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Simulation of Convergent Networks for Intelligent Transport Systems with VSimRTI

1.1. Introduction

For the realization of Intelligent Transportation Systems (ITS), ad hoc networks based on IEEE 802.11p have a long history in research. This technology envisions a decentralized information exchange between mobile vehicles, and also with stationary roadside stations to enable communication with central stations in the public data network (i.e. the Internet). This approach offers several advantages such as the direct exploitation of the broadcast characteristics of the radio channel, which is useful for short message broadcasting in the vehicle's vicinity. However, scalability is a big challenge in this approach, due to a limited communication range and a lack of deterministic quality of service (QoS). With the new generations of cellular networks (mobile phone networks), these drawbacks of vehicular ad hoc networks could be overcome. Cellular networks, e.g. 5G, are emerging as a capable solution not only for mobile Internet services, but also for ITS-specific traffic safety and efficiency matters. Cellular networks exhibit the major advantage of a nearly unlimited communication range, due to their architecture, with only a short wireless part between the mobile device and the base station, and the wired part through the backbone. However, this architecture introduces a particular delay overhead, which makes meeting the strong requirements of many safety applications questionable. A solution could be an intelligent combination of vehicular ad hoc networks and cellular networks to link the advantages of both approaches.

The multi-aspect simulation environment VSimRTI [SCH 11] is a comprehensive framework that connects various simulation tools together to cover all aspects needed

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for a proper evaluation of new cooperative mobility solutions for Intelligent Transportation Systems (ITS). Vehicle movements and sophisticated communication technologies can be modeled in detail. VSimRTI couples different simulators to allow for the simulation of various aspects of future ITS. In the following sections, we describe how we have extended the VSimRTI architecture to enable the simulation of cellular networks. Consequently, we have developed the novel cellular communication simulator VSimRTI_Cell that introduces a grade of abstraction of cellular networks. The developed simulation tool is lightweight and fast enough for larger scale scenarios. However, particularly from the vehicular application perspective, the simulator models important features which are not considered in other related frameworks [PRO 14a, PRO 14b]. Moreover, the new extended VSimRTI architecture not only allows for the analysis of vehicle networks based on cellular communication, but also novel hybrid solutions that combine ad hoc and cellular communication in an intelligent way.

This chapter is structured as follows. In section 1.2, we resume the fundamentals of the system of cooperative vehicles, such as message types, application categories and the specific concept of facilities. Then, section 1.4 introduces the new cellular simulator VSimRTI_Cell in closer detail. In section 1.5, we perform a short simulation study on generic safety and efficiency applications to present the individual advantages of ad hoc and cellular communication as well as a hybrid approach in converging networks in the context of ITS. Finally, section 1.6 concludes this chapter.

1.2. Fundamentals of cooperative ITS

1.2.1. *Message types*

The information exchange in ad hoc networks among vehicles, and among vehicles and infrastructure units is standardized to guarantee interoperability. The two most important message types are the Cooperative Awareness Message (CAM) [ETS 14a] and the Decentralized Environmental Notification Message (DENM) [ETS 14b].

Cooperative Awareness Messages (CAMs) are distributed within the ad hoc network, and provide information of presence, position and the basic status of a vehicle to neighboring vehicles that are located within a single-hop distance. Vehicles generate, send and receive CAMs, as long as they participate in the ad hoc network. By receiving CAMs, vehicles are aware of other vehicles in their vicinity and are informed about their positions, movements, basic attributes and basic sensor information. CAMs are generated and sent by a vehicle periodically.

Decentralized Environmental Notification Messages (DENMs) are used to alert road users to a detected dangerous situation, e.g. a hazardous location, roadworks or a risk of collision with another vehicle. In general, the processing procedure of sending a DENM is as follows: after the detection of a dangerous event, the vehicle immediately broadcasts a DENM to other vehicles which are concerned by the event and are located within the same geographical area. The transmission of the DENM is repeated with a certain frequency and persists as long as the event is present. According to the type of event detected, the DENM is relayed by other vehicles. The termination of the repeated DENM broadcasting is either achieved automatically once the event disappears, after a predefined expiry time, or by a vehicle that generates a special DENM to communicate that the event has disappeared. A vehicle, which receives a DENM, processes the information and, if the information in the DENM is relevant for the driver, it presents an appropriate warning or information on the vehicle's HMI (Human Machine Interface).

