In cases where the speed limit would be exceeded by the calculation result of GLOSA no speed recommendation is given and the TTG is displayed on the HMI instead. This applies to vehicle$_C$ in Figure 2b. In the same scenario vehicle$_D$ approaches the stop line and displays a speed advice on the HMI which is the maximum speed limit of 50 km/h in this example. Speed advice and TTG are displayed on the HMI along with the simplified intersection topology.

B. Metrics for the Technical Evaluation

Based on our experience from real-world tests and related work, we define a set of well-established and newly created metrics for the technical evaluation of GLOSA systems. They cover all related system components necessary for the functionality of the GLOSA system, include system and communication performance, and also consider application related measures and infrastructural aspects. Combined, they allow the holistic evaluation and analysis of GLOSA performance. An overview is shown in Table I.

TABLE I
OVERVIEW OF TECHNICAL GLOSA METRICS

Metric	Symbol	Range	Unit
Latency	t_{lat}	[0,∞)	ms
End-to-End Delay	$E2ED$	[0,∞)	ms
Message Delivery Ratio	MDR	[0,1]	-
Packet Delivery Ratio	PDR	[0,1]	-
Stability of the Prediction	SP	[0,1]	-
Distance Between Measured Position and MAP Lane Data	d_{lane}	[0,∞)	m
Information distance	d_{info}	[0,∞)	m

To understand the influence of the distance between vehicle veh to the traffic light RSU, we divide the area around the traffic light RSU in different distance bins, or ranges dr. Without loss of generality, we use a distance range length of $50m$. A dr of $150m$ then represents the region $100m$ to $150m$ away from the traffic light.

1) Latency and End-to-End Delay (E2ED): Under the condition of a time-synchronized system, the latency time t_{lat} in a distance range dr between two selected GLOSA system components i and j is formulated as

$$t_{lat}(i, j, dr) = t_j - t_i \text{ for } t_j \geq t_i \quad (1)$$

where t_x represents the point in time, when the execution of the GLOSA component x was started.

This metric allows to assess the delays that arise due to the execution and processing times of each GLOSA component in the system architecture. For example, it is possible to calculate the latency for decoding of a MAP message or for the computation of a speed recommendation.

In addition to latencies inside a single ITS station, also end-to-end delays (E2ED) can be calculated. We list three relevant end-to-end delays for the GLOSA system:

- $E2ED_{NaT}$: packet transmission delay between Networking and Transport layer in RSU and Networking and Transport layer in OBU
- $E2ED_{FAC}$: message transmission delay of SPAT and MAP between Facility layer in RSU and Facility layer in OBU
- $E2ED_{GLOSA}$: information delay between Traffic Light Controller (TLC) interface in RSU and in-vehicle HMI visualization of GLOSA calculation result

For the technical evaluation of the GLOSA system it is straightforward to assess $E2ED_{GLOSA}$ as it provides the most relevant information from an application point of view. However, $E2ED_{FAC}$ and $E2ED_{NaT}$ allow deeper investigation of communication related aspects. These delays are commonly not part of GLOSA simulation studies, however, they have a profound effect on the system performance as we will show in Section IV.

2) Message Delivery Ratio: By fixing a certain time period T_{dr} in which the vehicle veh was in the distance range dr, the message delivery ratio $MDR_{mes,A}$ during an intersection approach A can be implemented as follows:

$$MDR_{mes,A}(RSU, dr) = \frac{\#Rec_{mes}(veh, RSU, T_{dr})}{\#Sent_{mes}(RSU, T_{dr})}, \quad (2)$$

where mes represents the message type (either SPAT or MAP); the number of received messages is denoted by $\#Rec_{mes}$ and the number of sent messages by $\#Sent_{mes}$. The average message delivery ratio $\overline{MDR}_{mes}$ is then calculated by an arithmetic mean over all approaches of interest.

Analysis of the MDR enables a detailed assessment based on the reception of each message type during an intersection approach. This is important because the calculation of a speed advice or TTG requires information from MAP and SPAT. Additionally, this metric delivers insights about communication performance in terms of reception distance between vehicle and RSU.

