Multi-hop for GLOSA Systems: Evaluation and Results From a Field Experiment

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***Abstract*—Green Light Optimal Speed Advisory (GLOSA) systems contribute to the reduction of CO_2 emissions and fuel consumption by giving speed advice to drivers based on current and future traffic light signal phase timings so they can avoid unneeded stopping and acceleration. These systems have been well investigated by means of simulations and real-world tests. In previous work we have shown that simulations tend to overestimate the communication quality to be expected in urban environments and that in a real-world test, IEEE 802.11p-based GLOSA cannot always reach the required information distance.**

Although multi-hop information dissemination can help alleviate this problem, it has not yet received much attention from the research community in the context of GLOSA systems. In this paper we present results from extensive field tests with almost 200 traffic light approaches. We find that two-hop dissemination of signal phase and timing information from traffic lights increases the maximum information distance by around 35% and is able to support continuous updates even in challenging environments.

***Index Terms*—Multi-hop, GLOSA, DRIVE C2X, Experiment**

I. Introduction

Within the automotive domain, the reduction of CO_2 emissions and fuel consumption is a major field of action in order to comply with regulations and to meet customers' expectations. Green Light Optimal Speed Advisory (GLOSA) systems are one possible way to achieve this by transmitting traffic light phase times to approaching vehicles [1]–[3]. This allows the vehicle to compute speed recommendations to pass the traffic light during green phase, when possible. In the ETSI ITS-G5 system, this is done using Map Data Messages (MAP) and Signal Phase and Timing Messages (SPAT) [4] based on wireless IEEE 802.11p communication.

These systems have been thoroughly assessed by means of simulation. However, we have shown in previous work [5] that simulations often overestimate the information distance, that is, how far in advance a vehicle can be reached using IEEE 802.11p communication. In a real-world scenario, signal attenuation (e.g., due to trees, pedestrian bridges, or overhead tram lines) has a decisive influence on the performance of the GLOSA systems. Our real life tests showed that distance related requirements from simulations [1], [2] could not always be met and that continuous information reception cannot easily be achieved in practice. This is important for GLOSA as dynamic changes in queue length estimation [6] or prediction algorithms for non-static traffic light programs [7] require short update intervals to adjust the speed advice or Time-to-Green (TTG) display in the vehicle.

Both enhancement of communication distance and continuous message reception called for further investigation. Multi-hop information dissemination seems to be a promising approach, which has already shown its benefits for active safety applications [8], [9]. Unfortunately, multi-hop mechanisms for GLOSA systems have hardly been examined in detail so far. Therefore, we perform an extensive real-world experiment to compare multi-hop and single-hop broadcast communication for GLOSA systems. In detail, our main contributions include:

- We develop an experimental design to assess the impact of multi-hop communication for GLOSA systems.
- We present results of the two-hop communication experiment with the GLOSA system developed in DRIVE C2X on a test track near Ingolstadt, Germany.

II. Related Work

Based on different approaches and frameworks, the positive environmental impact of GLOSA has been shown in simulation studies, where potential reductions in fuel consumption and CO_2 emissions from 7% up to 11% [1]–[3] were observed. According to findings in [1], GLOSA systems have positive effects on the environment for information distances up to 500m and 600m. Alsabaan et al. [10] presented a computational approach to find the optimal speed for approaching equipped traffic lights. They propose an idealized multi-hop protocol based on Vehicle-to-Infrastructure (V2I) information broadcast with discarding mechanisms in the vehicles and Vehicle-to-Vehicle (V2V) unicast. Unfortunately, no details about the environmental impact of multi-hop information forwarding or its communication performance are given. Both call for a deeper investigation of multi-hop for GLOSA systems. In our previous work [5], we technically evaluated GLOSA systems. Analyzing Field Operational Test (FOT) data from the DRIVE C2X test site in Gothenburg, Sweden, we found a tendency of over-estimating communication performance in simulations compared to real life measurements. Achievable information distances varied for each intersection and approach direction.

Therefore, we suggested evaluating multi-hop forwarding for GLOSA systems to increase communication performance. Approaching vehicles need to be continuously updated to provide accurate information about queue lengths before the intersection [6] or when semi- or fully adaptive traffic lights change their signal phases with only short lead times [7].

