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Designing a C-ITS Communication Infrastructure for Traffic Signal Priority of Public Transport

Thomas Otto [1,*], Ina Partzsch [1], Jörg Holfeld [1], Michael Klöppel-Gersdorf [1] and Victor Ivanitzki [2]

[1] Fraunhofer Institute for Transportation and Infrastructure Systems IVI, 01069 Dresden, Germany; ina.partzsch@ivi.fraunhofer.de (I.P.); joerg.holfeld@ivi.fraunhofer.de (J.H.); michael.kloeppel-gersdorf@ivi.fraunhofer.de (M.K.-G.)

[2] Benz + Walter GmbH, 65185 Wiesbaden, Germany; victor.ivanitzki@benz-walter.de

* Correspondence: thomas.otto@ivi.fraunhofer.de

Abstract: Looking ahead: transforming conventional public transport prioritization into C-ITS G5 services. The city of Frankfurt aims to digitize its public transport prioritization system in order to fulfill the requirements of future public transport communication standards and, moreover, to build on this very infrastructure for the development of imminent C-ITS services. Therefore, the communication systems of the mobility and transport provider VGF (Verkehrsgesellschaft Frankfurt am Main mbH) are being revised fundamentally by implementing new technologies for Car2X C-ITS G5 communication. The hardware components of the C-ITS system are strategically positioned with the help of a newly developed planning tool that identifies and determines the range of communication. For highly significant sites and locations of the hardware components, the calculated data are validated by utilizing measurements within a mobile setup. The operational stability and the development of previously unused potential are then carried out via the combination of the C-ITS services TSP (Traffic Signal Priority) and GLOSA (Green Light Optimized Speed Advisory). The overlay of the C-ITS services results in a high level of operational stability. As a result, potentials can be adequately employed through the sensible shifting of waiting times to the stops and a smooth flow of traffic through information on optimal speed and remaining times of the traffic light potentials. This paper presents a new methodology with which it is now possible to plan and evaluate C-ITS with regard to service distribution and radio propagation.

Keywords: public transport; C-ITS; GLOSA; TSP; roadmap

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1. Introduction

1.1. Status Quo

In May of 1980, the VÖV publication 04.05.01 "Technical requirements for computer-operated control systems—data radio transmission method" was published in Germany, and it helped define the transmission method for analog data radio prioritization of public transportation, which, at the time, was still the most common method for traffic light prioritization. This VÖV document not only described the radio interface but also contained information on the data content. The data telegrams of the R09 family, which are relevant for controlling traffic lights, were specified in 1990 alongside the VÖV publication 04.05.1/supplement 2.

The most common and widely used method for vehicle prioritization in Germany, Austria, and Switzerland is the so-called reporting point principle. This method includes a registration process in which public transport vehicles are logged and registered with the traffic light signaling system via pre-registration (optional) in the traffic signal system, followed by a main registration, a door closing criterion (also optional), and, finally, a deregistration using R09.xx telegrams. Furthermore, beacon radio systems or satellite-supported GNSSs (Global Navigation Satellite Systems) are typically used for locating vehicles [1].

1.2. Motivation

For some time now, the state of connected, cooperative, and intelligent transport systems (C-ITSs) has evolved, as the process through which these systems are developed shifted from theoretical research to practical testing until they were ready for area-wide deployment. As of today, the ITS is ready for the market and is gradually being rolled out in vehicles from well-known automobile manufacturers. The basic idea of an interaction between infrastructure components, such as the traffic light system (TL) and the vehicle, including the driver, is the continuous exchange of data and information in order to improve the quality of traffic flow and ultimately increase traffic safety. Due to the high potential that can be reached through cooperation, collaboration, and digitization, quite a few C-ITS services are currently being implemented, including their new characteristics for optimizing traffic control.

The most common ITS service, TSP (Traffic Signal Priority), is currently the focus of international attention. This benefits all road users and traffic participants but is primarily intended to increase the effectiveness of public transport, e.g., in North America [2], Europe [3,4], and Asia [5]. Initially, the process of prioritization was individually examined. Today, the service is viewed as an integral part of mobility solutions. The full cycle/approach of cooperative services is realized by SRM messages, which are used to send data from vehicles to the infrastructure (V2I). To complete the communication cycle, the infrastructure then sends a response back to the vehicles using SSM messages. From this point on, the original ITS application becomes a C-ITS service. The optimization of traffic can subsequently be solved by the cooperation and adaptation of the TL control on the one hand and influencing the behavior of the vehicles, drivers, pedestrians, etc., on the other hand.

In order to leverage all the potentials of C-ITS, new control mechanisms are necessary; these differ fundamentally from current procedures, for example, with regard to the ways in which local public transport is prioritized. In the near future, within the next few years, the predominantly widespread method of analog, mostly R09.xx data telegrams, will have to be replaced. The paradigm shift from today's static reporting procedure to linear recording using standardized C-ITS messages opens up completely new perspectives that must be taken into account, especially when considering the need to conform with regulatory bodies.

The singular transmission of a vehicle's position via the registration points has reached its limits in terms of its capabilities, especially in the case of inconsistent traffic flow, such as traffic jams on individual access roads and intersections. In the future, linear and dynamic detection of vehicles entering a traffic light system via C-ITS will offer a significant improvement in potential.