1.2.2. *Application categories*

Enhancing vehicle safety and improving traffic efficiency are the two most important aims of vehicular networks. Moreover, communication capabilities in vehicles also allows popular digital services to be provided to the users. The ETSI [ETS 09, ETS 10] and the Car2Car Communication Consortium Manifesto [CAR 07] define several scenarios and use cases for these objectives. The following section gives a brief overview of how vehicular networks are used to share information to advance vehicle safety, increase traffic efficiency or enable comfort applications.

1.2.2.1. *Traffic safety applications*

Vehicular safety applications are characterized, in general, by vehicular communication which is used to mitigate the occurrence of dangerous situations and accidents. Applications, installed in a vehicle, monitor the vehicle's state and the activities of the driver. Relevant pieces of information are transmitted after a relevance check to vehicles in the vicinity. For example, information about the position and speed of a vehicle via CAM or about dangerous locations on the roadway is transmitted via DENM. The received information is used by the safety applications in the vehicle to either inform the vehicle driver or automatically optimize the safety systems for the best possible reaction to a dangerous situation [SCH 11].

For improved vehicle safety, a *Cooperative Awareness* (CA) application and a *Road Hazard Warning* (RHW) application are specified. The CA application warns a vehicle driver if an emergency vehicle, a motorcycle, or a slow driving vehicle is approaching or if a vehicle runs the risk of a collision at an intersection. This application uses the information of the periodically broadcast CAMs for its detections. The RHW application informs drivers about hazardous locations in their close vicinity, e.g. about vehicles driving in the wrong direction, about accidents, roadworks or signal violations. Here, DENMs are used to disseminate information about the dangerous situations.

1.2.2.2. *Traffic efficiency applications*

By exchanging traffic-related information among vehicles and traffic infrastructure units, vehicular traffic efficiency applications improve the efficiency of the transportation network. The received information is analyzed and used, for example, to inform the driver about delays to be expected and to optimize the vehicle's speed and route depending on the traffic conditions [SCH 11].

For an improvement in traffic efficiency, the basic set of applications defined by the ETSI [ETS 10] proposes a *Cooperative Speed Management* (CSM) application and a *Cooperative Navigation* (CoNa) application. The CSM application aims to optimize the vehicle's speed for a better traffic flow. Thus, the application provides either regulatory speed limit information or transmits information necessary for an optimal speed calculation by vehicles at specific road segments or at intersections. Thus, a vehicle can optimize, for example, its speed to reach a traffic light system during the green signal phase. The CoNa application provides services and information, e.g. about the current traffic situation, to allow the vehicles to optimize their travel routes. This application offers a recommended itinerary based on traffic information, enhanced route guidance and navigation, as well as a limited access warning and detour notification.

1.2.2.3. *Comfort applications*

Comfort or infotainment applications are not directly related to the vehicles' mobility, but are part of today's digital lifestyle. This group includes applications like e-mailing, browsing or media streaming. An important aspect of this group is that these applications do not necessarily rely on cooperative M2M information exchange. They are mostly realized on an individual basis and should be evaluated individually. Hence, the evaluation in the later sections will not consider these applications.

1.2.3. *Supporting facilities*

The Facilities Layer is essential to implement vehicular applications in vehicles. It is a sublayer of the Application Layer and provides generic support facilities to the applications. All facilities are classified into three main categories: application support, information support and communication support [ETS 09, ETS 10]: Application support facilities provide common support functionalities for the applications, e.g. station lifecycle management, automatic services discovery, download and initialization of new services and HMI generic capabilities. Furthermore, CAM and DENM management belong to this category. Communication support facilities comprise services for communication and session management, for example the addressing mode and the session support. Information support facilities provide common data and database management functionalities for the applications. An example of an information support facility is the Local Dynamic Map (LDM).

