Exploring GLOSA Systems in the Field: Technical Evaluation and Results

Rainer Stahlmann[a,c], Malte Möller[a], Alexej Brauer[b], Reinhard German[c], David Eckhoff[b]

[a] *AUDI AG, D-85045 Ingolstadt, Germany*
[b] *Technische Universität München, D-85748 Garching b. München, Germany*
[c] *University of Erlangen, Computer Networks and Communication Systems, D-91058 Erlangen, Germany*

Abstract

Green Light Optimal Speed Advisory (GLOSA) systems are believed to be able to lower CO_2 emissions, fuel consumption, and travel times by avoiding unnecessary stopping at intersections. Approaching vehicles are given speed recommendations 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 extended version of our IEEE VNC 2016 publication [1], we present a holistic concept for the technical evaluation of IEEE 802.11p-based GLOSA systems. We first give a comprehensive survey on GLOSA systems and studies all around the world and identify remaining problems. We introduce metrics to cover the whole spectrum of GLOSA operations and particularly focus on (modeling) problems we encountered in the field that are often not taken into consideration in simulation studies. We demonstrate how this concept can be 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, and also to identify sources of potential problems or bottlenecks.

Based on our findings, we argue that most GLOSA simulation studies are too optimistic in terms of communication performance. Lastly, we give recommendations on how real-world GLOSA systems can be further improved to support a sufficient level of performance.

Keywords: GLOSA, EAD, ESC, DRIVE C2X, Field Trial, Evaluation

---

1. Introduction

Green Light Optimal Speed Advisory (GLOSA) systems are among the first Cooperative Intelligent Transport Systems (C-ITS) applications to utilize Car-to-X (C2X) communication technology. Giving speed advice to the driver when approaching a traffic light is believed to allow for introducing environmental benefits through lowering CO_2 emissions and fuel consumption [2, 3, 4]. 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) [5]. 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. These systems can function even at low market penetration as they do not rely on other vehicles and are therefore envisioned to act as an enabler of Car-2-X technology.

GLOSA systems have received much attention both from industry and academia. They were tested in Field Operational Tests (FOTs), evaluated analytically or by means of simulation. Unfortunately, we observe that many of these studies are carried out independently of each other, and, for example, that simulation studies often neglect insights gained from FOTs [6]. This can cause these studies to be too optimistic in terms of communication performance and subsequently to overestimate the environmental impact of GLOSA systems. In addition to that, many studies only focus on a specific part of the GLOSA system, abstracting away from effects that can considerably affect the recommendations given to the driver.

In this paper, which is an extension of our IEEE VNC 2016 publication titled "Technical evaluation of GLOSA systems and results from the field" [1], we take a holistic approach. This includes all related GLOSA modules in the On-Board Unit (OBU) as well as the Roadside Unit (RSU) in order to evaluate their performance based on data from an extensive field test within the DRIVE C2X [7] project. We extend our previous work by providing more insights into GLOSA application and algorithms, including HMI design, as well as detailed field test set-up. We present a comprehensive survey of related work all around

---

Email addresses: `rainer.stahlmann@audi.de` (Rainer Stahlmann), `malte.moeller@audi.de` (Malte Möller), `alexej.brauer@tum.de` (Alexej Brauer), `reinhard.german@fau.de` (Reinhard German), `david.eckhoff@tum-create.edu.sg` (David Eckhoff)

Preprint submitted to Journal of Computer Communications *March 17, 2018*

the globe and extend the discussion of GLOSA systems to focus more on non-functional requirements. Furthermore, we present new results to give more insights on the performance of the measured GLOSA system and additionally show how these results can be modeled and thereby taken into account in analytical and simulation studies.

Our main contributions include:

- We give a detailed description of a real IEEE 802.11p-based GLOSA application as it was realized for field operational testing within the pan-European FOT DRIVE C2X.
- We present a holistic approach for the technical evaluation of GLOSA systems, including all aspects of the system.
- We discuss both functional and non-functional requirements of the system and evaluate to what extent the real system met those requirements.
- We present results of technical evaluation for the deployed GLOSA system within DRIVE C2X with a particular focus on effects that often have been neglected in simulation studies.

The remainder of this paper is structured as follows: In Section 2 we present an extensive overview of related work, Section 3 introduces the DRIVE C2X GLOSA application with related metrics and concepts for the technical evaluation. In Section 4 we discuss data acquisition and the experimental design. Section 5 reports the FOT results. Finally, Section 6 concludes our work and provides an outlook on future activities.

2. Related Work

GLOSA systems have gained interest from different research domains, such as computer science, civil engineering, and transportation research. This led to the creation of a broad range of simulations as well as real-world implementations, but also various terminologies. In the following, we summarize relevant publications in the context of technical evaluation of GLOSA systems.

2.1. GLOSA in Simulation

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 the case of more vehicles in the road network [2]. They introduce the information distance, which is the distance between vehicle and traffic light when information about the 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 a 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.

Effects of longer communication ranges were investigated by Krajzewicz et al. [9], where they found, based on their chosen simulation set-up, that communication ranges of 1000m and above allow vehicles to cross intersections without the need to stop.

In a driving simulator study conducted by Staubach et al. [10] speed advice was given to 30 test persons during intersection approaches. They found a reduction in average fuel consumption of 15.9% in urban scenarios and 18.4% in rural scenarios. Significant differences in measured speed profiles between approaches with and without speed recommendations were seen from distances to intersection of 400m and below in rural and 300m and below in urban scenarios.

The limitations that come with higher traffic densities for the reduction of CO_2 emissions of GLOSA systems is investigated by Eckhoff et al. [4]. While, according their simulations, up to 11.5% of CO_2 emissions can be saved in low density scenarios, 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.

A traffic simulator study evaluating the impact of an enhanced Eco-Approach and Departure (EAD) application was conducted by Xia et al. [11]. In addition to information obtained from SPAT, preceding equipped vehicles are also considered by the algorithm, thus enhancing the computation of recommended speeds. Moreover, their design focuses on building platoons of vehicles to cross the intersection during green phase time. They point out that communication range should equal the link length, that is the length of the road segment between neighboring intersections, for optimal fuel savings. Additionally, they identified the required communication delay to be 2s and also that further lowering it only slightly impacts fuel savings. Both metrics are important requirements for GLOSA systems and therefore considered in our technical evaluation concept.

Lee et al. [12] developed and evaluated a Cooperative Vehicle Intersection Control (CVIC) algorithm based on IEEE 802.11p for automated vehicles through a coupled communication network and traffic simulation framework. The intersection controller executes the algorithm based on the states of approaching vehicles. For this purpose

Basic Safety Messages (BSMs) [5] are used to transfer information between the controller RSU and vehicles' OBUs. In addition to a different system architecture compared to our GLOSA application, their technical evaluation is solely focusing on the investigation of packet drop rates at certain distances (150m, 300m and 450m) from the RSU.