Mittag et al. [11] compared effects of single-hop and multi-hop information forwarding in Vehicular Ad-Hoc Networks (VANETs) by using analytical models and simulation. They concluded that multi-hopping could improve communication performance in Non-Line-of-Sight (NLOS) situations, however, only minor benefits could be observed in dense traffic. The authors further note that the additional channel load could be problematic. It is therefore important to better understand the potentials of multi-hop information dissemination for real-world GLOSA systems to weigh the benefits against the introduced channel load. Multi-hop beaconing in VANETs was also analyzed by Librino et al. [8] based on simulation study and real-world measurements. According to authors, network-coding based forwarding strategy exceeds randomized strategy and both approaches outperform single-hop broadcast. Renda et al. [9] evaluated multi-hop information propagation with real-world test data from highways in Italy. They equipped three vehicles with IEEE 802.11p compliant radios to measure Packet Delivery Ratio (PDR) and packet inter-reception times, aiming to improve active safety applications in NLOS situations. Additionally, a simulation was conducted which showed that advantages in communication performance mostly disappear after the fourth hop.

We contribute to the state of the art with an in-detail evaluation of multi-hop communication for GLOSA systems, which need a separate investigation as requirements of GLOSA differ from active safety applications in terms of information distance and latencies. Moreover, we conduct our real-world experiment in urban environments, where GLOSA systems would typically be installed.

III. Green Light Optimal Speed Advisory

GLOSA systems aim to reduce CO_2 emissions and fuel consumption based on knowledge about current and future traffic light signal phase timings. When approaching the intersection, the driver can be supported by two operation modes: speed recommendation and Time-to-Green (TTG). To this end, SPAT and MAP [4] are broadcast from a Roadside Unit (RSU) which is connected to the Traffic Light Controller (TLC). SPATs contain information on traffic light status as well as current and next phase timings for each lane of the intersection, whereas MAPs inform about the intersection topology. At least one message of each type (from the same intersection) is needed for the GLOSA application to compute a speed advice or TTG, when possible. This computation is done on the on-board unit of the car as it depends on the vehicle's position, its speed and on its planned route. Our GLOSA algorithm always maintains the speed limit and no speed advice above this limit is given. More details about our GLOSA application can be found in [5].

TABLE I
Overview of test scenarios

Scenario Name	RSU Set-up	Veh_{app}	Veh_{rel}
$NoRelay$	SHB	Approaches intersection	-
2-*HopDriving*	TSB	Approaches intersection	Approaches intersection
2-*HopParked*	TSB	Approaches intersection	Parks on side of street

IV. Multi-hop Information Forwarding

Routing in a communication network is the process of transporting information from a source to a destination, which usually involves intermediate nodes to relay data packets. In VANETs, many applications do not require information to be forwarded outside of the communication range of the sender, meaning transmissions are usually Single Hop Broadcast (SHB) and only intermediate neighbors will receive packets. For packets that need to be transmitted beyond the communication range of the sender, multi-hop relaying can be applied where intermediate nodes or relays forward the packet until it reaches its destination.

Topology Scoped Broadcast (TSB) was one of the first forwarding schemes to be developed. It addresses all nodes that can be reached with at most n hops and hence provides control over the dissemination distance in terms of hops. The GeoNetworking protocol with previously mentioned communication mechanisms is mainly standardized in [12]. For the sake of simplicity, we only consider SHB and TSB for disseminating SPAT and MAP in our field experiment.

V. Experimental Set-up

The objective of our real-world test is the technical evaluation of multi-hop information dissemination and its effects on GLOSA systems by means of information distance and Message Delivery Ratio (MDR) for continuous reception of messages. For this purpose we compare an SHB system with a 2-hop relaying setup as we expect the best cost-value ratio based on 2-hop capabilities according to findings in [9]. We introduce three test scenarios, which are summarized in Table I and involve the following communication nodes:

- RSU: is directly located at the stop line of the intersection and either transmits traffic light and intersection topology information in SHB or TSB (with n = 2 hops).
- Relaying vehicle (Veh_{rel}): forwards received packets in scenarios, where multi-hop is active.
- Approaching vehicle (Veh_{app}): destination of relayed packets and measurement node for technical evaluation.

