Simulation of Telecommunication and Automotive Behavior in real time

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Abstract. Safe autonomous driving requires close coordination between vehicles. This requires a reliably high quality of communication for advanced autonomous driving scenarios. Only with the introduction of the concept of network slicing in the next generation cellular mobile radio network (5G), radio resources can be reserved exclusively for V2X communication. However, the fundamental problem of wireless communication, the high variance of the achieved quality of service, remains. Fluctuations in channel attenuation and/or utilization lead to message delays or interruption of communication. The vehicle coordination can be done implicitly by using the sensors installed in the vehicle (e.g. LIDAR, ultrasound, radar) or explicitly by wireless communication between vehicles. The paper describes a new way of coupling existing simulators for relevant aspects of autonomous driving to create a real-time simulation platform for the integrated investigation of V2X communication in realistic scenarios. In this presentation, the developed simulation setup as well as simulation results concerning mobile radio influences on autonomous driving are presented.

Keywords: Mobile Communications · Autonomous Driving · Simulation · LTE · 5G

1 Introduction and Motivation

The automotive industry is currently undergoing a phase of major change. At the same time as vehicles are increasingly equipped with electrical components more and more computer technology is finding its way into vehicles enabling substantial enhancements in driver assistance systems and automated driving functions.

Safe autonomous driving requires close coordination between vehicles. This requires a reliably high quality of service of communication for advanced scenarios of autonomous driving, which is currently not available at a broad range. The develop-

M. Bargende et al. (Hrsg.): *22. Internationales Stuttgarter Symposium*,
Proceedings, S. 165–178, 2022. https://doi.org/10.1007/978-3-658-37009-1_12

ment of mechanisms for predicting and assuring quality of service in future mobile networks in interaction with connected and autonomously operating vehicles requires comprehensive simulations.

As part of the research project SMART, founded by the Federal Ministry of Education and Research, the goal is to couple existing simulators for relevant aspects of autonomous driving to create a real-time simulation platform for the integrated investigation of V2X communication in realistic scenarios. This platform will be used to evaluate the mechanisms for negotiating and predicting the quality of service of the communication, which were developed in SMART, in terms of their benefits and feasibility.

By taking a holistic view of the different simulation domains, the addressing of research and industry-relevant problems is achieved. Challenging V2X applications, such as platooning or cross-vehicle hazard detection beyond intersections, can be simulated in a realistic environment.

The mobile radio simulation platform (MFS), developed by IKR (Institute of Communication Networks and Computer Engineering at the University of Stuttgart) takes over the simulation of the mobile radio channel characteristics, the message generation and its transmission. The simulation of realistic vehicle behavior is carried out by TWT GmbH in the simulation platform Tronis®, which also has an interface to the widely used vehicle traffic simulator SUMO (Simulation of Urban Mobility) from the German Aerospace Center (DLR). Physical vehicle models are used in Tronis®, therefore the driving behavior can be adapted by means of sensor data and speed controllers. In addition to developing the simulation platform, mechanisms to increase driving efficiency through intelligent communication will be implemented and evaluated.

Through the coupling, the sub-simulations benefit from the more realistic modelling of the scenario. For example, for the network simulation, the calculation of the radio channel can be improved by precisely taking into account vehicle movement and shadowing effects caused by buildings or other road users. Algorithms for controlling autonomous vehicles benefit from the precise calculation of latencies during communication.

For the simulation of the mobile communication we selected a discrete-event simulator that was developed at the Institute of Communication Networks and Computer Engineering (IKR) at the University of Stuttgart. It consists of an application layer that describes the network scenario and model libraries for LTE systems and the mobile radio channel. The general paradigm of this simulator is the subsequent simulation of discrete system events, independent of the required simulation duration and the specific time of occurrence. This leads to a behavior where the results of simulated events are not time-synchronized to the real time as depicted in Fig. 1. To realize a real-time capable simulation of the mobile communication, we have to speed up the simulation of the events as much as possible, such that all events that occur within a certain time period will be simulated within