2.2. Real-world Implementations of GLOSA

Closing the gap between GLOSA simulations and real-world prototypes, Xia et al. [3] 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.

Based on a controlled field test of their Eco-Speed Control (ESC) application on the Virginia Smart Road, Chen et al. [13] report a reduction in fuel consumption of 17.4% and a decrease in travel time of 8.4% based on measurements of 192 intersection approaches using their test vehicle. Their algorithm aims to optimize fuel consumption and computes speed profiles upstream and downstream of the intersection. It is activated at 250m from the signalized intersection due to geographical limitations.

Hao et al. [14] developed an EAD application for actuated signal control, which takes into account SPAT messages as well as distance to the preceding vehicle. Their application was deployed and tested on 10 intersections in Palo Alto, CA. In addition to energy savings of 6% for trips with activated EAD segments, authors found a significant reduction in emissions, in particular a reduction of 7% of CO, 13% of NOx and 18% of HC.

Further pre-series development activities of GLOSA systems are shown in [15] and [16]. 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 communication performance are given in the five aforementioned papers.

Brief insights about a GLOSA prototype system and its technical evaluation are given by Iglesias et al. [17]. 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. [18] 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. [19] 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.

2.3. Traffic Light Control and Phase Time Prediction

Impacts of different traffic light signal timing types and traffic scenarios are evaluated by Stevanovic et al. [20] in a traffic simulation study. Speed advices are computed by a central control application that also takes into account queue length in front of the traffic light. According to their findings, GLOSA has positive effects for traffic efficiency but only a minor impact on fuel consumption. Moreover, fully and semi-adaptive traffic light programs cause limitations as accurate signal timing information is not always available.

An approach to overcome challenges for GLOSA systems caused by semi-adaptive and fully adaptive traffic light programs is introduced by Bodenheimer et al [21]. Unexpected changes in remaining phase times due to non-static traffic light programs lead to drastic changes in given speed advice, showing the importance of 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.

2.4. Technical Evaluation in C-ITS

Looking into the technical evaluation of C-ITS, several effects were observed by Netten et al. [22] 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. The authors argue for an integration of performance criteria from technical evaluation in standardization activities and documents.

According to Gozalvez et al. [23] 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.

Their findings were derived from an extensive field test in Bologna, Italy, which contains 22 RSU locations and more than 70 different RSU configurations in urban areas. However, no further details about the impact of the explored constraints on applications such as GLOSA are given.

On a motorway test site close to Trento, Italy, Visintainer et al. [24] 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, as 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.

3. 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.

3.1. GLOSA in the DRIVE C2X Framework

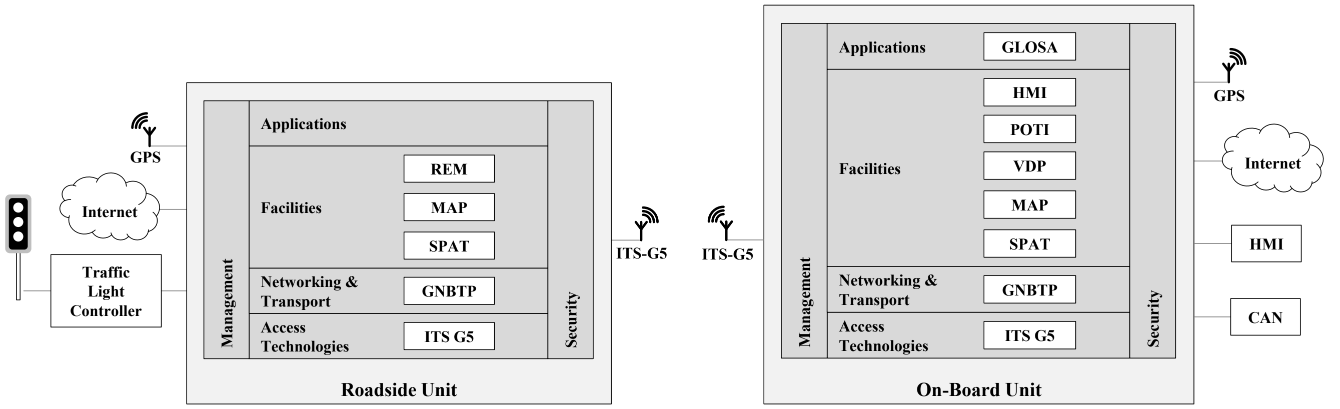
Before looking into the concept for technical evaluation it is necessary to understand the overall system architecture in which our GLOSA application is integrated. Figure 1 shows hardware interfaces, layer architecture, and software components of the RSU and OBU subsystems that establish ITS-G5 compliant C2X communication. As shown in Figure 1a, there are several hardware components attached to the RSU. A Global Positioning System (GPS) receiver provides positioning information and enables time synchronization. Connection to the Traffic Light Controller (TLC) 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 [5]. 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 subsystems. Within the RSU in Figure 1a, Roadside Equipment Management (REM) provides information from the TLC 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 recommendation was configured to be at least 50% of the speed limit in order to avoid confusing drivers of vehicles without GLOSA.

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 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



(a) Roadside Unit (RSU) (b) On-Board Unit (OBU)

Figure 1: Simplified DRIVE C2X system specification and protocol stack derived from [7] with relevant GLOSA software and hardware components.

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.

Algorithm 1 shows the pseudo-code of the GLOSA algorithm which is executed on-board the equipped vehicle. Depending on traffic light phase and velocity of the approaching vehicle, different operation modes are visualized on the in-vehicle HMI. Based on the current velocity, the GPS position, the distance between vehicle and stop line, the traffic light signal phase timings as well as the allowed speed limit, the function calculateSpeedAdvice() computes a speed recommendation. There are several possibilities on how this speed can be computed, including different driving strategies such as accelerating, braking, freewheeling or coasting. We refer the reader to [4], which includes a more detailed description about a different implementation of driving strategies. To calculate the remaining TTG, the function calculateTimeToNextGreenPhase() is called, which is takes the signal phase timing and status information from received SPAT messages into account.

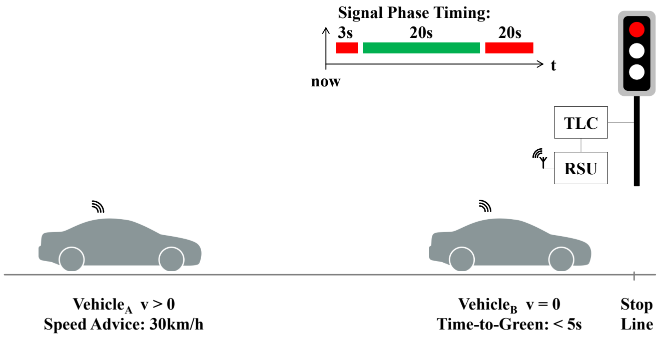
Figure 3 shows the HMI concept of the GLOSA application for the instrument cluster display in an Audi test vehicle within DRIVE C2X. Depending on the situation, the driver can be informed with two different operation modes of the GLOSA system when approaching an equipped intersection in order to support this driving maneuver.