The Local Dynamic Map (LDM) is a conceptual data store which contains topographical, positional and status information within a surrounding geographic area [ETS 14c]. It is relevant to the safe and successful operation of applications. Data can be received from a range of different sources, e.g. on-board sensors, neighboring vehicles, infrastructure units and traffic centers. Thus, the LDM is able to provide information on the surrounding traffic and RSU infrastructure to all applications that require it.

1.3. Overall simulation framework

The assessment of new solutions for Intelligent Transportation Systems is a challenging task. The Vehicle-2-X Simulation Runtime Infrastructure VSimRTI enables the evaluation of collaborative mobility applications and the assessment of new autonomous and cooperative functions of conventional and electric vehicles. VSimRTI connects various simulation tools together to cover all aspects needed for a proper evaluation of new cooperative mobility applications and Advanced Driver Assistance Systems. VSimRTI facilitates the generation of realistic large-scale synthetic probe data for algorithm validation and system testing [PRO 11, WED 09, QUE 08]. Moreover, VSimRTI enables the analysis of elastic mobility scenarios where drivers, traffic infrastructure and cloud services are joined together into one collaborative network.

The aim of the VSimRTI project is to make the preparation and execution of simulations as easy as possible for users. All management tasks, such as synchronization, interaction and lifecycle management, are handled completely by VSimRTI (see Figure 1.1). Several optimization techniques, such as optimistic synchronization, enable high performance simulations [NAU 09]. Special ITS features, e.g. traffic infrastructure units, charging stations and the CAM and DENM message types, introduced in section 1.2, are supported by VSimRTI. Moreover, the various configuration options and comprehensive user documentation assure a high usability.

In contrast to existing fixed simulator couplings, the VSimRTI simulation infrastructure makes the easy integration and exchange of simulators possible [SCH 11]. Thus, the high flexibility of VSimRTI enables the coupling of the most appropriate simulators for a realistic presentation of vehicle traffic, electric mobility, wireless communication and the execution of mobility applications. Depending on the specific requirements of a simulation scenario, the most relevant simulators can be used.

VSimRTI uses an ambassador concept inspired by some fundamental concepts of the High Level Architecture (HLA) [IEE 10]. Thus, it is possible to couple arbitrary simulation systems with a remote control interface. Attaching an additional simulator only requires that the ambassador interface is implemented. For immediate use, a set of simulators is already coupled with VSimRTI. For example, the traffic simulators SUMO [KRA 12] and PHABMACS, the communication simulators OMNeT++ [VAR 08] and ns-3 [HEN 08], the cellular network simulator VSimRTI_Cell, the application simulator VSimRTI_App, and several visualization and analysis tools are prepared for VSimRTI. Figure 1.1 shows a typical simulation set-up implemented with VSimRTI.

VSimRTI has been used by various automotive companies and research institutes to evaluate collaborative mobility applications.

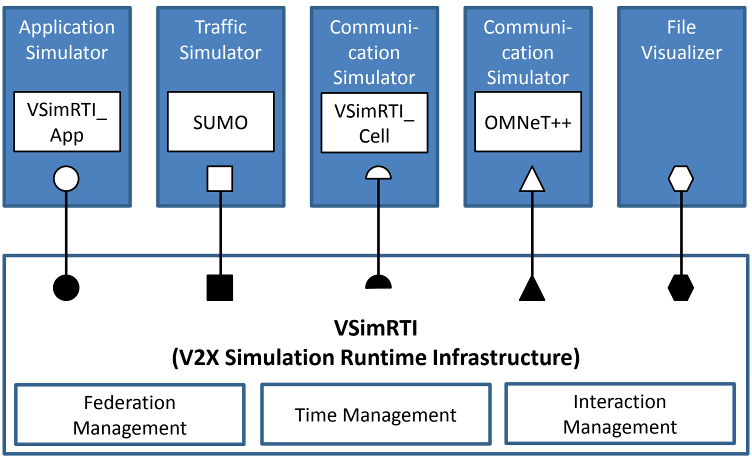


Figure 1.1. *Structure of a typical VSimRTI simulation set-up*

1.4. Simulation of cellular networks

Cellular networks are comprehensive systems with a high number of entities. Moreover, these networks offer very extensive configuration opportunities to match the requirements of the relevant operator. These facts lead to very different characteristics of the particular systems. Hence, the simulation of cellular networks from the perspective of the applications is a challenging task.