Even though analog radio frequencies for voice radio will no longer be awarded/granted from 2028 onward, the influence of the VDV (Verband Deutscher Verkehrsunternehmen, Association of German Transport Companies) on the German Federal Network Center has ensured that large parts of the analog radio frequencies for the prioritization of public transport can be retained until 2038. However, this requires a remapping of the 20 kHz frequency to a 12.5/25 kHz frequency from 2028 on. This form of remapping is currently possible with newer radio modules via a software update, yet the older devices may need to be replaced completely [6]. The VDV, however, has not yet received further assurance from the Federal Network Agency that the analog radio frequencies will be retained after 2038.

Due to this technological shift, transportation and mobility providers as well as local authorities are currently working on replacing their procedures for the vehicle registration points, which have existed for 30 years, since C-ITS enables a new way of vehicle prioritization, specifically for public transportation. As this development is based on a continued exchange of messages between vehicles and the metropolitan infrastructure instead of merely triggering at pre-defined locations, the radio coverage of C-ITS must be precisely planned, measured, and verified. Hence, the purpose of this paper is, on the one hand, to demonstrate a method to carry out planning and measurement. The system was calibrated with praxis data, the results were then compared with factual measurements, and ultimately, these results and algorithms were validated. On the other hand, C-ITS services demonstrate how they can be combined in order to benefit from the maximum traffic potential in terms of efficiency, safety, and effectiveness.

2. Materials

2.1. C-ITS Services for Public Transport

Among current C-ITS features and upcoming C-ITS services in the near future, the most useful services within the field of public transportation are "Traffic Signal Priority" (TSP) and "Green Light Optimized Speed Advisory" (GLOSA). A comprehensive literature review of the international research conducted on the C-ITS service GLOSA can be found in [7]. At this point in time, the research clearly indicates that there are no imminent plans for a roll-out, despite the fact that the service has already been scientifically examined in a wide variety of studies and evaluated accordingly in interaction with adaptive controls [8–11]. These insights bring forth the novelty of this paper.

Traffic Signal Priority is a system that allows public transport, emergency vehicles, and other authorized vehicles to receive prioritized treatment at traffic signals. In the future, several priority levels will be implemented when using C-ITS. When an authorized vehicle approaches a traffic light, the TSP system detects its presence and adjusts the signal timing to provide a green light for the authorized vehicle, or it reduces the waiting time, allowing the vehicle to pass through the intersection faster and more safely. TSP can also help improve the efficiency and reliability of public transport services, reduce response times for emergency vehicles, and enhance overall traffic flow in urban areas [12].

The TSP system conclusively raises the efficiency of traffic lights under certain traffic conditions in which the optimization of green light phases is possible, thus resulting in an undersaturated traffic system. In circumstances in which a traffic light cannot be optimized freely, the Green Light Optimized Speed Advisory provides another possible option. This system makes use of vehicle-to-infrastructure (V2I) communication in order to provide drivers with speed recommendations that are optimized to help them pass through a series of traffic lights without stopping. GLOSA also utilizes real-time data on the timing of traffic lights combined with information on the speed and location of individual vehicles in order to calculate the optimal speed advisory for each vehicle approaching their next traffic light. In general, GLOSA aims to reduce fuel consumption and emissions while improving traffic flow and safety by providing drivers with the previously described data and information. The remnant availability of the saved travel time for public transport can subsequently be used for passenger stops and passenger changeovers [13,14]. GLOSA can generally be recommended from an economic point of view under certain constraints, e.g., the complexity of the junction itself [15].

The European project C-ROADS deploys different C-ITS services all over the European continent and is responsible for the harmonization of these services [16,17].

2.2. Area of Study: Underground Railway Section U5

The scope and the investigated area of interest for C-ITS G5 piloting is the aboveground section of the underground railway, i.e., the U5. This specific test site starts at the most southern stop, "Konstablerwache", where the intersection of "Eschenheimer Anlage/Eckenheimer Landstraße" and the tunnel entrance/exit is located. The investigated area then continues north until the last stop and terminal destination of the U5, the stop "Preungesheim".

The total distance between the starting point and endpoint of the U5 area of study is approximately 5.1 km, of which approximately 0.5 km is located within the tunnel and 1.2 km is located on the surface roads, where the track merges with other forms of traffic. The remainder of the selected route has its own railroad tracks with level crossings at intersections. There are currently eleven stops in total along the entire route, and nine of these stops are heavily frequented intersections for the aboveground section of the U5. In addition, there are four intersections at which a higher frequency of emergency vehicles can be expected to cross.

In terms of investigative studies of the U5 and in regard to public transport prioritization, all intersections with traffic lights along the test route have been fully examined. It should be duly noted that an intersection with traffic lights may consist of several nodes and/or sub-nodes with corresponding individual signalization. Therefore, the registration chains were evaluated for the location of the individual registration points for all traffic lights. Here, the log files of the onboard computer data, which belong to the Automatic Vehicle Monitoring (AVM) System of Frankfurt's public transport provider VGF (Stadtwerke Verkehrsgesellschaft Frankfurt am Main mbH, Frankfurt am Main, Germany), were used.

All traffic lights on the U5 are in mutual communication with the traffic control center. Here, adaptive decisions are made as to which signaling program is applied/enforced/rendered. The logic of the local control systems for the intersections uses a form of detection when deciding whether individual signal groups in the frame should be adapted locally. There is no direct communication between the signalized intersections, e.g., for the exchange of signal plans or current information status.