Operation mode one, a speed recommendation, is depicted in Figure 3a. It gives a speed recommendation to the driver that allows for crossing the intersection during a green traffic light phase. In this example the recommended speed is 30 km/h which is visualized in the green framed box. In operation mode two, Time-to-Green (TTG), the remaining time to the next green traffic light phase (28 s) is shown in the red framed box (see Figure 3b).

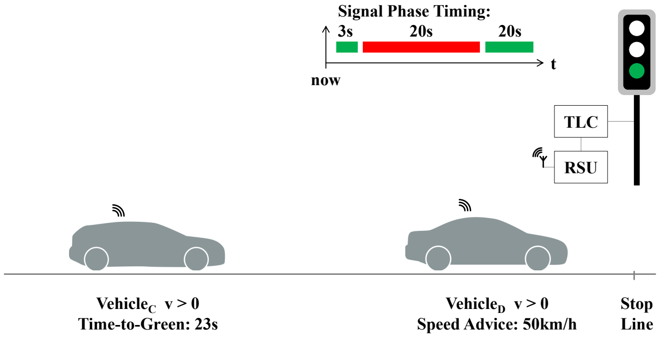
In both cases, arrows represent the intersection crossing possibilities of the lane to which the vehicle is currently matched to. As there exist various intersection layouts with different traffic light programs for straight crossing and left or right turns, precise map matching of the vehicle needs to be performed in order to display the correct information to the driver. Therefore, the map matching algorithm takes into account the vehicle's GPS position as well as information from the vehicle bus system, e.g. the status of the turn signal lever. Knowledge about the intersection layout is derived from information in received MAP messages. Please note that the traffic light icons in the left section of the display and text in the center allow to differentiate between both operation modes and are therefore not showing the current phase of the traffic light program.

Algorithm 1 Pseudo code of in-vehicle Green Light Optimal Speed Advisory (GLOSA) algorithm.

```
phase = getCurrentTrafficLightPhase();
ttg = calculateTimeToNextGreenPhase();
velocity = getVelocityFromCanBus();
if (phase == GREEN) then
    advice = calculateSpeedAdvice();
    if advice <= getSpeedLimit() then
        showOnHmiDisplay(advice);
    else
        showOnHmiDisplay(ttg);
else
    if (velocity > 0) then
        advice = calculateSpeedAdvice();
        if (advice >= (getSpeedLimit()/2)) then
            showOnHmiDisplay(advice);
        else
            showOnHmiDisplay(ttg);
    else
        showOnHmiDisplay(ttg);
```



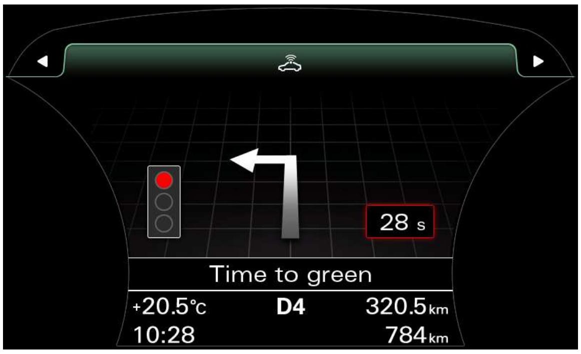
(a) Scenario 1: Current phase of traffic light program is red



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

Figure 2: Intersection approach scenarios

(a) Operation mode 1: Speed recommendation



(b) Operation mode 2: Time-to-Green (TTG)

Figure 3: Instrument cluster display of GLOSA

3.2. 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 1.

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.

3.2.1. 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

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

where t_x represents the point in time, when the execution of the GLOSA component x was started. Note that both points in time have to be logged when the vehicle was in the same specific range band dr.

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, end-to-end delays (E2ED) can also 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 TLC interface in RSU and in-vehicle HMI visualization of GLOSA calculation result

For the technical evaluation of the GLOSA system it is natural 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 5.

Table 1: Overview of metrics for technical evaluation of GLOSA

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

3.2.2. Message Delivery Ratio (MDR)

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.

3.2.3. Packet Delivery Ratio (PDR)

The 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.

3.2.4. Stability of the Prediction

The existence of semi-adaptive and fully adaptive traffic lights makes reliable prediction of signal transitions a challenging task [21]. 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 vehicles approaching an intersection Int on the matched lane $lane$ during time period T. $\#Adj$ denotes the number of those approaching vehicles, where at least one unexpected adjustment in the traffic light program was detected during an approach towards the equipped intersection. In short, it can be understood as the percentage of approaches on a certain lane that were not affected by the adaptivity of the traffic light.

It is also important to understand how certain adjustment types are distributed in comparison to others. This can be computed by only counting certain adjustment types, such as traffic light phase extensions, or sudden traffic light signal changes, in the numerator of (3).

3.2.5. 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

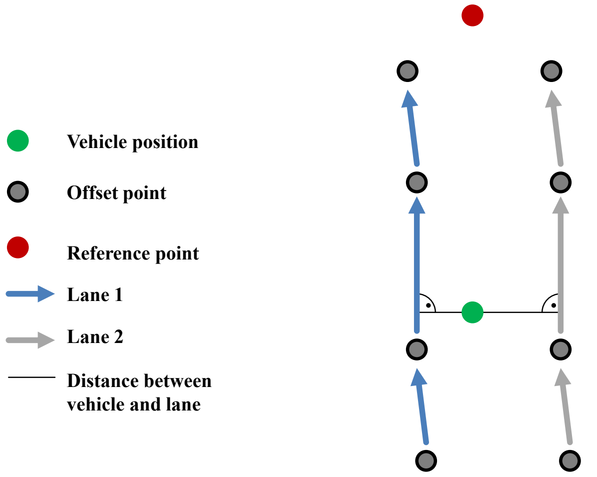


Figure 4: Distance between measured vehicle position and MAP lane data in a two lane intersection approach scenario.

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 $d_{\text{lane}}(p_{veh}, \text{MAP})$. 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 desired distance. Figure 4 illustrates the relation between measured position and MAP lane data.

3.2.6. *Information Distance*

We define the information distance as the distance between approaching vehicle and stop line at the point of time when the driver is informed for the first time during an intersection approach by a speed advice or TTG display on the in-vehicle HMI screen. Formally, the information distance $d_{\text{info,A}}(p_{veh}, p_{sl}, t_{\text{info}})$ 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 $\overline{d_{\text{info}}}$ is then computed by the arithmetic mean over all approaches.

As mentioned in Section 2, this is a core metric for the description of the performance of GLOSA systems, which was introduced by Tielert et al. [2]. Note that typically there is a difference between traffic light stop line positions and the RSU position at an intersection. Hence, information distances of an intersection usually differ from RSU communication range.