The simulation of cellular networks is commonly divided into two different perspectives which have different stages of abstraction. On the one hand, the link level simulation comprises the lower layers (MAC, PHY) and the radio channel. In this way, it models, for instance, the radio link between a NodeB and the UE. On the other hand, the system level simulation focuses on the higher layers and is used for the network view. This level considers, for example, a set of NodeBs and the associated UEs.

Nowadays, different system level simulation frameworks are proposed, concentrating on LTE cellular systems. The longest standing open-source LTE system level simulator is based on MATLAB [IKU 10]. In its original version, it is limited to the downlink and does not consider several important features as broadcast. The C++ based framework LTE-Sim is already very feature rich [PIR 11]. It supports uplink, downlink, several schedulers, handover and more. The well-established communication simulator OMNeT++ is used to build up the end-to-end system SimuLTE [VIR 14]. The latter concept is appealing, as OMNeT++ is already coupled to the existing simulation infrastructure VSimRTI. Even though some of these approaches have a detailed model base, they have several shortcomings for larger scale scenarios. The simulators are more or less tied to one access technology, namely LTE. More significantly, while the direct modeling approach is sufficient for simple ad hoc communication, for larger scale scenarios of cellular system simulation, the given simulators are too complex to configure and the detailed simulation is computationally too expensive. In contrast, trace-based cellular simulation is a promising approach that claims to be much faster than system level simulation [GOE 14]. Similar to the empirical radio propagation modeling, the trace-based technique derives models from real-world measurements. Hence, it works without particular assumptions for the network set-up and configuration.

The new simulator VSimRTI_Cell introduces a similar grade of abstraction of cellular networks to the trace-based simulation. The core models are even based on a dedicated measurement campaign. The developed simulation tool is lightweight and fast enough for larger-scale scenarios. However, particularly from the vehicular application perspective, the simulator also models important features that are not regarded in the other frameworks [PRO 14a, PRO 14b]. The conceptual design of the VSimRTI_Cell simulator has the following key aspects:

Technology: VSimRTI_Cell is independent from the current releases of standardized cellular access technologies such as UMTS-HSPA, LTE or even 5G;

Deployment and Coverage: VSimRTI_Cell introduces a very flexible network deployment concept, which ranges from configuring individual cells to regions of equal coverage;

Network Load: VSimRTI_Cell considers the fact that V2X communication has to coexist with data traffic generated by other users (e.g. with smartphones or USB dongles). The simulation only computes the V2X communication;

Features: VSimRTI_Cell provides important functionalities for the specific needs of V2X communication. For instance, the GEO entity provides the functionality for geographic addressing and information exchange. Moreover, the implemented MBMS functionality allows simultaneous broadcasting of messages to all vehicles in a region or cell.

With the named aspects in mind, the following important metrics for network qualification are identified to be collected within an initial measurement campaign. From these metrics, suitable simulation models are developed:

– transmission delays (see section 1.4.2);

– reliability towards packet losses (see section 1.4.3);

– available data rates (see section 1.4.4).