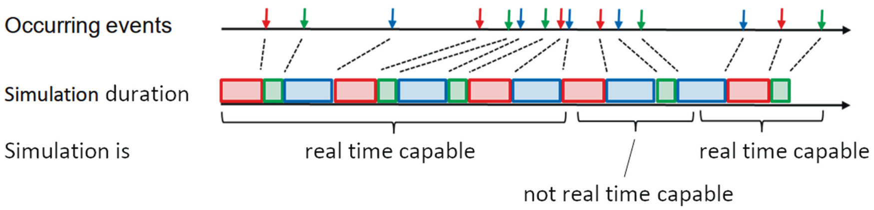


Fig. 1. A discrete-event simulation allows a time-efficient calculation. But, real-time behavior is typically not supported.

this same period which also defines the minimal synchronization interval for a combined simulation of the mobile communication and automotive behavior in real time. Both required adaptations will be part of this work.

2 Virtual Validation of Autonomous Driving Functions

Simulation of individual, multiple or connected automotive functions up to the simulation of the entire vehicle are an essential part of modern vehicle development. In order to check the functions of an autonomous vehicle, at least one visualization of the scenario is required to simulate a camera image. Additional sensor signals, such as those of a radar system, increase the simulation depth.

Tronis® offers a platform for virtual validation and prototypical development of autonomous vehicle functions. With this environment, various modules for localization and automatic map generation were prototypically implemented and evaluated. For this purpose, a 3D world with a motorway, city, country road and village was developed in the Unreal Engine.

2.1 Photorealistic Visualization

A virtual world that mimics the real environment very accurately and precisely allows test engineers to create test scenarios, execute these test cases and cover the most critical test cases to validate the safety of the vehicles. Such a simulation environment also makes it possible to increase test coverage by training the data through slight modifications to the environment.

For a realistic representation of road environments (see Fig. 2), the individual modular roads were modelled from scratch. In the process, the roads were adapted according to a German specification. The road set includes modular straight lines, T- and X-intersections, each with different extensions such as pavements or tree islands.

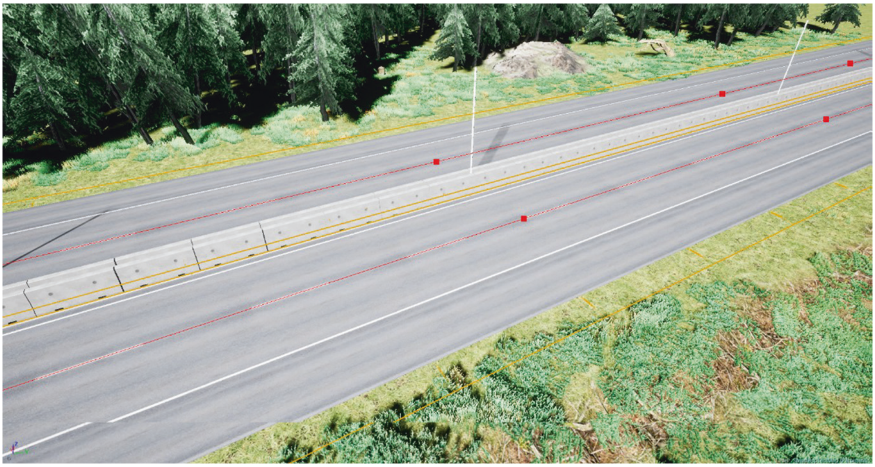


Fig. 2. Realistically modelled highway in Tronis®

2.2 Use Cases for Automotive Driving

Platooning. In platooning, several vehicles join together to form a vehicle train, with one vehicle taking the lead. LTE systems support the V2V communication of one vehicle to 19 other vehicles. In addition to exchanging vehicle data such as position, acceleration and speed, messages are needed to manage the platoon. This includes events such as joining/leaving a platoon and determining the platoon leader.

For the investigation of V2X applications such as platooning, a freeway scenario is suitable. The motorway scenario is a straight section of a motorway and includes 6 adjacent lanes with a length of at least 2 km, as shown in Fig. 3. For the definition of the mobile radio characteristics, a rural environment can be assumed.