Table 2: Overview of non-functional requirements of GLOSA

Metric	Requirement
End-to-End Delay ($E2ED$)	$<$2s
Message Delivery Ratio (MDR)	$\geq$50%
Information Distance (d_{info})	$\approx$Link Length

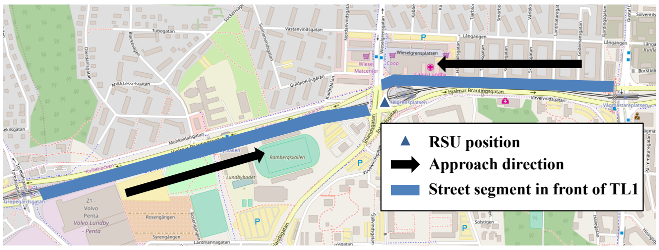
3.3. *Non-functional Requirements*

In the following we provide a short overview about non-functional requirements for GLOSA systems based on wireless communication in terms of system latencies, communication coverage and information distance. They are important for the technical evaluation, as they can be influenced most by communication and application design. We give a summary in Table 2.

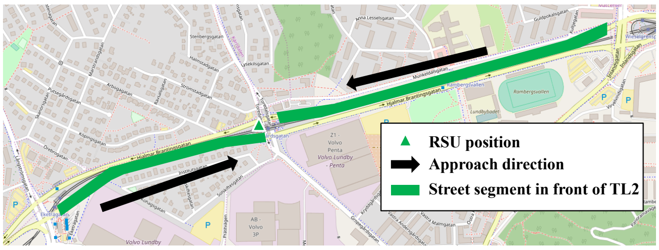
Investigating system latency in GLOSA systems, it was found in [11] that an E2ED below 2s does not negatively influence fuel consumption and CO_2 emissions, which is an important requirement as it directly impacts the main objective of GLOSA systems. However, user acceptance tests e.g. through driving simulator studies are needed to assess which delays are acceptable for human drivers in the context of GLOSA systems. This might lead to a lower limit compared to the 2s mentioned above. To the best of our knowledge, such user acceptance tests have not been conducted and hence it is an open research question. As a result, we define an E2ED below 2s as maximum requirement.

Communication coverage requirements for GLOSA are lower than for active safety applications, where according to Bai et al. [25] a PDR of $\geq$80% is considered as good for communication in Vehicular Ad-Hoc Networks (VANETs). In the case of wireless GLOSA systems, the reception of one SPAT and one MAP is sufficient to activate the application and continuously compute HMI displays of GLOSA during an intersection approach. However, dynamic changes due to adaptive or semi-adaptive traffic lights as well as queue length estimations require continuous reception of updated messages in order to continuously update the speed recommendation on the HMI display. Considering the frequencies of MAP and SPAT messages and the required end-to-end delay of 2s, we conclude that the MDR should be $\geq$50% in these cases.

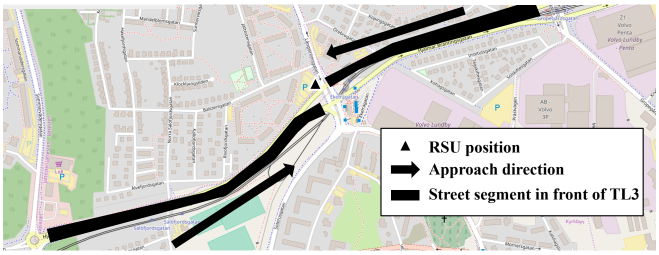
Regarding the information distance, we observe a wide range of proposed values from simulation studies, reaching from 300m [8], 300m to 400m [10], 500m to 600m [2] and up to 1000m [9]. However, as our GLOSA algorithm computes a speed advice or TTG for the approach towards the next equipped intersection, the information distance depends on the link length before this intersection and therefore, from an application perspective, should be equal to the length of this link. An information distance which is smaller than the link length could negatively impact the reduction of fuel consumption, whereas higher information distance would result in providing information to the



(a) Traffic Light TL1



(b) Traffic Light TL2



(c) Traffic Light TL3

Figure 5: Excerpts showing layout of equipped intersections. [1]

driver too early. Hence, this requirement for our GLOSA system solely depends on the layout of the urban road network.

4. Field Operational Testing

We first introduce the set-up in which our GLOSA system was tested in the field, followed by information about data collection and data processing of our experiments.

4.1. 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 under naturalistic driving conditions, i.e. uncontrolled testing in real traffic situations. Tests and data acquisition of the GLOSA system were carried out from June to September 2013. For a more detailed understanding of intersection topology and layout, map excerpts for each of the equipped intersections are shown in Figures 5a to 5c.

Table 3 shows locations and test set-up for the equipped intersections on the test site. Furthermore, it provides information about the link length, i.e., the continuous, non-interrupted street-section directly in front of the equipped and signalized intersection that each vehicle needs to travel on while approaching this intersection.

4.2. Data Collection and Data Processing

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 [7]. 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.

5. Data Analysis and Results

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 2) 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 allow a detailed comparison.

5.1. Latencies

As a first step, we investigated latencies of components composing the in-vehicle GLOSA system (see Figure 6). 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. Furthermore, we analyze latencies for the execution of the lane matching calculation.

Our measurements in Figure 6a 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 dependent on the distance between vehicle and RSU, albeit the slight increase in average delays. Figure 6b shows 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. Latencies that arise due to the lane matching algorithm are depicted in Figure 6c resulting in an average delay that lies between 12ms and 14ms. Again, no major dependency on the distance between vehicle and RSU can be observed in Figures

---

[1] Map © OpenStreetMap www.openstreetmap.org/copyright

Table 3: Description of equipped intersections on test site

Traffic Light	RSU GPS Position	Approach Directions	SPAT Tx Frequency	MAP Tx Frequency	Approximate Link Length
TL1	57.72034, 11.93463	West, East	2Hz	1Hz	890m 600m
TL2	57.71837, 11.91863	West, East	2Hz	1.5Hz	590m 910m
TL3	57.71667, 11.90861	South-West, North-East	2Hz	1.5Hz	820m 590m

6b and 6c. Differences in latency higher than one order of magnitude between GLOSA calculation result and HMI display, lane matching and decoding of MAPs are caused by a higher complexity in the task for handling of MAPs.

The retrofitted prototype system created some far outlier measurements for latencies, as this metric also depends on selection and design of hardware as well as software components like the CPU and the operating system of the OBU. We expect that lower latencies of the in-vehicle GLOSA components can be achieved for production vehicles due to a deeper integration of the C2X technology in the vehicle architecture. In contrast to that, more congested scenarios with a larger number of communication nodes would negatively influence successful channel access and consequently lead to a higher delay.

To the best of our knowledge, processing delays have not been considered in simulation studies evaluating GLOSA systems although our results show that they cannot be fully neglected. Taking into account the findings of [24], 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 $E2ED_{GLOSA}$ of between 330ms and 640ms, lying clearly below the requirement of 2s. Note that the latencies for lane matching can be neglected for this estimation as this module is executed in parallel and therefore is not part of $E2ED_{GLOSA}$.