3) Packet Delivery Ratio: The Packet Delivery Ratio (PDR) seems quite similar to the MDR, however, these metrics differ with regard to the layers they are evaluating. The PDR provides information about activities on the Networking and Transport layer, whereas the MDR evaluates the Facility layer. Even in cases where a SPAT or MAP message fit into one GeoNetworking packet due to their message sizes, the PDR gives additional insight as it allows to examine service channel load and congestion.

The calculation of the packet delivery ratio PDR_A for an approach A is the same as for the MDR in (2), if instead we use $\#Rec_{mes}$ for the counted received packets and $\#Sent_{mes}$ for the number of sent packets. The average packet delivery ratio $\overline{PDR}$ is then calculated also by an arithmetic mean over all approaches of interest.

4) Stability of the prediction: The existence of semi-adaptive and fully adaptive traffic lights makes reliable prediction of signal transitions a challenging task [14]. Based on detectors such as induction loops or optical systems, or even triggered by pedestrians, these traffic lights can change their signal phases with only little lead time. It is therefore desirable to measure the stability of the GLOSA prediction. A low stability implies that the speed recommendation given to the driver regularly changed during an intersection approach, impacting the benefit of the GLOSA application and also the user experience for the driver. This is especially critical when the approaching vehicle is already close to the traffic light, as a mismatch between HMI information and traffic light is then obvious and confusing.

There are several types of adjustments that can occur due to changes in the traffic light program. In one case, current traffic light phases can either be extended or shortened during their execution, whereas in another case unexpected traffic light signal changes appear. It is possible to detect these situations by comparing the remaining phase time and signal state information of two subsequent SPAT messages. If the signal state, e.g. green traffic light phase, is similar in both messages, an increase of remaining phase time stands for an extension, whereas a decrease larger than a second indicates shortening of the current traffic light phase.

The stability of the prediction SP at the matched lane $lane$ of the intersection Int can then be formulated as follows:

$$SP(Int, lane, T) = 1 - \frac{\#Adj(Int, lane, T)}{\#A(Int, lane, T)}, \quad (3)$$

where in (3), $\#A$ are the counted approaches on the matched lane $lane$ of an intersection Int during time period T, whereas $\#Adj$ denotes the number of those, where at least one adjustment happened during an approach.

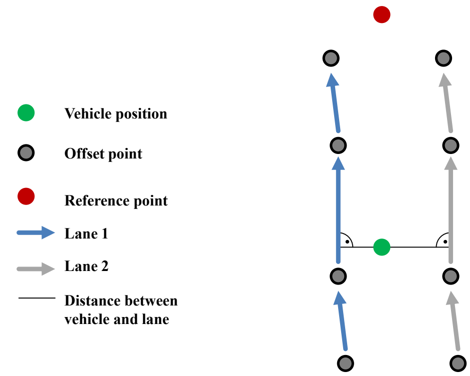


Fig. 3. Distance between measured vehicle position and MAP lane data.

It is also important to understand how a certain adjustment type is distributed in comparison to others. This can be computed by only counting certain adjustment types in the numerator of (3).

5) Distance Between Measured Position and MAP Lane Data: During the preparation of our field tests, we found that despite the successful receiving and decoding of SPAT and MAP messages, sometimes the GLOSA application would not display speed recommendations. The main reason for this was a disagreement in the measured GPS position and the intersection topology provided by the MAP message.

This metric allows to identify and analyze relevant positioning errors for the GLOSA application based on the collected data by measuring the distance of the supposed vehicle position to the lane defined in the MAP message $d_{lane}(p_{veh}, \text{MAP})$. Assuming the offset points Op_x and the position of the vehicle p_{veh} are given in GPS coordinates, we convert them into reference Cartesian coordinates using the Mercator projection. After choosing for each lane of interest the two offset points closest to the vehicle position, one can apply common linear algebra to calculate the position of the point p_l for each lane l that is closest to the vehicle position p_{veh}. Finally, transforming the positions p_l and p_{veh} back to GPS coordinates and applying Vincenty's formula yields the requested distance. Figure 3 illustrates the relation between measured position and MAP lane data in a two lane intersection approach scenario.