As we want to create many realistic intersection approaches the velocity of the approaching vehicle is similar to velocities in dense and free flow traffic in urban areas where GLOSA systems usually are deployed. Thus, it varies between 25 km/h and 50 km/h in our tests. Moreover, we assume two different roles for the relaying vehicle. In scenario 2-*HopDriving* with activated multi-hop communication, the relaying vehicle also

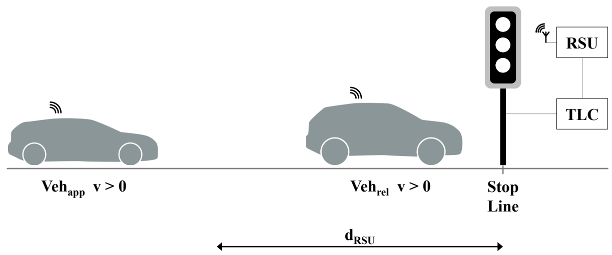


Fig. 1. Test scenario 2-*HopDriving*

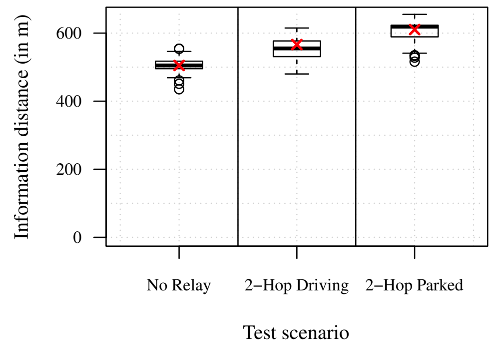


Fig. 2. Information distance for all test scenarios. The boxes reach from the 25% to the 75% quantile while the whiskers extend to 1.5 times interquartile range. The bold line marks the median, the red cross shows the mean.

approaches the intersection. It is located between the approaching vehicle and the RSU. In scenario 2-*HopParked* the relaying vehicle is parked. Parked vehicles as relaying nodes have been shown to be a promising approach to improve traffic safety at intersections [13].

Figure 1 depicts example positions of communication nodes for scenario 2-*HopDriving*. At the beginning of each approach, both vehicles are positioned outside the communication range d_{RSU} of the RSU, and Veh_{app} is within communication range of Veh_{rel}. Continuing the approach of both vehicles, Veh_{rel} enters d_{RSU} and information forwarding begins as soon as Veh_{rel} receives a packet from the traffic light RSU. As modification for scenario 2-*HopParked*, Veh_{rel} is parked 145m away from the RSU and within d_{RSU} on the opposite side of the road to forward received packets from the RSU.

In order to evaluate multi-hop communication in real-world tests, we deployed our GLOSA system on a straight 900m long test track near Ingolstadt, Germany. It represents an example part of the road network as various intersection layouts exist in urban areas. We carried out our experiment under controlled testing conditions over several days. All nodes were equipped with IEEE 802.11p communication devices. Their test set-up is shown in Tables II and III. To realize multi-hop communication, we configured the number of hops for TSB to n=2.

VI. Data Analysis and Results

For the impact evaluation of multi-hop information propagation in GLOSA systems we chose relevant metrics which we introduced in [5]. This selected subset helps to analyze and quantify communication performance and range.

We define the distance between stop line and approaching vehicle at the point in time when a first activation of the GLOSA application was shown on the Human-Machine Interface (HMI) during an approach as the information distance d_{info} (requiring the reception of both one SPAT and MAP). This could either be at the point in time of the first speed advice or TTG display. Furthermore, we compute the Message Delivery Ratio (MDR) during an approach and within a certain time period. This is defined as the number of successfully received messages by Veh_{app} divided by the number of messages transmitted by the RSU. This metric allows to analyze message reception during an intersection approach and helps to compare how communication performance changes when multi-hop mechanisms are enabled.

In our experiment we conducted a total of 194 intersection approaches, almost equally distributed across all test scenarios, which generated more than 61000 successful message receptions at the approaching vehicle. We plot the comparison between these scenarios in terms of information distance in Figure 2. The maximum information distance of 554m in scenario *No Relay* rises to 746m in scenario 2-*HopDriving* and 748m in scenario 2-*HopParked*. Thus, measurements show an increase in maximum information distance of around 35% when applying TSB instead of SHB, which is beneficial for GLOSA due to an earlier activation of the application during an approach. Investigating the role of the relaying vehicle, we observe better results when the vehicle is parked on the side of the road (scenario 2-*HopParked*) compared to driving in traffic ahead (scenario 2-*HopDriving*), which results mainly due to the varying distance between both vehicles in scenario 2-*HopDriving* and other vehicles in-between.