We recommend including latencies in future simulations of GLOSA systems. Therefore, we provide probability distributions (see Figure 7) and their characteristics for integration into simulation frameworks. Based on their visual appearance in histograms, we first chose the parametric probability distributions and then fitted the parameters via maximum likelihood estimation. In case of latencies for the decoding of MAP messages, we found a suitable exponential distribution, which is plotted in Figure 7a and characterized by a rate of $\lambda_{\text{MAP}} = 0.0035$. In both cases, for latency measurements of GLOSA calculation together with HMI result (Figure 7b) and lane matching (Figure 7c) we chose truncated normal distributions with a lower bound of 0. The estimated mean values and standard deviations are $\mu_{\text{GLOSAHMI}} = 16.40$, $\sigma_{\text{GLOSAHMI}} = 4.71$ and $\mu_{\text{LaneMatching}} = 13.41$, $\sigma_{\text{LaneMatching}} = 4.38$.

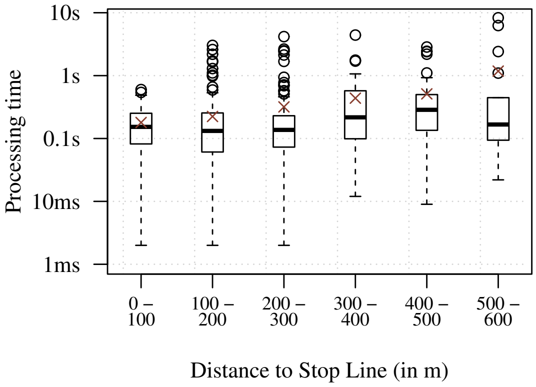
Furthermore, the selection of hardware and operating system is important for real world systems as they mainly influence delays in the system.

5.2. Message Delivery Ratio (MDR)

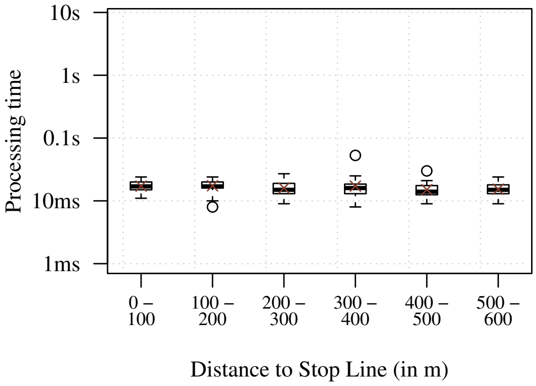
When looking at the Message Delivery Ratio (MDR) for MAP and SPAT messages across all intersection approaches (Figure 8), we observe reliable message reception for distances of up to 150m between vehicle and traffic light RSU. Distinguishing between the delivery ratio of SPAT messages (Figure 8a) and MAP messages (Figure 8b), we observe a slight, yet not significant increase of successful reception caused by the higher transmit frequency (see Table 3) 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 of MAP and SPAT for different approach directions for all three traffic lights in Figure 9. For traffic light TL1 (see Figure 9a) 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.

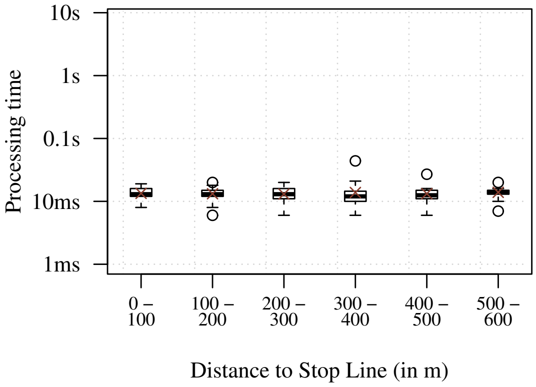
In comparison with TL1, traffic light TL2 provides quite low message delivery ratios as depicted in Figure 9b. Eastern approach direction shows a communication distance of around 150m only (MDR of $\geq$50%). Results for approaches from the West are also quite small ($\geq$50% at 100m) even though both road segments are quite straight over a longer distance. This is mainly caused by the elevation of the terrain in combination with the RSU antenna beam and the mounting position of the roof antenna on the test vehicles, all in all negatively influencing signal reception on vehicle side. For both approach directions the road descends towards the intersection. Differences between the two approach directions occur due to an underpass close to the intersection separating opposite lanes. RSU signals are attenuated by the underpass for approaches from the West.



(a) Latencies caused by decoding of MAP messages.

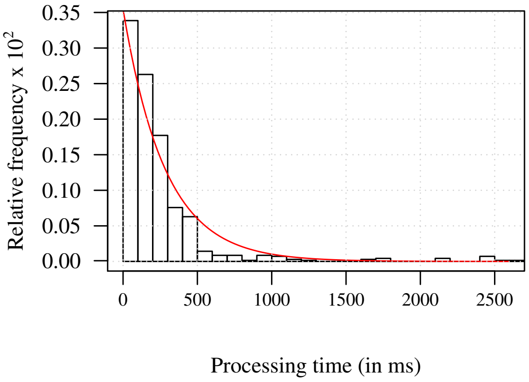


(b) Latencies caused by GLOSA calculation and HMI display.

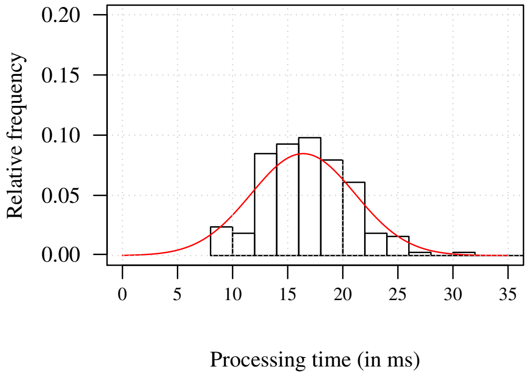


(c) Latencies caused by the lane matching algorithm during approach.

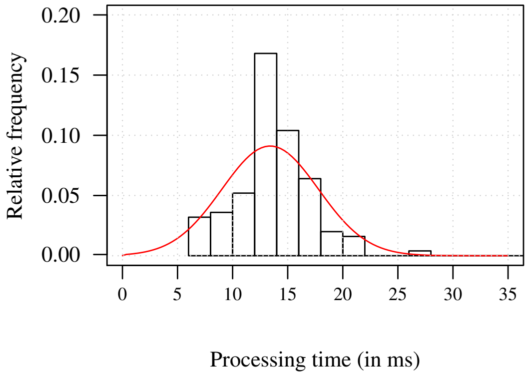
Figure 6: Latencies of selected GLOSA components; y-axis is in log scale.



(a) Exponential distribution for decoding of MAP messages.



(b) Truncated normal distribution for GLOSA calculation and HMI display.