2.3. Objectives and Challenges

The goal of the examination, analysis, and evaluation was to clarify and answer the following questions and use cases in order to provide a future-oriented conceptualization of public transport acceleration:

- Which method can be used to determine the communication ranges that are necessary to send the minimum requirements of all currently defined registration points with C-ITS G5? (See Section 3.1).
- On which sections of the U5 track are public transport vehicles able to reduce delays? When exactly does this happen? (See Section 3.2).
- Which algorithm can be used to determine the C-ITS service that best suits the current state of traffic? (See Section 4).

2.4. Novelty and Innovation

Although many of the aspects of the GLOSA and TSP services have already been extensively considered both scientifically and technically over the past 10 years or so, there have still not been any widespread implementation efforts. This is due to several reasons, and this is where the novelty of this paper begins. The following list represents the main aspects and innovations that were examined:

- Range anxiety: The range anxiety studies were mostly theoretical. However, theoretical investigation is only one aspect. The novelty here is that these investigations took place theoretically and practically and were matched to suit the target system.
- The propagation models for radio communications in planning tools must be adapted to the G5 standard. This is often not considered or not sufficiently considered in the current tooling. Here, a new tool that permanently adjusts itself on the basis of the collected data is shown.
- So far, the C-ITS services have been described and evaluated individually. However, in interactions, much greater potential can be tapped. This aspect was thoroughly considered for the first time.

3. Methodology and Results

3.1. Communication Range

3.1.1. Facts and Background Information

Due to the different ranges of frequency and the resulting differential of physical properties, communication via C-ITS G5 (approx. 5.9 GHz) [18–20] has lower communication ranges compared with analog radio in the 2 m bandwidth [21]. As a result, the first question that needs to be answered when transitioning from the status quo to C-ITS is the determination of which communication range is necessary to send in the form of minimum requirements, as all registration points are defined by C-ITS today.

In general, it must be ensured that the vehicles are able to send the corresponding registration points to the traffic light control module. To comprehensively answer the question of the necessary and available ranges, radio propagation planning needed to take place on the one hand, and radio measurements were needed on the other hand; these were both carried out at all nodes along the U5 area of study.

For radio propagation planning via C-ITS G5, a methodology based on the research results of [22] was used. With the help of a newly developed communication planning tool, the radio propagation was estimated for all traffic light-controlled intersections in the U5 area of study outside the tunnel. Next, a check was performed to determine whether all registration points that were being used for public transport prioritization within the network and that would be replaced by linear detection in the future [6] were also in the communication range of the new C-ITS G5 radio technology. This ensures that public transport prioritization will be able to work in the future. As a result of the linear detection of the public transport vehicles and the transition from the registration point method to linear influence using the estimated time of arrival object, the combination of the C-ITS services TSP and GLOSA will result in highly noticeable improvements for public transport prioritization and operational stability.

3.1.2. Method of Evaluation

- Step 1: Extraction of registration points. In the first step, the registration points for each traffic light were extracted from the entire route of the U5 area of study. For this purpose, the log files of the AVM onboard computer of the public transport provider VGF were evaluated.
- Step 2: Localization of the registration points. The registration points were located on the basis of the determined GNSS positions from the onboard computer system of the VGF AVM. To compensate for the positioning errors in the GNSS system, the arithmetic average values of all messages sent from a vehicle were estimated and used.
- Step 3: Positioning the Roadside Unit (RSU). The positioning of the RSU was based on on-site inspections. The positioning was carried out carefully, considering the cable feed from the signal control module to the RSU, which must not exceed 100 m due to the usage of PoE (Power over Ethernet), a common method of powering RSUs.
- Step 4: Radio propagation planning. Based on the positions of the registration points, the C-ITS G5 radio propagation planning tool was used. The results were displayed as radio levels on a color scale from dark red to light yellow. The brighter an area, the better the communication performance. It can be assumed that sufficient radio coverage is guaranteed in all red and yellow areas for the transmission of the registration points to the traffic lights. The presentation of the radio propagation tool results on the one hand and the localization of the registration points on the other hand clearly show, on a visual basis, whether the registration points are within the communication range or outside the communication range.
- Step 5: Radio measurement. The radio propagation planning tool works on the basis of learned and referenced data sets. It must always be ensured that the radio propagation is modeled sufficiently and precisely. Therefore, if there are registration points on the border regions for the radio propagation shown, they must be validated with real measurements. For the radio measurement, however, only the driving relation of the U5 was recorded. Tests showed (compare Figure 1) that the results from the radio propagation planning tool matched the radio measurements. This means that the communication ranges can also be validated and estimated at locations that are not actually measured on the basis of the results of the radio propagation planning tool.