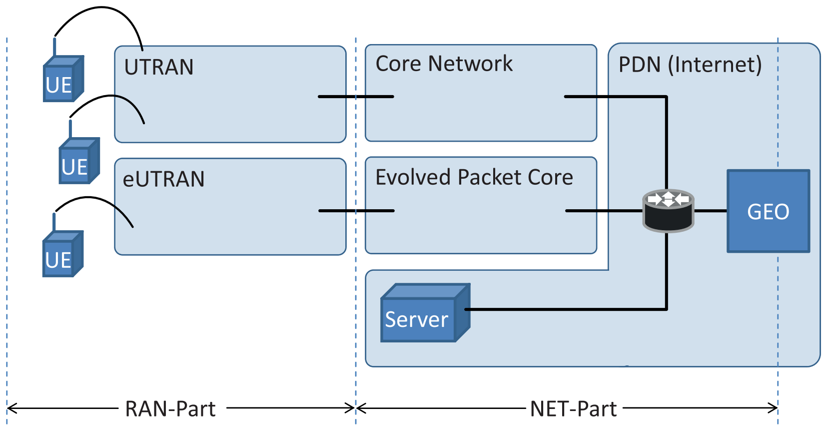


Figure 1.2. *Black box assumption for the cellular system for V2X communication*

The measurement campaign for data collection focused on an end-to-end connection from a smartphone to a server via UMTS. This approach considers the network as a black box, without further assumptions for the specific deployment of the components of NodeBs, RNC, Gateways, etc. in between. Figure 1.2 shows this general assumption for the cellular system for V2X communication. It is based on the established assumption for V2X communication via the central infrastructure. Hence, direct communication uses cases where approaches as D2D are currently not considered. Beside mobile UEs and stationary servers in the PDN, the system also includes a GEO entity, which is introduced for the specific needs of Geographic Messaging in the V2X communication context. The GEO is also located in the PDN. It is explained in closer detail in section 1.4.5. The assumption for the cellular system separates one part for the Radio Access Network (RAN-part) and one part for the Core Network and general public data network (NET-part). The separation intends to enable a more flexible configuration of the overall system.

As the real-world measuring of the communication metrics can be a comprehensive task [GOE 14], the presented concept aims not only to use the data from its own measurement campaign, but also to integrate collected data from others. In this way, the VSimRTI_Cell should also be configured with data from network operators, with measurements from other researchers [SER 09, PRO 09, TEN 10] or with community-driven databases. Several projects such as OpenSignal (www.opensignal.com), RootMetrics (www.rootmetrics.com) and Sensorly (www.sensorly.com) collect crowd-sourced information about the mobile network performance and coverage.

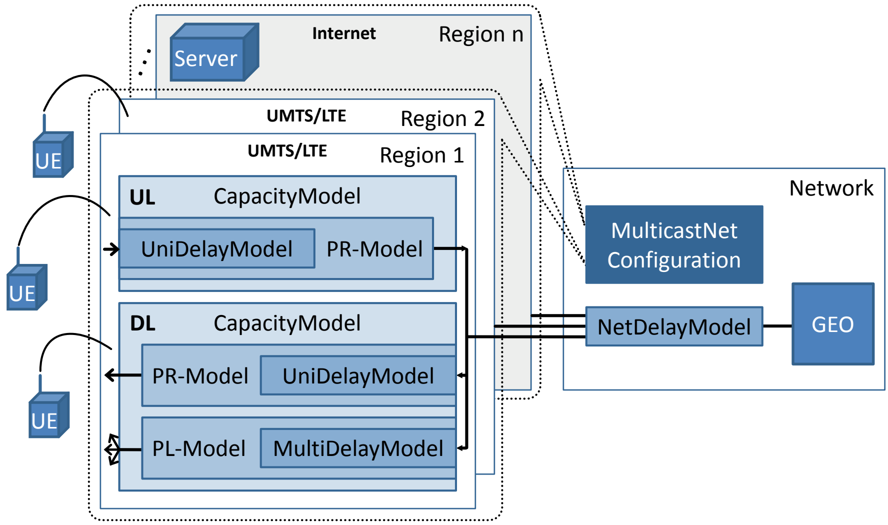


Figure 1.3. *Architecture of the VSimRTI_Cell simulator*

Figure 1.3 shows the architecture of the VSimRTI_Cell. The concept, first, includes multiple regions with specific geographical extensions to create a radio access network with the according coverage properties. Every region consists of one Uplink and one Downlink module to simulate the packet transmission in the RAN-part. In this context, Uplink and Downlink always refer to the direction towards, respectively from, the GEO entity. For instance, a transmission from an Internet-based server towards a vehicle would include an Uplink between the server and the GEO, and a Downlink between the GEO and the vehicle. While the Uplink direction only allows point-to-point communication, the Downlink direction supports point-to-point (Unicast) as well as point-to-multipoint (Multicast) communication. The Uplink module is composed of the three nested models for the Delay, the Packet Retransmission and the Capacity. The Downlink module includes two individual paths for Unicast and Multicast, which share the same Capacity. The Downlink path for Unicast is also composed of the same models for the Delay and the Packet

Retransmission as the Uplink path. The Multicast transmission needs to account for different characteristics. In contrast to reliable ARQ-based Unicast, Multicast only employs FEC with the chance of Packet Losses. Moreover, Multicast typically exhibits a different delay based on the MBMS scheduling period. For this reason, the Downlink Multicast chain provides a separate Delay Model and the Packet Loss Model. All in all, the models for each path (Uplink Unicast, Downlink Unicast and Downlink Multicast) can be individually configured to simulate the according RAN properties.