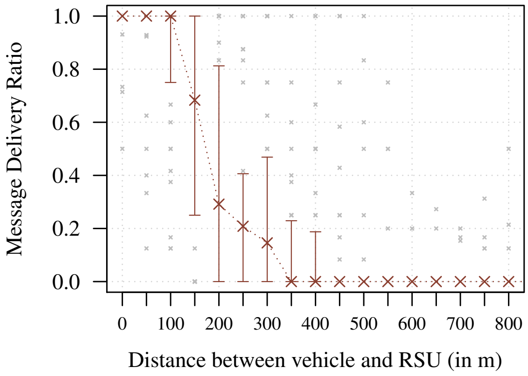


(c) Truncated normal distribution for lane matching algorithm.

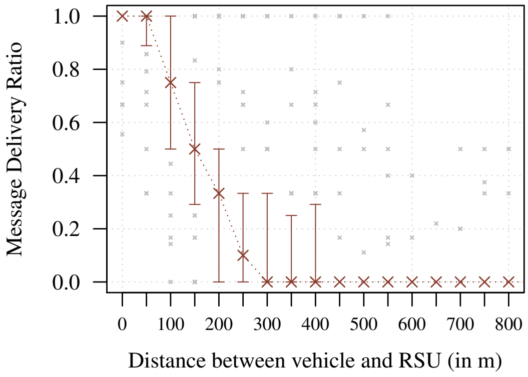
Figure 7: Histograms and fitted probability distributions (density functions) for latencies of selected GLOSA components.

For traffic light TL3 in Figure 9c the communication distance for both approach directions is higher than in case of TL2. North-east approaches deliver considerable results for distances up to 400m, whereas south-west approaches achieve shorter communication distances due to signal attenuation caused by buildings and broad-leaved trees which are located close to the road.

Observing the achieved MDRs, we confirm findings of [23] also from an application layer perspective, that is, a high sensitivity of GLOSA systems regarding RSU location and antenna mounting height. 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. The same applies for negative impacts from terrain such as elevation or infrastructural influences like overhead lines



(a) SPAT messages



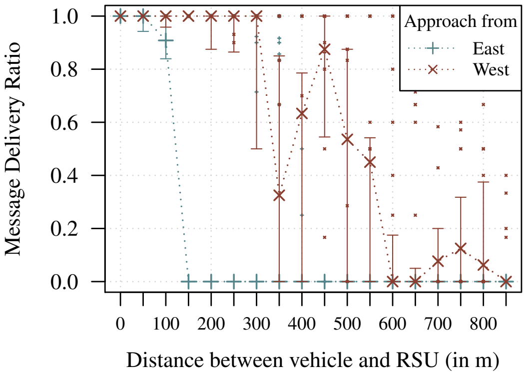
(b) MAP messages

Figure 8: 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.

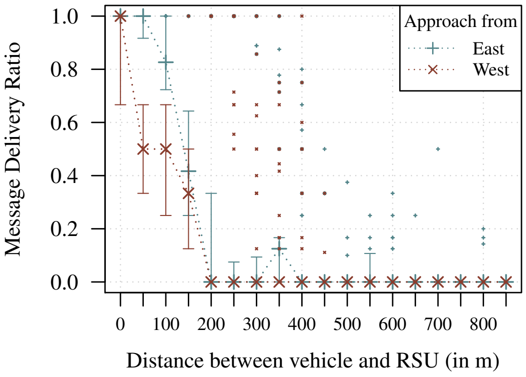
or underpasses. Furthermore, antenna characteristics can significantly affect connectivity and communication ranges [26]. Continuous reception of SPAT messages is important, especially in cases where adaptive traffic light programs can cause sudden changes of the signal which requires updated speed advices or TTG information [21]. In both cases these updates need to be provided to the driver without any loss of information or unnecessary delays. With regard to the non-functional requirements (see Subsection 3.3), we note that the requirements for the Message Delivery Ratio cannot be sufficiently met for all traffic lights and approach directions. Therefore, further improvements are needed, e.g., the use of multi-hop message forwarding for GLOSA systems [27].

5.3. Information Distance

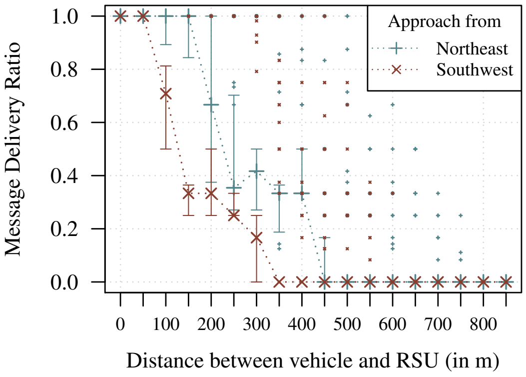
Lastly, we show the achievable information distance of our GLOSA system for all traffic lights and approach directions, that is, the distance from the RSU at which a driver was recommended a speed or displayed a TTG for the first time during an approach. Our results are shown in Figure 10 in the form of a box plot.



(a) Traffic light TL1



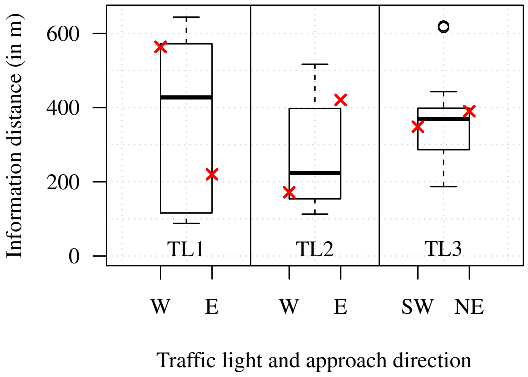
(b) Traffic light TL2



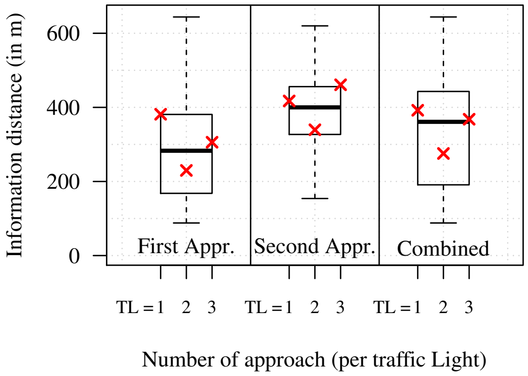
(c) Traffic light TL3

Figure 9: MDR of MAP and SPAT for all three traffic lights. Plotted is the median MDR depending on the distance to the traffic light RSU. Error bars extend from the 25% to the 75% quantiles.

We observed a maximum information distance of 644m, but also that each traffic light shows distinct characteristics in terms of median information distance and distribution of the recorded values (see Figure 10a). 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.



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



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

Figure 10: 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.