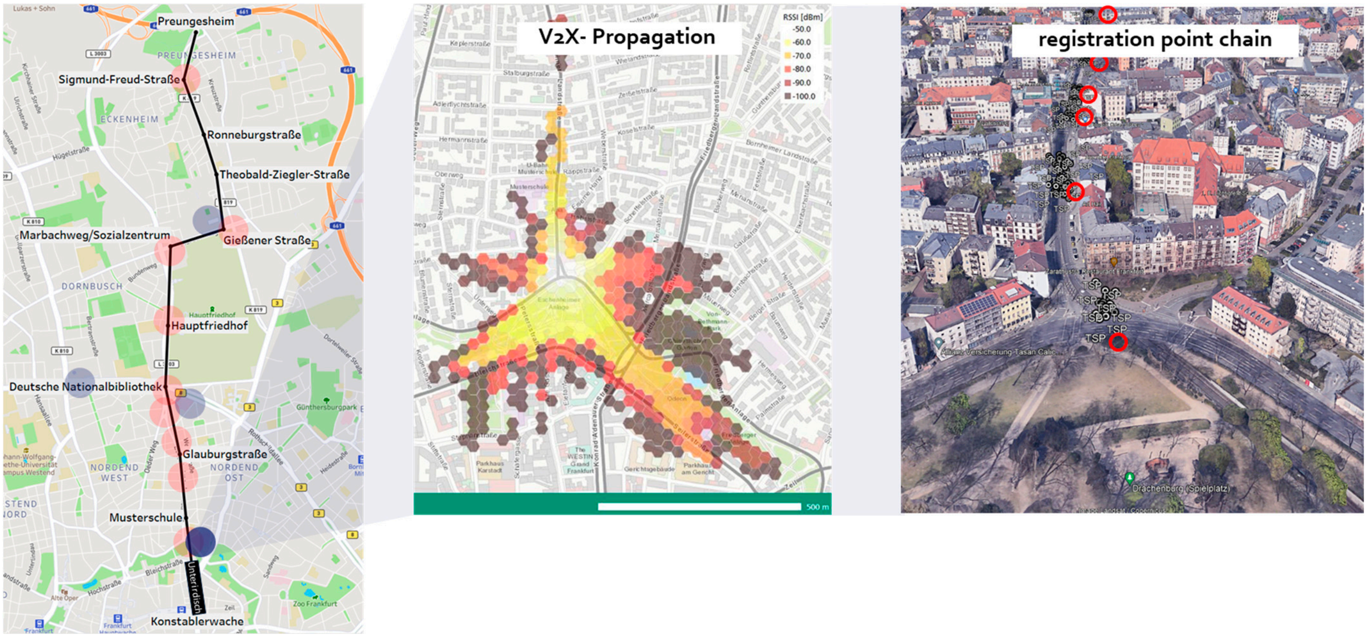

Figure 1. From left to right: U5 railway section with intersections; calculated communication ranges for C-ITS G5 in the area of study, U5 at intersection "Eckenheimer Landstr./Eschenheimer Anlage"; registration point chain shown as red circle for this intersection.

3.1.3. Tools and Results

As described above, the communication ranges were evaluated in two ways:

1. Simulation of radio propagation via our radio propagation planning tool;
2. On-site radio measurement.

From a scientific standpoint, it is quite interesting to consider the singular use of only one of these tools; however, for practical implementation, both tools were combined and considered integrally. This scientific approach, i.e., the combination of both tools, is a new approach, on which this paper builds. The combination and fusion of these results for both tools are needed for an optimal result in the course of the deployment. Likewise, the measured data are directly fed back into the planning tool for further evaluation and calibration of the tool itself.

The following paragraph includes a more in-depth and detailed description of both methods.

Radio propagation planning tool for C-ITS G5.

The radio coverage was estimated using the radio propagation planning tool. The analysis was based on a trained model of C-ITS G5-based propagation measurements.

Thus, potential RSU locations were selected for the estimation of the radio coverage on existing intersections. On the basis of the location of the registration points, their accessibility when using C-ITS G5 was predicted. The representations of the radio propagation planning of the individual RSU locations took place along the entire corridor of railway section U5. For example, the traffic light at the intersection "Eckenheimer Landstr./Eschenheimer Anlage" is shown in Figure 1. The map on the left depicts the locations of the intersections on the entire route. The middle figure depicts the results of the radio propagation planning tool. The image on the right visualizes the location of the registration points.

Radio measurement and evaluation.

The radio propagation planning tool works on the basis of learned and referenced data sets. Therefore, reception within critical areas needed to be validated by measurements. A mobile setup of a C-ITS G5-based RSU was developed by Fraunhofer IVI for validation. It consisted of a tripod, which could lift the RSU to a height of approx. 4 m, and a mobile power supply. Moreover, a C-ITS G5-based Onboard Unit (OBU) was used in a test vehicle to carry out the V2I-communication measurements. Both components successfully sent and received messages that were transferred to a backend via mobile communications and stored in a separate database. Since the assembly height of the productive RSU as well as the antenna of the OBU on the vehicles of the VGF are higher, it can be assumed that the results of the present measurements currently underestimate the communication ranges that can actually be achieved.

Result 1:

From a scientific standpoint, it is quite interesting to consider the singular use of only one of these tools; however, for practical implementation, both tools were combined and considered integrally. Both tools complement each other seamlessly. The data from the radio measurement and evaluation can thus permanently flow back into the planning tool for calibration. This is especially important for data sets in which new areas are being developed.