The second major part of the VSimRTI_Cell models the NET-part. The network enables the configuration of an additional network delay. It furthermore comprises the GEO with its configuration of the Multicast regions. The GEO functionality is implemented in the VSimRTI_Cell. Mobile nodes such as vehicles and stationary servers are the nodes which actually attempt sending and receiving messages. Their application logic is implemented in the VSimRTI_App application simulator.

The following sections give further details about the Region and Cell concept, the transmission models and the functionality for Geographical Messaging.

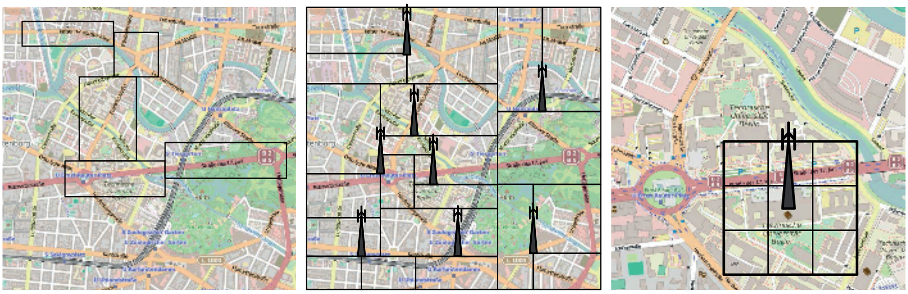
1.4.1. *Regions and cells*

According to the VSimRTI_Cell design aspects, we developed a region concept that aims at the flexible configuration of the cellular network deployment. In the first instance, regions are independent from actual cells and do not necessarily conform to them. Figure 1.4 shows the possible definitions allowed by this concept. The underlying simulation models allow for the definition of arbitrary polygons as regions. For the sake of simplicity, we decided to present the configuration with rectangular regions, although this would introduce a certain abstraction towards the real-world characteristics:

Free definition (regions ! = cells): this definition typically applies for measured (trace-based) or crowd-sourced data. For instance, the named measurement campaign collected the points for the metrics of the latency, the packet loss and the data rates mainly in connection to their position. The measuring points with equal or similar values are aggregated to the different regions. A further mapping to a certain base station is not performed;

Exact definition (1 region == 1 cell): this definition applies when network operator data about the individual base station positions and their coverage areas are available;

Intra-cell definition (n regions == 1 cell). For more detailed investigations of different coverage areas inside a single cell, the region definition also enables, for example, the configuration of a central region with a more capable parameter set compared to the regions at the cell edges.



(a) Free definition (b) Exact definition (c) Intra-cell definition

Figure 1.4. *Different definition possibilities for cellular regions in VSimRTI_Cell. For a color version of this figure, see www.iste.co.uk/hilt/transportation.zip*

For practical reasons, the region configurations need to account for two specific situations. First, the whole scenario area may not be covered with a particular region definition, but nodes may move to an uncovered location. In this case, the global region always defines a default configuration. Second, multiple region definitions may be configured to overlap for certain locations. In this case, the configuration of the smallest region is always selected for the transmission calculation.

1.4.2. *Delay models*

The delay models, regardless of the employment as UniDelayModel, MultiDelayModel or NetDelayModel, always constitute the core component for the simulated packet transmission. We developed four different basic delay types to simulate the transmission time for every packet statistically:

constant is the most basic delay type of VSimRTI_Cell. It always yields the same configured delay for every sent packet. This more synthetic model is mainly intended to be used for debugging or primary clarifications. Moreover, it can model a constant offset for the NetDelayModel;

simpleRandom extends the constant delay type. It defines a minimum and maximum bound for the delay ($minDelay$, $maxDelay$) and a possible number of discrete $steps$ (n). With this configuration, the simpleRandom type randomly generates n different uniformly distributed delays in the interval of $[minDelay, maxDelay]$;