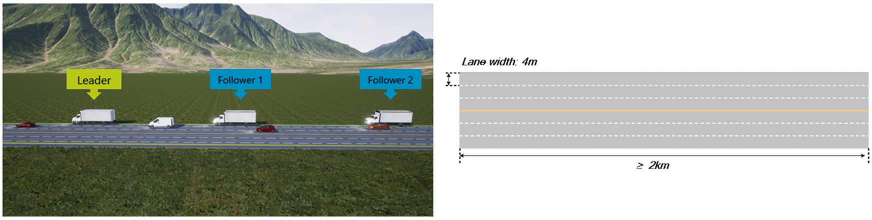


Fig. 3. Platooning in a Freeway Scenario

At the beginning of the simulation, the vehicles are distributed one after the other at the start of the road. During the simulation, the vehicles move forward on the 3 lanes in each direction. In order to determine the vehicle density, a distance is chosen during the initialization of the simulation, which depends on the target speed of the vehicles v_{max} and is calculated as follows:

$$d_{mean} = 2.5\,\mathrm{s} \cdot v_{max}. \tag{1}$$

This vehicle spacing applies to all lanes, so that the density is the same on the entire stretch of road. The density is especially important for simulations with many vehicles. Using a so called wraparound in both directions, the freeway is virtually infinite in length. The freeway scenario offers a variety of uses in the analysis of V2X applications. The necessary basic mechanisms were implemented in SUMO and Tronis®.

Application "Traffic situation with overtaking". If, for example, the exchange of DENM messages for the communication of critical driving intentions between vehicles is to be investigated, then it is required that dangerous driving maneuvers can be provoked in the simulation. Overtaking maneuvers are critical because drivers often overlook faster traffic in the adjacent lane. A DENM-based approach is able to provide a solution to this problem and increase driving safety. Therefore, based on the freeway scenario, two vehicle classes are adopted into the scenario that differ in their target speed. If a vehicle with a high target speed (140 km/h) is following a slower vehicle (max. 70 km/h), it will start to overtake after a certain time.

3 Physics-Based Simulation of Driving Assistance Controller and Vehicles

3.1 Distance Control

In order to be able to examine the sensor-based driving behavior of two or more road participants in detail, the vehicle control is carried out in Tronis® for this purpose. To achieve this, the detail simulation is decoupled from the co-simulation with SUMO. The vehicle behavior models available in Tronis® are used and extended in simulations with the SMART scenarios.

The Cruise Control (CC) system uses the Krauss model by default. The CC model in SUMO includes the standard CC/ACC and an extended CACC system including engine actuation delay. Based on the paper "Realistic Car-Following Models for Microscopic Simulation of Adaptive and Cooperative Adaptive Cruise Control Vehicles" [1], a first cooperative adaptive cruise control (CACC) controller was implemented in MATLAB.

The realistic CACC controller follows the concept from "Assessment of ACC and CACC systems using SUMO" [2] and is defined as follows. The control error e corresponds to the distance between the vehicles, minus a predefined safety distance $d_{default}$. For both modes, the same control strategy applies for the target speed

$$v_{i,k+1} = v_{i,k} + k_1 e_{i,k} + k_2 \acute{e}_{i,k} \tag{2}$$

with

$$\acute{e}_{i,k} = v_{i-1,k} - v_{i,k} - t_d a_{i,k}. \tag{3}$$

The only difference are the parameters $k_1, k_2 > 0$. Here, the index k describes the current time step and i the respective vehicle with $i = 0$ as leader. The time gap parameter $t_d[s]$ is specified by the user and describes a safety time gap which, multiplied by the current acceleration $a_{i,k}[m/s^2]$, adjusts the target speed and affects the target distance to the vehicle in front. The term $t_d a_{i,k}$ can be interpreted as an acceleration-dependent safety distance.

The controller can be operated in two modes, "gap control mode" and "gap-closing control mode". For this purpose, [2] proposes the parameters shown in Table 1.