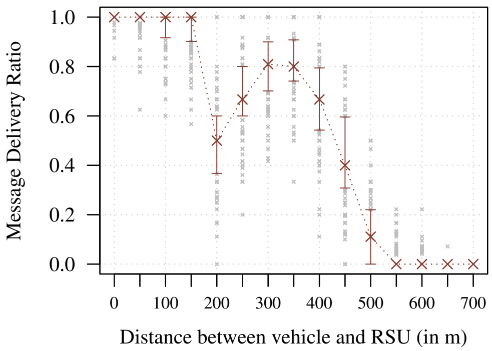
Examining the Message Delivery Ratio (Figure 3) we can also see the extended communication range in cases of multi-hop information forwarding. Using only SHB, we observe signal attenuation due to obstacles (e.g. trees and other vehicles) and self-cancelling reflections caused by 2-ray ground path loss between RSU and Veh_{app}, leading to a considerable drop in MDR at around 200m to the RSU (see Figure 3a). In a

TABLE II
OVERVIEW OF VEHICLE TEST SET-UP

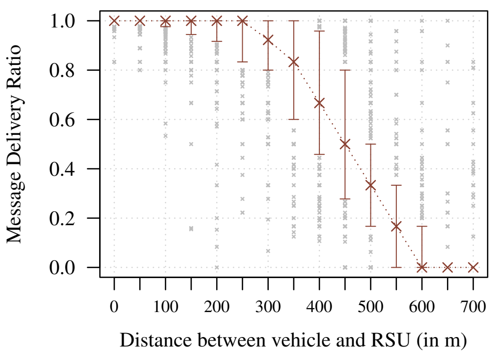
	Veh_{app}	Veh_{rel}
Vehicle type	Audi A6 Avant	Audi Q7
Communication unit	Denso WSU	NEC Linkbird
Roof antenna type	Integrated, Omnidirectional	Retrofitted, Omnidirectional
Transmission power	10dBm	10dBm

TABLE III
OVERVIEW OF RSU TEST SET-UP

Communication unit	Denso WSU
Antenna type	Omnidirectional
Antenna mounting height	3m
Transmission power	10dBm
MAP, SPAT Tx frequency	1Hz, 4Hz



(a) Single Hop Broadcast (SHB)



(b) 2-*HopDriving* and 2-*HopParked* using TSB

Fig. 3. Combined MDR of MAP and SPAT across all approaches. Plotted is the median MDR depending on the distance to the traffic light RSU. Error bars extend from the 25% to the 75% quantiles.

real-world GLOSA installment this is problematic as dynamic traffic lights could still change their signal phases and other vehicles in front could also affect the speed recommendation as the queue length has to be taken into account. This issue completely vanishes once 2-hop forwarding is enabled (Figure 3b), as the relaying vehicle, be it a parked or a driving one, could successfully establish a Line-of-Sight (LOS) communication with both the approaching vehicle and the traffic light RSU. Our results show that in order to reach information distances as assumed in many simulation studies, a multi-hop setup is required to bridge communication gaps caused by foliage, architecture, self-cancelling, other vehicles or even antenna characteristics [14].

VII. Conclusion and Future Work

We investigated multi-hop communication for GLOSA systems in an extensive real-world experiment and identified benefits in terms of extended information distance and improved communication coverage for a two-hop scenario. Single hop broadcast suffers from signal attenuation caused by foliage, architecture or other vehicles blocking the line-of-sight. This is often disregarded when investigating GLOSA systems by means of simulation. In order to achieve information distances and update intervals required for the successful and effective operation of GLOSA we suggest applying multi-hop mechanisms, ideally using parked cars.

Future work deals with the investigation of high density scenarios with more communication nodes, impacts on channel load and end-to-end latency as well as a comparison of different GeoNetworking mechanisms for GLOSA systems based on simulations.

Acknowledgment

We would like to thank the European Commission for co-funding 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.

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