gammaRandom addresses the particular characteristics of the RAN-part. The measurement campaign identified that the distribution of the transmission delays in a real-world environment sufficiently conforms to the gamma distribution. This delay type allows us to configure the minimum and the expectation value of the delay ($minDelay$, $expDelay$);

gammaSpeed is the most sophisticated delay type. It is based on the gammaRandom type and also includes impairments for higher vehicle speeds according to a fitting of the measurements from our campaign. Figure 1.5 displays the probability distribution for the gammaSpeed delay type at different speeds with the measured values of $minDelay = 40\ ms$ and $expDelay = 80\ ms$ for a representative set of HSPA transmissions. According to this diagram, most packets have a delay between 50 ms and 200 ms. However, this is only one possible parameterization and this type also qualifies for the modeling of other mobile network generations such as HSPA+ or LTE and even 5G.

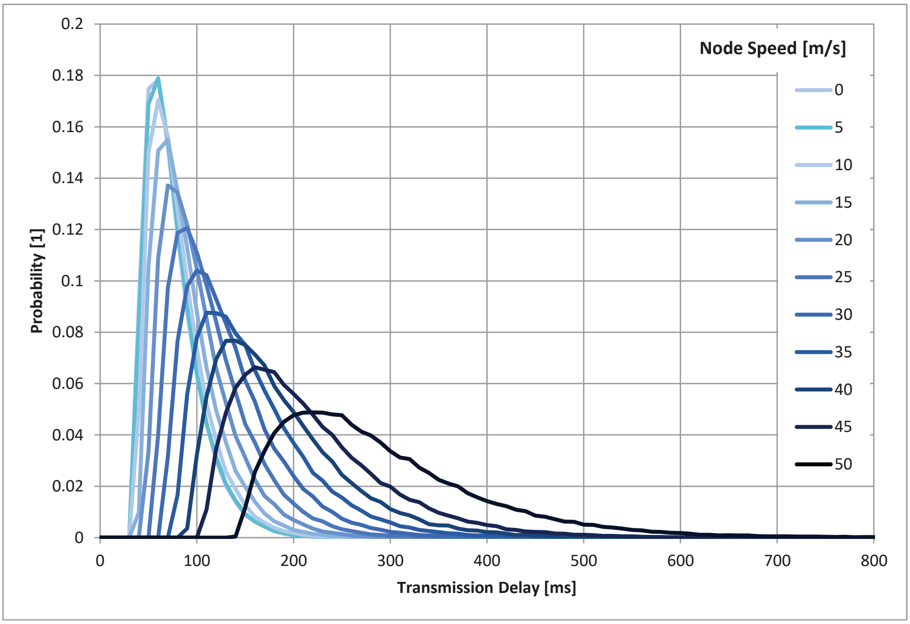


Figure 1.5. *Probability distribution of the gammaSpeed delay at different speeds. For a color version of this figure, see www.iste.co.uk/hilt/transportation.zip*

1.4.3. *PR-Model and PL-Model*

We developed a PR-Model and a PL-Model to address the effect of individual packet transmission impairments between the node and the base station due to inappropriate signal coverage. However, when a reliable connection with ARQ is assumed, no packet is effectively lost, but retransmitted. This is in turn connected with an additional delay. Hence, the Packet Retransmission Model is particularly employed for the reliable Unicast transmissions in Up- and Downlink. For the Broadcast communication in Downlink, where only FEC can be applied, the Packet Loss Model simulates complete packet drops.

The configuration of the coverage quality parameter between 0 and 1 determines the probability of a retransmission (PR-Model) or a packet loss (PL-Model) for each transmission attempt. In case of a packet loss with or without retransmission, the packet will always occupy the channel resources even for unsuccessful transmissions. The parameter value of 0 implies an unimpaired transmission for each model. A value smaller than 1 gives the probability of loss or retransmission in percent. A value of exactly 1 leads to a packet drop in each model. This behavior can be employed to account for entirely disconnected regions in tunnels or shadowed urban canyons. However, the PR-Model optionally reports a packet drop notification to the sender node to consider a reliable transport protocol such as TCP.