Table 1. Parameters for different operating modes of the CACC controller

Operating modes	$k_1[s^{-1}]$	$k_2[s^{-1}]$
Gap Control	0.45	0.25
Gap Closing Control	0.01	1.6

The approach for the change from gap control to gap closing control has been adapted. The transition takes place when the vehicle is very close to its target distance (e is small) and target speed (difference v_lead - v_ego is small). The controller shifts the weighting from the distance dependency $k_1 e_{\mathrm{i},k}$ with $k_1 = 0.45 > k_2$ and is more oriented towards the current speed difference $k_2 \acute{e}_{i,k}$ with $k_2 = 1.6 > k_1 = 0.01$. This avoids fluctuation between action states (braking, accelerating, braking, …) around the target distance. The adaptation compared to the proposal from [2] allows a smoother transition between the modes. The necessity for this resulted from an investigation with acceleration and braking processes. A possible high-frequency jumping between the modes is avoided, since distance and speed always leave and reach the set distance and set speed again during catching up and braking.

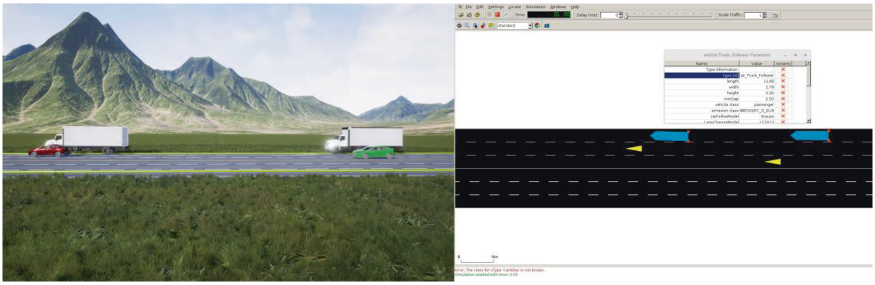
CACC with CAM-Logic. Realistic CACC controllers are developed in Matlab and extended for evaluation by quality of service, reception probability and a look ahead based on the information in CAMs (Cooperative Awareness Messages) from the LTE mobile radio simulation. Concepts for the averaged parameters of the external Matlab controllers, for example for the quality of service prediction, were developed and implemented.

Loss of CAM messages occurring in mobile communications can lead to the loss of knowledge about the speed of the vehicle in front (v_lead). In such situations, the controller must rely solely on the distance sensor. The loss of information leads to a lower performance and influences the adaptive part $\acute{e}_{i,k}(v_{i-1,\mathrm{k}}, v_{i,k}, t_d, a_{i,k})$ of the controller, which determines the additional safety distance. Thus, this part of the controller is adapted in case of a failure of the CAM signal and the safety margin is increased by means of a t_gap_factor $t_{CAMAfailure} > 1$. The following applies: $t_d = t_d \cdot t_{CAMAusfall} > t_d$.

3.2 Traffic Simulation

Tronis® and SUMO are adapted to the simulation platform for the purpose of integration. The co-simulator SUMO is used for the macroscopic simulation of vehicles that are outside a certain field of view (see Fig. 4).

The detailed vehicle simulation can be taken over by Tronis®. For example, platoon vehicles with defined physical properties, as well as sensors and controllers, are simulated. The Simulation of Urban Mobility (SUMO) software is used to simulate the macroscopic background traffic. SUMO is an open-source package for simulating a large number of traffic participants and is designed for large networks. In addition to the simulation of vehicles, it also enables cross-traffic simulation with pedestrians. For the synchronization of the simulators Tronis® and SUMO, data such as number of vehicles, vehicle position and orientation, or other events must be exchanged.



Name	Value
Type Information:	
type [id]	Car_Truck_Follower
length	11.66
width	2.79
height	3.20
minGap	2.50
vehicle class	passenger
carFollowModel	Krauss

Error: The class for vType 'CarFlow' is not known.
Simulation started with time: 0.00

Fig. 4. Coupling of Tronis® (left) and SUMO (right). Tronis®-Trucks are displayed in blue and cars in yellow.