3.1.4. Comparison of Radio Propagation Planning and Radio Measurement

The comparison of the radio propagation planning with the radio measurement brought forth two major findings: the validation of the planning tool and the specific evaluation of neuralgic points of interest. The image below, Figure 2, compares the radio propagation planning with real radio measurements using the example of the intersection "Eckenheimer Landstr./Eschenheimer Anlage". The levels that were assessed during a measurement around this RSU location can be found on the left side, while the prediction results (radio propagation planning) are shown over a larger area on the right side. The gray dashed line serves as a comparison axis between both views, highlighting the RSU location.

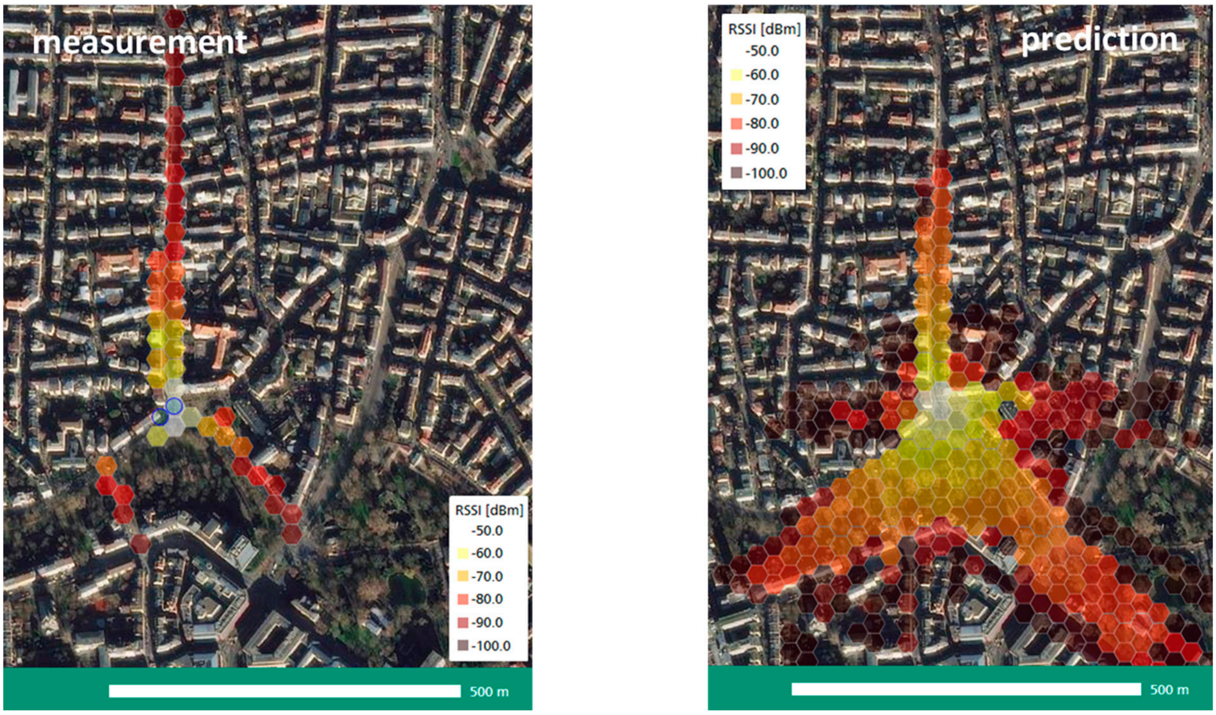

Figure 2. Comparison of the measurement results with prediction results from a selected location (code ELS) for radio coverage, taking into account the buildings. Please note that the measurements on the left side were obtained while driving on the road.

In the second step, the reporting points assigned to the route and the traffic lights were added as an additional display layer. At this point, the task consisted of identifying neuralgic points of interest, thus clarifying the question of where the registration points were and which reports no longer reached the assigned traffic light in terms of technological communication ability. To estimate the radio accessibility at the registration points, the calculated reception values were examined by radio measurements at intersections where the radio propagation planning tool outputs critical accessibility. This is shown as an example in Figure 3.