6) Information distance: We define the information distance as the distance between vehicle and stop line at the point of time when the first speed advice or TTG information was displayed to the driver on the HMI during an approach. Formally, the information distance $d_{info,A}(p_{veh}, p_{sl}, t_{info})$ is computed using vehicle position p_{veh}, the stop line position p_{sl}, and the time of initial information t_{info} during an approach A. The average information distance $\overline{d_{info}}$ is then computed by the arithmetic mean over all approaches.

As introduced in Section II, this is a core metric for the description of the functional performance of GLOSA systems, which is already used in research, e.g. in simulations or real world prototypes. Note that typically there is a difference between stop line position of an approach and the RSU position at an intersection.

TABLE II
DESCRIPTION OF EQUIPPED INTERSECTIONS ON TEST SITE

Traffic Light	RSU GPS Position	Approach Directions	SPAT Tx Frequency	MAP Tx Frequency
TL1	57.72034 11.93463	West, East	2Hz	1Hz
TL2	57.71837 11.91863	West, East	2Hz	1,5Hz
TL2	57.71667 11.90861	South-West, North-East	2Hz	1,5Hz

IV. FIELD OPERATIONAL TESTING

We added logging capabilities to all GLOSA components in Figure 1. Time-stamped and location-referenced logging files are created locally and stored at the OBU or RSU using the DRIVE C2X logging API [2]. For example, this allows to capture exactly when a SPAT message was decoded or when and where the computation result of the GLOSA algorithm was available. Collected log files were then batch processed, enabling us to compute the introduced metrics in order to conduct a holistic technical evaluation of the tested GLOSA system.

We first introduce the set-up in which our GLOSA system was tested in the field, followed by the influences of external factors on our experiments. Lastly, we show results from the data that was collected during the field trial.

A. Test Set-up

Our GLOSA system, consisting of three fully equipped traffic lights and 10 retrofitted prototype vehicles, was deployed on the DRIVE C2X test site in Gothenburg, Sweden. Test vehicles were equipped with a Nexcom VTC 6100 in-vehicle computer with an integrated wireless communication module. The FOT was conducted by applying naturalistic testing, that is uncontrolled testing under real driving conditions. Tests and data acquisition of the GLOSA system were carried out from June to September 2013. Table II shows locations and test set-up for the equipped intersections on the test site.

B. Influences of External Factors

When conducting field experiments, several external conditions need to be considered, influencing C2X communication and consequently the performance of the GLOSA application. According to Gozalvez et al. [17] a multitude of factors such as Non-Line-of-Sight (NLOS) conditions, bridges, terrain elevation, trees, high density traffic or heavy vehicles negatively impact C2X communications in urban areas. In addition, vehicle integration plays an important role as investigated by Härri et al [18], showing influences of vehicle roof type and losses due to cabling, connectors, and chipsets. Lastly, also the driver affects the overall performance of the system due to individual driving styles and behavior in intersection approach scenarios.

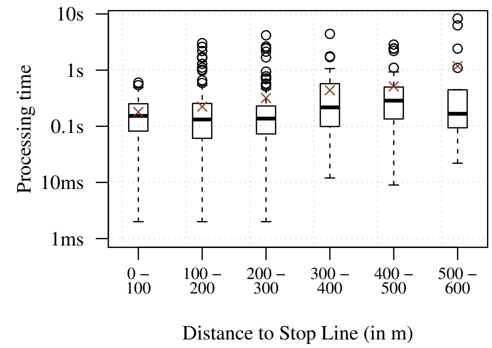


Fig. 4. Latencies of MAP decoding; y-axis is in log scale.

C. Data Analysis and Results of Technical Evaluation

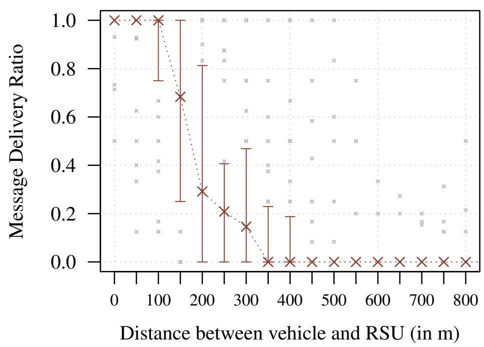
Within this section, we present the results for selected metrics covering in-vehicle latencies, message delivery ratios, and information distance. For the computation of presented metrics, we only considered data generated within a 1500m radius around the traffic light RSU. This distance is larger than any maximum information distance reported in the literature (see Section II) and also larger than the maximum possible transmission range of the deployed antennas. We captured around 40 approaches covering both approach directions for each of the three equipped intersections which allows a detailed comparison.