4 Mobile Communication with LTE/5G for Automotive use Cases

Modern applications in the field of semi-autonomous driving like communication-based distance control and tele-operated driving rely on mobile communication services which are often described as vehicle to everything (V2X) communication. Nowadays, two different communication systems are under study for such purposes: Wireless Local Area Networks (WLAN) and Long Term Evolution (LTE), respectively 5th Generation (5G). We decided to consider the LTE/5G systems as those systems are supported by public available infrastructure, which could be used for the tele-operated driving use case or for the support of infotainment systems in the car as well. We have to mention, that we will not consider those use cases in the current work, but they will be considered in the Celtic-Next AI-NET ANTILLAS project based on the framework that was developed in SMART. The current work will be considered distance-control systems based on LTE/5G V2X communication.

The LTE and 5G systems are public mobile communication systems that are defined in a bunch of subsequent releases by the 3rd Generation Partnership Project (3GPP) community. Within the work as described in this article, we consider relevant parts of the LTE/5G Releases 14 to 16.

These public mobile communication systems are structured in cells with a diameter in the range of 1 km in urban regions and larger cells in rural areas. A base station per cell provides a coverage of connectivity via radio frequency (RF) signals for the mobile user equipment's (UE) in the same cell. User equipment's typically transmit data towards the base station in the uplink direction or receive data from the base station in downlink direction. As all user equipment's share the same channel, some medium access control mechanisms are required. Therefore, time division and frequency division medium access control methods take place and divide the shared channel into sub frames with a bandwidth of 180 kHz and a transmission time interval (TTI) of 1 ms. Sub frames are further divided into resource blocks (RB), which are the smallest entity of mobile radio channel resources that can be allocated for the corresponding signals of single users by a scheduler.

4.1 Mobile Radio Channel Properties and System Aspects that are Relevant for the Simulation of the Mobile Communication

We will use a system level simulation which simplifies the physical layer simulation in the form that wave propagation is modeled on a level of power and gain or loss metrics instead of detailed electro-magnetic field analysis. The shaping of transmit and receive signals are not considered. Instead, we use block-error-ratio (BLER) curves that describe the error-rates for RBs in dependence of selected modulation schemes and the signal-to-noise ratio (SNR) at the receiver. This simplifies the modeling of signal processing and decoding. The block errors are evaluated and mapped to a packet loss probability which is finally used, to decide if a packet is lost. Further, the simulator considers discrete events like the generation and reception of packets, the resource scheduling, and channel calculations.

Typical effects of wave propagation that occur in mobile radio channels are path loss and shadowing. The path loss describes the power loss of the RF signal in dependence of the distance d in meter between transmitter and receiver. A general, but simplified path loss model can be given in the form $L_{path} = d^{-x}$ to illustrate the principle law. The exponent x defines the type of propagation ($x = 2$: line-of-sight, $x = 4$: non-line-of-sight, $x = 5 \ldots 6$: indoor-outdoor). Shadowing describes the effect, that some larger obstacles like hills or buildings are placed between sender and receiver, such that the wave has to propagate around the obstacle or got reflected which finally lowers the signal power.

We used the WINNER+ channel model as described in [3] (Chap. "Optimized Drive Systems for Electric All-Wheel Drive Vehicles") within our simulations. It is based on channel measurements which allow a realistic modeling of the channel losses. More specified, the UMi (B1) model was used. It considers an urban microcell deployment. It distinguishes a pure line-of- sight communication as we used it for simulations within a freeway environment and a mixed line- and non-line-of-sight communication as useful for simulations in an urban Manhattan-grid environment.

Further losses are the thermal noise power at the receiver and interferences that occur at the receiver, if at least two transmitters are sending at the same time in the same frequency range. The physical channel performance with power loss L_{Ch} can be summarized within the signal-to-interference-and-noise ratio (SINR) at the receiver side, e.g. $SINR = S_{Tx} L_{Ch} / (N_{Rx} + I_{Rx})$, where the interference power I_{Rx} is the sum of all undesired signals, S_{Tx} is the signal power at the transmitter and N_{Rx} the noise power at the receiver side. As the interference are caused by all possibly sending user equipment's, especially for the later discussed sidelink communication, the calculation will scale in the order of a M^2 with M as number of user equipments. This makes a fast channel calculation challenging.