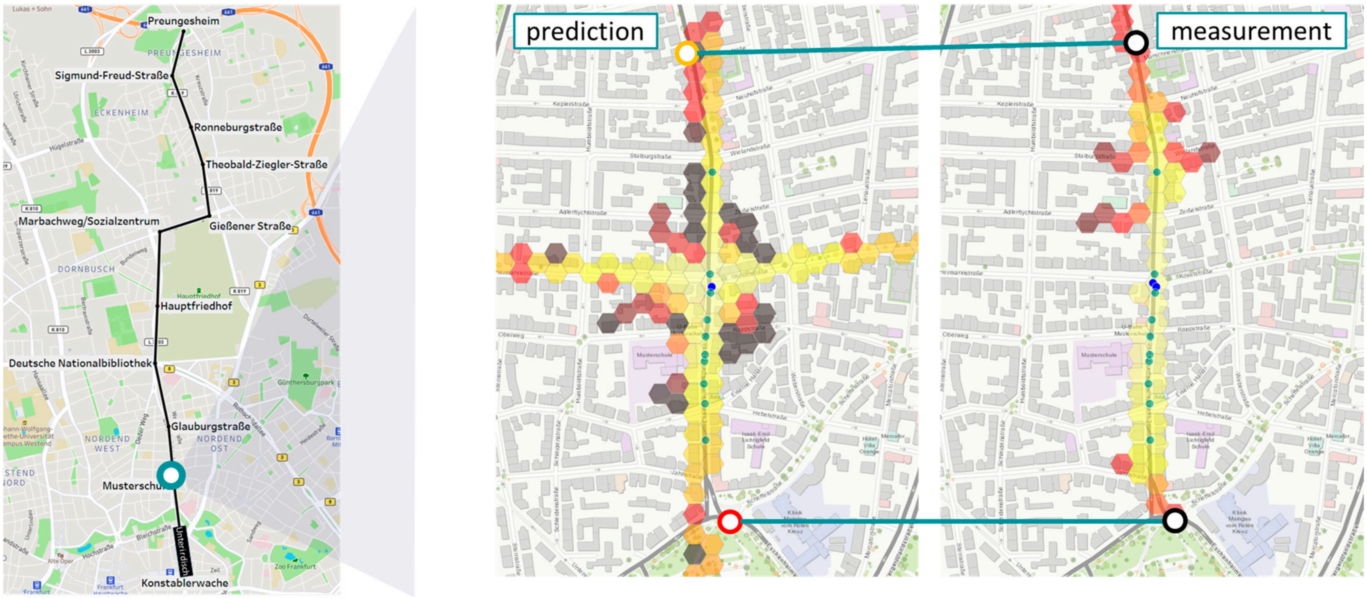

Figure 3. Communication ranges: scenario in the planning tool and comparison of real measurements.

The tool for radio propagation planning determined rather poor radio coverage for both the pre-registration points in the inbound direction and the pre-registration points in the outbound direction. However, the real measurements showed that these areas were not critical and that there was corresponding coverage. These so-called RSSI (received signal strength indicator) values can be seen as color-coded hexagons. The lighter the color value, the better the reception conditions. If there is no hexagon shown, there are no values because they were not measured or estimated. In the first case, no values could be received, or the measuring position was not sought. In the latter case, the values were not determined because they were outside the range or because of architectural shadowing caused by buildings around the site of testing.

Result 2:

From the combination of both tools, coverage with C-ITS cooperation could be demonstrated. On the one hand, the combined approach always provides new scientific knowledge, and on the other hand, it enables a much more time-saving evaluation compared with the conventional singular approach.

3.1.5. Comparison and Results

All intersections along the U5 track were examined using the radio propagation planning tool and, in critical cases, they were also examined by radio measurements. An evaluation of the signal strengths took place, including an evaluation of the communication ranges. Further radio measurements for verification were carried out at nodes where, according to the radio propagation planning tool, registrations points were not located or where they were only very close to the communication area. Additional validation of the radio propagation planning tool was carried out at other intersections. Thus, there were data sets for calibration as well as data sets for tool validation.

In the concluding discussion, the entire state of radio propagation on the U5 was considered. The estimation by the radio propagation planning tool is shown on the left (prediction) in Figure 4. The tool calculated the complete environment of each RSU and, by contrast, measured each section for both graphs with identical color coding, providing a visual comparison of the two areas. In addition, it should be noted that the network of measured RSUs contained fewer transmitters/receivers than previously considered since only borderline cases should be secured in the reporting points. Nevertheless, the consistently high availability of radio coverage can be observed along the U5 corridor as yellow to orange hexagons. The coloring was based on the maximum determined level of the hexagonal zone, so in the case of two RSUs, the stronger RSU was taken into account. It is possible that the better-received RSU is not the one with the smallest distance. For this reason, the individual results for each RSU location were previously tabulated. Figure 4 shows the radio coverage of the route in this section, resulting from the radio propagation planning tool on the one hand and the on-site radio measurements on the other.

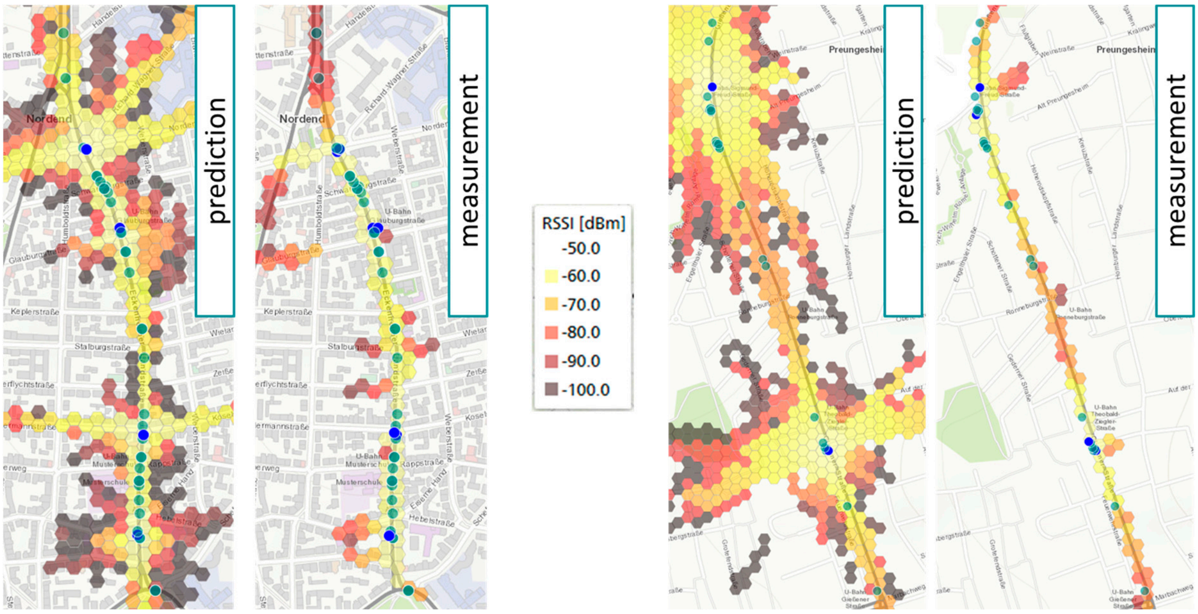

Figure 4. Comparison of the radio propagation based on the estimate (**left**) and the measurements (**right**) in the southern section of the U5 route.