As a first step, we investigated latencies of components composing the in-vehicle GLOSA system (see Figure 4). In detail, we examine latencies for the decoding and handling of MAP messages, calculation of speed recommendations or TTG, and their presentation in the HMI display.

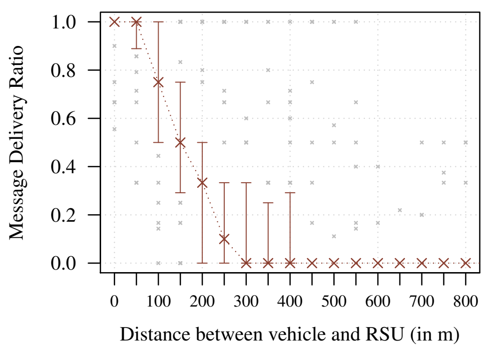
Measurements show, that the median latency for the decoding of MAP messages lies between 132 and 286ms across different distances between vehicle and traffic light RSU. We observe that these latencies are not heavily depending on the distance between vehicle and RSU, albeit the slight increase in average delay. The far outliers are likely resulting from the retrofitted prototype system in the vehicle and are not to be expected in a production vehicle due to a deeper integration of the C2X system in the vehicle architecture. Not shown is the execution time of the GLOSA algorithm and the presentation of the result on the HMI display, which measured around 15 to 17ms on average.

Taking into account the findings of [16], where the message transmission delay between the facility layers ($E2ED_{FAC}$) was approx. 40ms, and assuming that encoding SPAT and MAP messages in the RSU takes as long as decoding in the OBU, we expect a total end-to-end delay $E2ED_{GLOSA}$ in-between 330 and 640ms.

When looking at the message delivery ratio (MDR) for MAP and SPAT messages across all intersection approaches (Figure 5), we observe reliable message reception for distances of up to 150m between vehicle and traffic light RSU. Distinguishing between the delivery ratio of SPAT messages (Figure 5a) and MAP messages (Figure 5b), we observe a

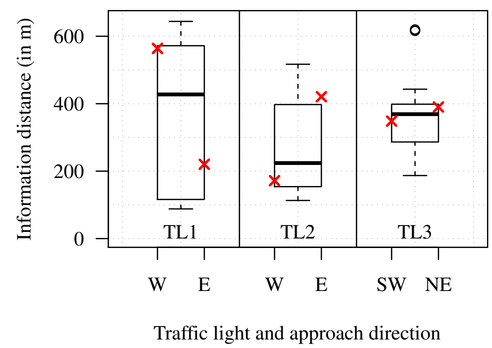


(a) SPAT messages

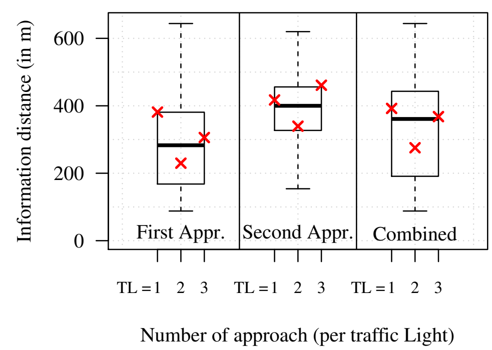


(b) MAP messages

Fig. 5. Message Delivery Ratio of MAP and SPAT messages across all intersections. Plotted is the median MDR depending on the distance to the traffic light RSU. Error bars extend from the 25% to the 75% quantiles. Outside data points are plotted in gray.



(a) Information distance for all traffic lights (TL) and approach directions.



(b) Information distance for first and second approaches towards an intersection.

Fig. 7. Information distances. Boxes extend from the 25% to the 75% quantiles, a thick line marks the median. Plotted in red are the average values for the items on the x-axis.