4.2 V2X Communication

The standardization community of LTE defined the so-called sidelink transmission especially for vehicle-to-vehicle (V2V) and V2X communication which was new in public mobile communications. It allows the direct transmission between user equipments respectively vehicles. The sidelink transmission in LTE Mode 3 requires a connectivity between the UEs and the LTE infrastructure (base stations) for management purposes as the scheduling of mobile channel resources will be handled in a centralized fashion. In situation where a vehicle is out-of-coverage, i.e. communication to the LTE infrastructure is unavailable, the LTE Mode 4 sidelink transmission can be used where the vehicles will schedule the channel resources based on the sensed channel utilization, i.e. the scheduling is decentralized.

The Sense Multiple Access/Collision Avoidance (CSMA/CA) algorithm controls the medium access and was standardized by the 3GPP in [4] for the decentralized scheduling. A UE predicts the future channel occupation in the selection window interval based on the sensed channel utilization in the sensing window. If a packet should be send, the UE will randomly select unoccupied resources, i.e. sub channels with low power levels that are received during the sensing phase. This is illustrated in see Fig. 5. A UE will use the same selected RBs several times in time period that ar related to the sending period of packets and change the RB selection afterwards. This procedure is called semi-persistent scheduling and allows the resolution of collision conflicts that may occur in presence of interference.

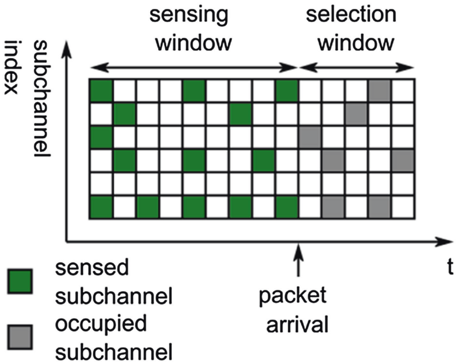


Fig. 5. The semi-persistent scheduling algorithm CSMA/CA is used in LTE Mode 4 for V2V sidelink transmission. It selects RBs randomized based on channel occupation within a sensing window. The RB selection pattern is persistent for the transmission of a bunch of subsequent packets.

The 3GPP considers several use cases for V2X communication as described in [5]. We will focus on platoon scenarios, where several vehicles can follow a leading vehicle autonomously. The communication can be used to manage the distance control or to organize the platoon, i.e. the role of each vehicle in the platoon. Information like vehicle position, movement and other properties can be send periodically by Cooperative Awareness Massages (CAM) as described in [6, 7]. The authors of [8] propose a traffic model that we consider in SMART: Vehicles are sending CAMs frequently in intervals of 100 ms with changing packet sizes. A 300 Byte large packet is followed by four smaller packets with a size of 190 Bytes. This pattern is then repeated as long the vehicle is in use. [9] shows, that CAMs will have a higher impact on the traffic load of the mobile communication system than Decentralized Environmental Notification Messages (DENM) which may be use to notify the appearance of an emergency breaking. Therefore, we will neglect the DENM in the simulation.

4.3 Developments for a Communication-Based Distance Control for Dynamic Mobile Radio Channels in the Presence of Interference and Power Losses

As already mentioned, some automotive use cases rely on mobile communications. Let us consider a vehicle platoon with communication-based distance control, e.g. a CACC controller, per follower. To ensure a safe, collision-free driving operation for the platoon, a stable communication is required as missing or non-updated information can mislead the control functions. But the channel typically shows a high dynamic, such that short outtakes can occur due to fading. Also a massive channel utilization can harm the transmission by interference. Some knowledge about the current channel performance can help to adjust the distance control strategy, e.g. increase the distance if the channel performance gets worse.