As discussed in Subsection 3.3, it is not necessary to achieve an information distance that is longer than the length of the intersection approach. This means that the street layout influences the required (and achievable) information distance. Ideally, the driver is given a speed advice or a TTG at the beginning of the intersection approach. In Table 4, we compare the observed maximum information distance with the length of each intersection approach. We observe that in the best case the coverage lies around 75% for both approach directions of TL3. For TL2, the results were considerably worse, only reaching around 43% for approaches from the west. Therefore, it should be the objective to further enhance the communication distances of MAP and SPAT messages, e.g., by means of multi-hop communication.

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 10b 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.

Table 4: Information Distance Link Coverage

Traffic Light	Approach Directions	Approximate Link Length	Link Coverage
TL1	West, East	890m 600m	72.3% 66.5%
TL2	West, East	590m 910m	43.5% 56.8%
TL3	South-West, North-East	820m 590m	75.6% 75.1%

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.

5.4. Discussion

Based on our observations collected during the FOT and the supporting simulation results from Dittrich et al. [28], we propose to add information about the current queue length of each lane in front of the equipped intersection to the GLOSA system. Giving more precise speed recommendations especially in cases of dense traffic helps improve the impact of the GLOSA application. A method for real-time estimation of queue lengths at signalized intersections is introduced by Comert [29] where analytical models make use of data from stop line detectors as well as from probe vehicles. This information can be integrated in messages and continuously broadcast by a connected RSU in the vicinity of the intersection. Once these messages are received by approaching vehicles, the GLOSA algorithm inside the vehicle takes the queue length into account and virtually transforms the stop line towards the end of the estimated tailback in front of the traffic light. It allows to consider an additional waiting time for the vehicle due to the tailback. This results in recommendations of lower speed values when approaching queued vehicles at the intersection and also helps create speed recommendations that are more applicable on busier roads.

In terms of simulation, it becomes obvious that some of the observed technological characteristics of GLOSA systems in the field are not adequately represented in many recent simulation studies. While this is not necessarily a problem when the goal is to learn about general potentials, limitations, and average benefits on a larger scale, it can become crucial when analyzing single intersections, e.g., to support the decision process of which traffic lights to equip. Factors such as the latency can be incorporated into simulation by adding random variables, where the probability distributions are calibrated by the findings presented in this paper. When it comes to the information distance and packet error rates, however, we observe that the influence of obstacles such as overpasses, foliage and buildings more or less deterministically affect the connectivity between the traffic light and the approaching vehicle. While these effects can be captured by obstacle shadowing models (e.g. [30]), high-detail 3-D map data is required which might not be available or takes considerable effort to create. Based on our results, we want to emphasize the necessity for more accurate simulation models in order to increase the reliability of simulation results to support a smooth introduction of GLOSA systems.

For system latencies, we showed that it is possible to stay below the required delay of 2s. However, communication coverage and information distance are more challenging and call for further improvements in order to reach the requirements. In a recent publication [27], we investigated the impact of multi-hop information forwarding for GLOSA systems from a technical perspective. Results from real-world tests with 194 intersection approaches confirm positive effects for GLOSA. Aided by multi-hop mechanisms, achievable maximum information distances could be increased by around 35% and communication coverage could significantly be improved in areas with poor reception. Hence, multi-hop can support reaching non-functional requirements (see Subsection 3.3) for GLOSA systems in terms of communication coverage and range, which could not fully be met during this FOT. We therefore suggest to apply multi-hop communication for GLOSA systems, e.g., by use of additional infrastructure nodes, or moving and parked cars.

6. Conclusion and Future Work

Green Light Optimal Speed Advisory systems consist of many interacting sub-components, 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 results obtained from the DRIVE C2X field trial. Our evaluation concept can be used for the future assessment of real-world GLOSA-enabled traffic lights. Giving a comprehensive review of 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.

In this extended version of our IEEE VNC publication [1], we give detailed insights on the expected performance of GLOSA systems in a real-world environment. 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. However, we also encountered outliers that are beyond the identified required delay of 2s. We observed information distances as low as 150m up to 600m, depending on environmental factors such as foliage or buildings. The identified requirement for the Message Delivery Ratio (MDR) of 50% could not always be achieved, indicating that IEEE 802.11p single hop GLOSA systems will not always perform as desired when approaching adaptive traffic lights. Possible solutions to this problem include the use of multi-hop strategies, that is, using additional RSUs, other cars or even parked vehicles as relay nodes to increase the MDR and thereby also the information distance.

We conclude that simulation studies that evaluate GLOSA systems on a larger scale should take these limitations into account. To this end, the results presented in this paper can serve as a guideline and input for the calibration or development of simulation and analytical models.

Future research directions include a comparison of the communication performance of different technologies for GLOSA systems, e.g., ad-hoc and cellular communication, and also their combination into a hybrid approach, which we believe constitutes an interesting field of research.

Acknowledgment

We would like to thank the European Commission for co-funding of DRIVE C2X. This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 270410.

References

[1] R. Stahlmann, M. Möller, A. Brauer, R. German, D. Eckhoff, Technical evaluation of GLOSA systems and results from the field, in: 2016 IEEE Vehicular Networking Conference (VNC), Columbus, OH, USA, 2016, pp. 1–8. doi:10.1109/VNC.2016.7835967.

[2] T. Tielert, M. Killat, H. Hartenstein, R. Luz, S. Hausberger, T. Benz, The impact of traffic-light-to-vehicle communication on fuel consumption and emissions, in: 2010 Internet of Things (IOT), Tokyo, Japan, 2010, pp. 1–8. doi:10.1109/IOT.2010.5678454.

[3] H. Xia, K. Boriboonsomsin, F. Schweizer, A. Winckler, K. Zhou, W. B. Zhang, M. Barth, Field operational testing of ECO-approach technology at a fixed-time signalized intersection, in: 2012 15th International IEEE Conference on Intelligent Transportation Systems, Anchorage, AK, USA, 2012, pp. 188–193. doi:10.1109/ITSC.2012.6338888.

[4] D. Eckhoff, B. Halmos, R. German, Potentials and limitations of Green Light Optimal Speed Advisory systems, in: 2013 IEEE Vehicular Networking Conference, Boston, MA, USA, 2013, pp. 103–110. doi:10.1109/VNC.2013.6737596.

[5] SAE International DSRC (Dedicated Short Range Communication) Technical Committee, Dedicated Short Range Communication (DSRC) Message Set Dictionary, Tech. rep., SAE, Technical Report J2735_200911 (November 2009).

[6] D. Eckhoff, A. Festag, M. Gruteser, F. Schimandl, M. Segata, E. Uhlemann, Working Group on Best Practices for Field Operational Testing, in: Dagstuhl Seminar 13392 - Inter-Vehicular Communication - Quo Vadis, Schloss Dagstuhl, Wadern, Germany, 2013, pp. 206–209.

[7] R. Stahlmann, A. Festag, A. Tomatis, I. Radusch, F. Fischer, Starting European Field Tests for Car-2-X Communication: The DRIVE C2X Framework, in: 18th ITS World Congress and Exhibition, Orlando, FL, USA, 2011.