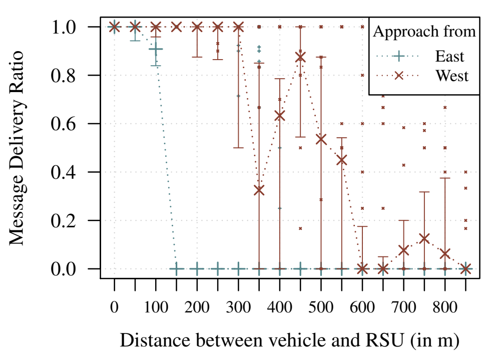


Fig. 6. MDR of MAP and SPAT for traffic light TL1. Plotted is the median MDR depending on the distance to the traffic light RSU. Error bars extend from the 25% to the 75% quantiles.

slight, yet, not significant increase of successful reception caused by the higher transmit frequency (see Table II) and the differing length of both message types.

The distribution of measurement points across the entire communication distance called for a more in-detail investigation. To this end, we plot the MDR for different approach directions for traffic light TL1 in Figure 6. We observe a considerable difference in delivery ratio between approaches from the East (0% for distances > 150m) compared to approaches from the West (>50% at 500m). The primary reason for this is, that approaching from the west guarantees an almost perfect LOS condition early on, whereas signal transmission from the east is heavily influenced by broad-leaved trees and overhead lines of a tram line which is located between the RSU and the road. Our results show that selecting the proper location for the RSU is crucial for GLOSA systems in terms of communication distance. Our findings further imply that simulations abstracting from signal attenuation by obstacles such as buildings or foliage will most likely overestimate the achievable communication distance.

Lastly, we show the achievable information distance of our GLOSA system for all traffic lights and approach directions, that is, the distance from the RSU at which a driver was recommended a speed or displayed a TTG for the first time during an approach. Our results are shown in Figure 7a in the form of a box plot.

We observed an overall maximum information distance of 644m, but also that each traffic light show distinct characteristics in terms of median information distance and distribution of the recorded values. This emphasizes the need to carefully evaluate not only each traffic light separately, but also each approach direction into the intersection. Simply placing an antenna on top of the traffic light will most likely not lead to the desired results.

The fact that a vehicle needs to receive both a MAP and SPAT message in order to give speed recommendations to the driver leads us to investigate the difference in information distance depending on the number of approach. Figure 7b shows that first approaches to a traffic light typically have a lower information distance than second or subsequent approaches. This is caused by vehicles storing the static topology information included in MAP messages received during the first approach. Subsequent approaches then only rely on receiving a SPAT message to compute a speed advice or TTG.

We therefore suggest configuring traffic light RSUs to also broadcast MAP messages containing topology information about other traffic light regulated intersections in the vicinity. Another option is to integrate detailed intersection topology into vehicles' navigation systems and to only broadcast MAP messages for update purposes.

V. Conclusion and Future Work

GLOSA requires a complex system of many interacting subcomponents, each focusing on one specific function. To handle this complexity, we presented a general and comprehensive set of metrics for the holistic evaluation of GLOSA systems. We illustrated the applicability of these metrics in real-world scenarios by discussing specific results obtained from the DRIVE C2X field trial.

Reviewing related work, in particular studies evaluating GLOSA systems by means of simulation, we found a general tendency of over-estimating transmission ranges and message delivery ratios, and also a neglecting of processing delays. Our real life measurements showed that environmental factors such as foliage or buildings play a significant role in the achievable wireless communication performance. We observed differences not only across traffic lights, but also between different directions of approach for the same intersection. In terms of latencies, we found that total end-to-end delays between 330ms and 640ms are to be expected for GLOSA systems. This is caused by the transmission delay, the processing of MAP and SPAT data, and also the time it takes to display the speed recommendation on the HMI.

Our evaluation concept can be used for the future assessment of real-world GLOSA-enabled traffic lights. The presented results from the DRIVE C2X FOT can support the creation of empirical simulation and analytical models.

Future work includes the consideration of multi-hop transmissions to improve GLOSA performance and in particular tackle the NLOS problem. Another interesting research direction is the comparison of wireless and cellular communication based GLOSA systems.

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