Therefore, we developed a method to forecast the quality of service based on the packet receive probability of subsequent CAMs within an adjustable time window which allows a short-term decision in the distance controller. The time window can be changed in 100 ms steps, according to the time interval between two subsequent CAMs, in the range of 100 ms to 1 s. The calculation of the packet receive probability is based on the simulation states at the prediction time. Therefore, we are using information like the vehicle position and velocity, path loss, shadowing loss, interference and receive power. Within the prediction time window vehicle positions can be linearly extrapolated to update then the path losses for the new positions. A recalculation of interference and shadowing effects is not done which keeps the computation effort low. Based on resulting SINR values the packet receive probabilities are determined. Our prediction metric specifies the probability, that at least one CAM will arrive within the justified time horizon.

We developed a proposal for a communication-based distance controller that is able to evaluate the forecast information about the service performance. This quality-aware controller consists of an ACC and CACC controller that are operated in parallel. Based on the service performance, the controller can adjust the proportional influence of ACC or CACC control softly which is done by the adjustment rule given as

$$a_{total,i} = \gamma_i a_{CACC,i} + (1 - \gamma_i) a_{ACC,i} \tag{4}$$

$$\gamma_i = min(p_0, p_{i-1})^e, e = 0.65 \tag{5}$$

Hereby, p_0 indicates the probability to receive a CAM from the leader and p_{i-1} stays for a corresponding probability to resceive a CAM from the vehicle ahead. The variation of e allows a further adjustment. The control rules for the ACC and CACC controller that are used in this context are based on [10] and defined by

$$a_{ACC,i} = \frac{-1}{T_{des}}(v_i - v_{i-1} + \lambda(d_{des} - d)) \tag{6}$$

$$a_{CACC,i} = \frac{a_{i-1}}{2} + \frac{a_0}{2} - \frac{3\omega_n}{2}(v_i - v_{i-1}) - \frac{\omega_n}{2}(v_i - v_0) - \omega_n^2(d_{des} - d) \tag{7}$$

$$d_{des} = 2m + T_{des}v_i \tag{8}$$

$$\lambda = 0.1\,\mathrm{s}^{-1}, T_{des} = 1.2\ \mathrm{s}, \omega_n = 0.2\ \mathrm{Hz}. \tag{9}$$

The platoon members are numbered by i based on their order in the platoon, i.e. the platoon leader is indicated by $i = 0$, a indicates accelerations, v velocities and d the distance between the i-th vehicle and the vehicle ahead ($i - 1$).

This controller was tested together with other controllers in a scenario where a leading vehicles follows the WLTP cycle (a standard driving pattern for vehicle testing) and multiple platoon member are following at a controlled distance. The CACC-based controllers are improved by a safety-mechanism which forces a hard fallback to a communication independent ACC controller if more than 5 subsequent CAMs are lost, i.e. the last received information is older than 500 ms!

We are able to show in some of our studies, that the proposed quality-aware controller leads to the most efficient energy use per vehicle of a platoon compared to other ACC and CACC based controllers. Especially for platoons with a length of 8 or more vehicles. In those cases, interference may impact the communication which will cause energy losses as due to the hard fallback, control differences have to be equalized.

4.4 Improvements that Enable a real-time-capable Simulation of Mobile Communications for Automotive use Cases

For the achievement of real time simulations, we used various methods to speed up the simulation of the mobile communication: parallelization and approximation of calculations, distributing calculations over several time steps, modified configuration of the simulation. Protocol stack activities, channel loss calculations and the prediction of the quality of service can be parallelized as those calculations are done per communicating UE pair. As channel conditions like path loss and shadowing a slow changing effects, we reduced their update frequency which also allows a distributed calculation over a period of 100 ms. The prediction of the channel quality can be simplified by setting the transmission probability to zero if a vehicle pair has a distance above 600 m, as a transmission above this distance will be very unlikely.