[8] K. Katsaros, R. Kernchen, M. Dianati, D. Rieck, Performance study of a Green Light Optimized Speed Advisory (GLOSA) application using an integrated cooperative ITS simulation platform, in: 2011 7th International Wireless Communications and Mobile Computing Conference, Istanbul, Turkey, 2011, pp. 918–923. doi:10.1109/IWCMC.2011.5982524.

[9] D. Krajzewicz, L. Bieker, J. Erdmann, Preparing Simulative Evaluation of the GLOSA Application, in: 19th ITS World Congress, Vienna, Austria, 2012.

[10] M. Staubach, N. Schebitz, F. Köster, D. Kuck, Evaluation of an eco-driving support system, Transportation Research Part F: Traffic Psychology and Behaviour 27, Part A (2014) 11–21. doi:10.1016/j.trf.2014.09.006.

[11] H. Xia, G. Wu, K. Boriboonsomsin, M. J. Barth, Development and evaluation of an enhanced eco-approach traffic signal application for connected vehicles, in: 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013), The Hague, The Netherlands, 2013, pp. 296–301. doi:10.1109/ITSC.2013.6728248.

[12] J. Lee, B. B. Park, Investigating communications performance for automated vehicle-based intersection control under connected vehicle environment, in: 2015 IEEE Intelligent Vehicles Symposium (IV), Seoul, South Korea, 2015, pp. 1342–1347. doi:10.1109/ivs.2015.7225902.

[13] H. Chen, H. A. Rakha, A. Loulizi, I. El-Shawarby, M. H. Almannaa, Development and preliminary field testing of an in-vehicle eco-speed control system in the vicinity of signalized intersections, IFAC-PapersOnLine 49 (3) (2016) 249–254. doi:10.1016/j.ifacol.2016.07.042.

[14] P. Hao, G. Wu, K. Boriboonsomsin, M. Barth, Eco-approach and departure (ead) application for actuated signals in real-world traffic, Transportation Research Board (TRB) 96th Annual Meeting 14 (15) (2017) 1–18.

[15] R. Braun, F. Busch, C. Kemper, R. Hildebrandt, F. Weichenmeier, C. Menig, I. Paulus, R. Presslein-Lehle, TRAVOLUTION – Netzweite Optimierung der Lichtsignalsteuerung und LSA-Fahrzeug-Kommunikation, Straßenverkehrstechnik 53 (2009) 365–374.

[16] M. Zweck, M. Schuch, Traffic light assistant: Applying cooperative ITS in European cities and vehicles, in: 2013 International Conference on Connected Vehicles and Expo (ICCVE), Las Vegas, NV, USA, 2013, pp. 509–513. doi:10.1109/ICCVE.2013.6799846.

[17] I. Iglesias, L. Isasi, M. Larburu, V. Martinez, B. Molinete, I2V Communication Driving Assistance System: On-Board Traffic Light Assistant, in: 2008 IEEE 68th Vehicular Technology Conference, Calgary, BC, Canada, 2008, pp. 1–5. doi:10.1109/VETECF.2008.437.

[18] B. Schweiger, C. Raubitschek, B. Bäker, J. Schlichter, ElisaTM - Car to Infrastructure Communication in the Field, Comput. Netw. 55 (14) (2011) 3169–3178. doi:10.1016/j.comnet.2011.05.022.

[19] B. Bernais, A. Lotz, H. Pu, Design and implementation of a traffic light assistance system based on C2X and TSI messages, in: AmE 2016 - Automotive meets Electronics; 7th GMM-Symposium, Dortmund, Germany, 2016, pp. 1–6.

[20] A. Stevanovic, J. Stevanovic, C. Kergaye, Green Light Optimized Speed Advisory Systems - Impact of Signal Phasing Information Accuracy, Transportation Research Record: Journal of the Transportation Research Board 2390 (2013) 53–59. doi:10.3141/2390-06.

[21] R. Bodenheimer, A. Brauer, D. Eckhoff, R. German, Enabling GLOSA for adaptive traffic lights, in: 2014 IEEE Vehicular Networking Conference (VNC), Paderborn, Germany, 2014, pp. 167–174. doi:10.1109/VNC.2014.7013336.

[22] B. Netten, I. Passchier, H. Wedemeijer, S. Maas, C. van Leeuwen, Technical Evaluation of Cooperative Systems - Experience from the DITCM Test Site, in: 9th ITS European Congress, Dublin, Ireland, 2013.

[23] J. Gozalvez, M. Sepulcre, R. Bauza, IEEE 802.11p vehicle to infrastructure communications in urban environments, IEEE Communications Magazine 50 (5) (2012) 176–183. doi:10.1109/MCOM.2012.6194400.

[24] F. Visintainer, L. D'Orazio, M. Darin, L. Altomare, Cooperative Systems in Motorway Environment: The Example of Trento Test Site in Italy, in: Advanced Microsystems for Automotive Applications 2013: Smart Systems for Safe and Green Vehicles, New York, USA, 2013, pp. 147–158.

[25] F. Bai, D. D. Stancil, H. Krishnan, Toward understanding characteristics of dedicated short range communications (dsrc) from a perspective of vehicular network engineers, in: Proceedings of the Sixteenth Annual International Conference on Mobile Computing and Networking, MobiCom '10, ACM, New York, NY, USA, 2010, pp. 329–340. doi:10.1145/1859995.1860033.

[26] D. Eckhoff, A. Brummer, C. Sommer, On the Impact of Antenna Patterns on VANET Simulation, in: 8th IEEE Vehicular Networking Conference (VNC 2016), IEEE, Columbus, OH, 2016, pp. 17–20. doi:10.1109/VNC.2016.7835925.

[27] R. Stahlmann, A.Tomatis, R. German, D. Eckhoff, Multi-hop for GLOSA systems: evaluation and results from a field experiment, in: 2017 IEEE Vehicular Networking Conference (VNC), Torino, Italy, 2017, pp. 175–178.

[28] C. Dittrich, J. Lüßmann, F. Busch, R. Mänz, R. Stahlmann, C. Menig, Greener roads by talking traffic lights - knowledge about queue lenght and next traffic light signalling, in: International Conference on Sustainable Automotive Technologies (ICSAT), Chiemsee, Springer Germany Ltd., 2010.

[29] G. Comert, Effect of stop line detection in queue length estimation at traffic signals from probe vehicles data , European Journal of Operational Research 226 (1) (2013) 67–76. doi:10.1016/j.ejor.2012.10.035.

[30] C. Sommer, D. Eckhoff, R. German, F. Dressler, A Computationally Inexpensive Empirical Model of IEEE 802.11p Radio Shadowing in Urban Environments, in: 8th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2011), IEEE, Bardonecchia, Italy, 2011, pp. 84–90. doi:10.1109/WONS.2011.5720204.