Result 3:

In summary, the traffic light locations were initially used to determine the RSU locations. In a further step, the registration points were located, and an overall picture of the radio coverage was created. No registration points outside of radio coverage were identified, nor were any that could only be served via RSU-hopping. Nevertheless, hopping is a possible method and thus a helpful redundancy at cell boundaries of C-ITS G5 coverage. The C-ITS service TSP can thus be implemented with the current response times of the traffic lights without having to make any adjustments to the controllers in the first step.

3.2. Capacity and Delays on the Pilot Underground Railway Section U5

The analysis and evaluation of how and whether delays in the aboveground section of the U5 increased or decreased is an essential and fundamental basis for evaluating the acceleration of public transport vehicles and local rail transportation in the current state. On the basis of this information and procedure, the existing potential can be estimated and developed using the new concept.

The evaluation of the delays was time-differentiated with regard to the following criteria:

- Mean day of the week from Tuesday to Thursday;
- A mean over typical Saturdays;

- A mean over typical Sundays.

Furthermore, the evaluations were carried out for all trips/voyages that took place on the specified days on the basis of data records of the onboard computers of the VGF AVM system. For further chronological differentiation, the data records were evaluated in hourly slices.

Result 4:

The "outgoing" evaluation provided factual evidence that vehicles were already leaving the tunnel with delays. It was also shown that, on average, delays built up for vehicles, especially in the first section of the U5. Even on route and confined to its own tracks, a slight reduction in delays was possible, but this did not compensate for the losses resulting from the first section. The trips on the evaluated Saturdays and Sundays showed similar behavior. It is necessary to note that the delays for vehicles exiting the tunnel were much lower on Saturdays than on weekdays. On Sundays, for example, the trains left the tunnel with almost no delays and on time, and then they built up slight delays, especially in the first section.

The "incoming" evaluation showed that almost all vehicles started without delay. This means that the buffer times within the turning facilities were adequate, and it was a rare occurrence that a vehicle carried over a delay from the previous round, bringing it into the current trip. Subsequently, it was observed that the delays built up. The trips on the evaluated Saturdays and Sundays showed similar behavioral integrity, i.e., a rough punctual start at the turning facility and a gradual build-up of delay.

4. Discussion

The overall potential of the C-ITS services is derived from an intelligent combination of the individual services TSP and GLOSA. Below is a brief description of how the C-ITS services work, assuming that U5 receives 100% prioritization for public transport vehicles. This case is only given if the boundary conditions, which are defined by other traffic flows, are low. Figure 5 shows this optimal case for the TSP service.

(a) (b) (c)

Figure 5. Representation of C-ITS service TSP with full prioritization: (**a**) direction south–north with TSP at both intersections; (**b**) direction north–south with TSP at both intersections; (**c**) both directions.

No matter where the vehicles are located and when—i.e., completely independent of their location—prioritization takes place. The drivers are thus not informed about the optimal speed or optimal stop time. As soon as the passenger exchange is complete, the traction unit approaches an intersection at its target speed and receives a clearance signal.

As previously described, this reflects the optimal scenario and optimal business case. This is not possible everywhere, especially in cases of dense traffic and other traffic conditions or even political framework conditions. Examples include the prioritization of pedestrians and cyclists or the prioritization of other conflicting public transport vehicles. In this case, it makes sense to overlay the C-ITS services TSP and GLOSA to enable optimal traffic flow within the overall public transport acceleration concept (see Figure 6).

(**a**) (**b**) (**c**)

Figure 6. Representation of the combination of C-ITS services TSP and GLOSA: (**a**) direction south–north with GLOSA at first intersection and TSP at second intersection; (**b**) direction north–south with TSP at first intersection and GLOSA at second intersection; (**c**) both directions.

Figure 6a shows a typical trip out of town. Since the U5 trains move in the secondary direction, 100% public transport prioritization is not possible. The driver of the public transport vehicle and, in this case, the driver of a train, are now prompted with the visualization of the following information once he/she exits the tunnel:

- Stop: The information on remaining times can be used for an optimized layover at the stop, which is used for passenger changeovers.
- Route: On-route information about the optimum speed for approaching the traffic lights can be used to pass the traffic light energy efficiently when it turns green.
- Traffic lights: The information on remaining traffic light phases until the next signal change can be used for an energy-efficient approach.

It is not only rational but also sensible to take advantage of the residual time from previous stops and make use of this excess waiting time for an optimized and correspondingly longer passenger changeover. Doing so enables the vehicle/train to be fully prioritized at the next traffic light, where the driver can leave the stop as soon as the passenger changeover has occurred.