This approximation does not impact the quality of the simulation. The simulation duration can be further improved by some settings. As the simulator is written in JAVA which includes a heap memory and garbage collection provided by the runtime, we can increase the heap memory which will reduce the time consuming activities of the garbage collection if the heap size reach the limit and unused objects has to me removed. The simulator provides an additional library for statistical analysis which is useful for extensive studies, but not required for a live demonstration within the framework developed in SMART. Deactivation of the statistical analysis will also speed up the simulation. Overall, we achieve a speedup in time with a factor of up to 4.8 for a scenario with 400 vehicles. We can further show that a real time simulation of the mobile communication is possible for a reasonable scenario size with 200 vehicles.

5 Simulation Platform

A decentralized sim coordinator is used to control the sub-simulators contributing to the simulation. The main tasks are to setup the initial alignment of the data, the start of the simulation and the further alignment of time steps and simulation data in the course of the simulation (see Fig. 6).

Each of the partial simulators binds to an instance of the sim coordinator, whereupon this sim coordinator instance informs itself via DDS [11] about already existing instances and also listens for the joining of further instances. As soon as the sub-simulators necessary for the overall simulation have been discovered, the sim coordinator instances initiate the dispatch of the initial data of the respective linked sub-simulator and then report the completion of the dispatch. The sub-simulators then receive the command to process the corresponding data. The data for the coordination of autonomously driving vehicles are periodically exchanged between the simulators after coordination by the sim coordinator. The periodically sent messages, in the form of CAMs, contain information about position, movement and vehicle characteristics.

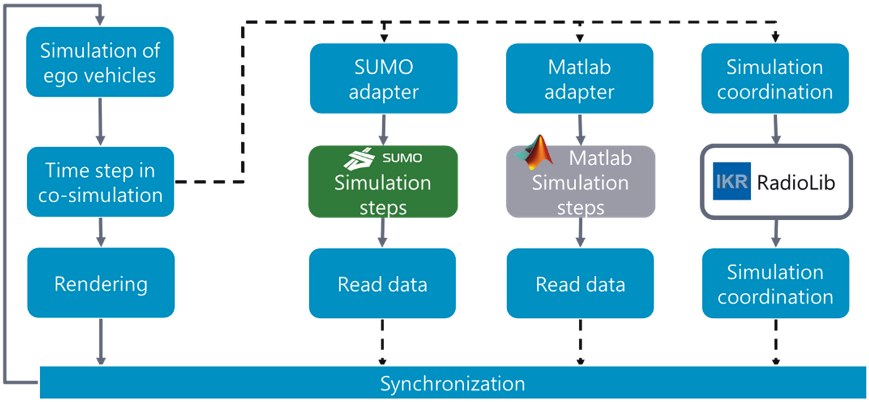


Fig. 6. Overall collaborative simulation platform

6 Conclusion and Outlook

For the overall simulation of scenarios of autonomous and connected driving, the two project partners developed a simulator coupling between the mobile radio simulator of the IKR and the vehicle simulator Tronis® of TWT GmbH. Loose interfaces and data exchange formats as well as a software module for coordinating the coupled simulation were defined and implemented for this purpose. The architecture allows the simple addition of further simulators. The service quality estimation of the mobile radio simulator is used in the coupled simulation by the vehicle simulator for vehicle control. It has been shown that considering the service level estimation can improve the energy efficiency of large vehicle platoons compared to a Cooperative Adaptive Cruise Control (CACC) controller without service level estimation.

TWT offers lectures and lecture series in cooperation with universities and colleges in the areas of automated and autonomous driving. At present, the system is being introduced and used in cooperation with the IFS at the University of Stuttgart.

Tronis® is provided as educational material and a tool for free use in collaborative programs. The work described in this article is used as basis for a new lecture for master students at the University of Stuttgart. It covers the development and evaluation of driving assistance systems for autonomous driving use cases as described in [12]. The work can be used for student projects and thesis. Parts of this work will be further developed within the AI-NET ANTILLAS project. The focus is on building competence around topics such as LTE, 5G or WLAN communication and cooperation between network and infrastructure providers and OEMs.

Acknowledgements. This work was funded by the German Federal Ministry of Education and Research (BMBF). We thank the funder that enables the SMART project and all colleges and students that contribute to the work of the SMART project.

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