According to the options presented above, there are different possibilities for combining the C-ITS services TSP and GLOSA. All feasible combinations of services are briefly shown and explained below in Figure 7.

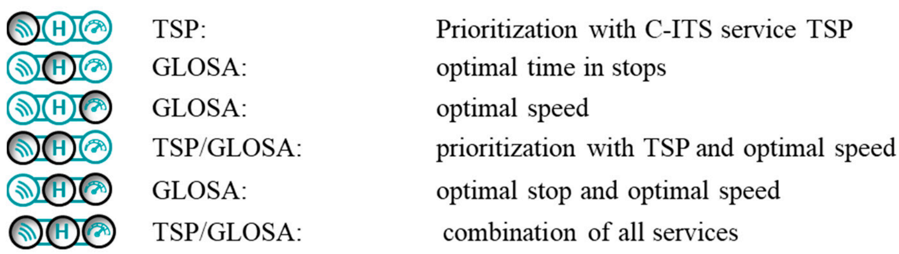

Figure 7. C-ITS services—explanation of symbols.

The consideration of cooperative services in the area of the C-ITS and the optimization of both the vehicles and the control of the infrastructure results in completely new objectives and questions. There is an extensive need for more research in this particular area. Some of the open questions that may have arisen will be addressed in the following paragraphs.

Q1: The overlapping of the services leads to impairments in the conventional detection of traffic lights, which must still be considered separately so that the potentials can be fully exploited. The question here is: how can this interaction be optimally designed in the future?

Q2: It should be noted that the quality of the forecast for the remaining time of the traffic lights and GLOSA speed recommendations has not yet been taken into account. The basis for the optimal utilization of the services and their potential is a highly accurate prediction of the state of signaling. If this is not the case, it is strongly not recommended to notify the C-ITS service, as there may be jumps in the forecast if the confidence in the forecast is low. This could have such a negative impact that vehicles, despite following all recommendations, would not arrive at the facility when the light turns green. This, in turn, would lead to a loss of trust among drivers and a low compliance rate. Even if all the information is available with the appropriate level of confidence, the proposed solution is still dependent on further boundary conditions. Depending on these factors, adjustments can be made to the concept. The question here is: how can C-ITS services be optimally adapted to the spatial and temporal circumstances?

Q3: Determining the optimal overlay of services is not possible without domain knowledge and significantly determines the effect. The question here is: how can future engineers be supported with appropriate tooling in order to obtain the optimum outcome f from the overall system?

Q4: In addition to the prioritization of public transport, the needs of other transport users, such as VRUs, are increasingly coming into focus. Adequately taking these participants into account without further increasing the complexity of the control systems will be a task for the future.

Q5: In terms of the integral view, there is a need for additional research in the distribution of intelligence for control and influence in the system. A clear separation between decisions at the traffic lights of the intersection (edge) and in the traffic management (cloud) needs to be investigated, developed, and deployed.

Q6: Resources, especially in cities, are limited. The mobility revolution requires completely new concepts here. The qualitative description of the social, traffic, and environmental effects is still open.

One should keep in mind that the aim of the roll-out is not just to deploy new technology but instead to focus on improving the conditions of the drivers, the experience of passengers, and the overall quality of service within the field of mobility.

5. Conclusions

With the gradual digitization of mobility, intelligent transport systems are becoming increasingly popular. Likewise, in an effort to standardize public transport prioritization, cooperative intelligent transport systems are being rolled out step by step in Europe and the world. The so-called C-ITS services and applications, in which the increase in efficiency and safety is based on the cooperation itself, are also on the rise across Europe and are enabling automated mobility by combining networking and cooperation/collaboration. This interaction between the participants and/or stakeholders offers additional potential that was previously unavailable, and it can be tapped into and compared to the original definition of the ITS.

For the prioritization of public transport, this means that the standard published in May 1980 is about to be superseded. As the underlying frequencies will no longer be available in the near future, the traditional methods of public transport prioritization have to gradually be replaced by new developments, e.g., C-ITS services, as described in this paper.

ITS services are essentially already being rolled out. Starting with applications such as hazard warnings on motorways, ITS services are currently being implemented on the infrastructure side in many urban areas. Here, for example, green light optimal speed advisory should be mentioned. Step by step, commercial vehicles are being equipped with the appropriate communication modules/components in order to be able to use and offer a broader spectrum of ITS services.

The basic idea of the cooperation between infrastructure—e.g., traffic lights—and vehicles consists of the mutual and continuous exchange of information, improving the quality of the traffic flow as well as increasing traffic safety. In order to be able to exploit the full potential of C-ITS, further development is needed, for example, in the field of traffic light control systems and tooling for applications in public transport.

The new control mechanisms differ fundamentally from the current procedures, for example, with regard to the way in which public transport is prioritized. The paradigm shift from today's static registration point procedure to linear and dynamic recording using standardized C-ITS messages opens up completely new perspectives that must be taken into account, as this will also provide continuous support in complying with the norms of regulatory bodies. Consequently, the standardized way of C-ITS communication and harmonization will have a Europe-wide scaling effect on the entire mobility sector. This means that the process is not only driven by transport companies in technical, regulatory, and administrative terms, but also receives support and, above all, impetus from the entire mobility industry. In the future, the entire mobility sector will benefit from the rollout of C-ITS—the networked intelligent transport systems.

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