1.4.4. *Capacity Model*

Our Capacity Model considers the channel load of a region and calculates the final delay for the individual packets. With the configuration parameter of the maximum available capacity for all simulated nodes, it allows investigations which are independent of the family and the generation of the mobile access technology. Furthermore, it respects static data traffic caused by other mobile users with smartphones, USB dongles and broadband cards. This is an important feature as V2X communication needs to share the resources with other applications. For these reasons, the region definition is particularly important for this model. For example, assume a network deployment with equal capacities in different cells. When this deployment is configured with regions of different size, the capacity needs to be adapted to the region size.

The second parameter of this model is the maximum user bit rate, which resembles the peak speed according to the user data plan. It is still possible to serve more simulated nodes in a certain region than the ratio of the available capacity divided by the maximum user bit rate. When every user demands its maximum bit rate, the result would be that the network gets congested locally and not every sender can transmit directly. This effect is modeled when the sender reserves the resources for the packet at the time of the transmission.

The Capacity Model maintains a resource map where all reservations are accumulated for their timespan. When a new sent packet exceeds either the maxNodeBitrate (the data plan limit is reached) or the available capacity (the network is congested in this region), the packet needs to be queued and thus further delayed until the channel is free again.

1.4.5. *Topological and geographical messaging*

The GEO entity in the Net-part of the VSimRTI_Cell provides functionalities for different addressing schemes. In a real core network deployment, these functionalities would be distributed over several entities, as for instance in LTE, the MME for node mobility management. The GEO is connected to all regions via the NetDelayModel to simulate an additional delay through the Net-part (Core Network and PDN). During simulation runtime, the GEO follows the node mobility. It maintains a table with the node positions and the mapping to the corresponding region. Every sent message in the Uplink goes through the GEO, which distributes the message in Downlink either for point or multipoint reception.

For conventional data traffic, the addressing between the nodes is realized by IP and involves multiple entities in the core network. The simulation can abstract from several aspects of a real core network. However, the user mobility and the router functionality, which are covered by the SGSN in UMTS or the MME and SGW in LTE, need to be accounted for at least. On that account, the GEO uses the knowledge of the current node positions to forward the messages to the Downlink transmission chain of the according region of the destination node. Many V2X communication use cases envision geographic messaging over cellular networks, similar to geographic ad hoc routing. For this purpose, the IP address is extended with the definition of the geographic destination area. The GEO translates the address to direct the packet to the according nodes.

Moreover, many V2X communication use cases demand the dissemination of the same information to multiple nodes in the area. Hence, they are a prime example for the utilization of MBMS and eMBMS (MBSFN) features to allow efficient and resource-saving broadcast transmission. Depending on the MulticastNet configuration, the GEO provides transmission modes similar to MBMS and MBSFN. The MulticastNet configuration defines which regions together form a compound for broadcasting or multicasting a packet. The GEO replicates the packet to be sent in every region compound covered by the destination area.

1.5. Simulation study

The following section presents a simulation study where the introduced cellular simulator VSimRTI_Cell is set into operation. In the study, ad hoc and cellular communication will be combined in one scenario to support the information exchange of V2X applications over converging networks. For a general statement on the communication performance, this simulation will not only address a single application. The evaluation will concentrate on application specific metrics which are significant for a broad spectrum of applications.

As introduced in section 1.2, many envisioned applications rely on the characteristic communication paradigm of periodic exchange of messages [ETS 09, ETS 10]. Hence, the definition of Cooperative Awareness Messages (CAM) is a central point in the specification of the V2X communication standards [ETS 14a]. Additionally, Decentralized Environmental Notification Messages (DENM) represent the second important message type [ETS 14b]. For the properties of node mobility and number of reporting nodes, CAMs and DENMs vary in the manner that CAMs inform about individual moving vehicles, while DENMs inform about (temporarily) stationary situations, which could be reported redundantly by multiple nodes. For the importance of communication reliability, this implies that a CAM possesses more critical requirements, while a lost DENM could be compensated with redundant ones. Due to this, we mainly focus the safety relevant evaluation of our simulation study on applications, which is based on the critical CAMs.

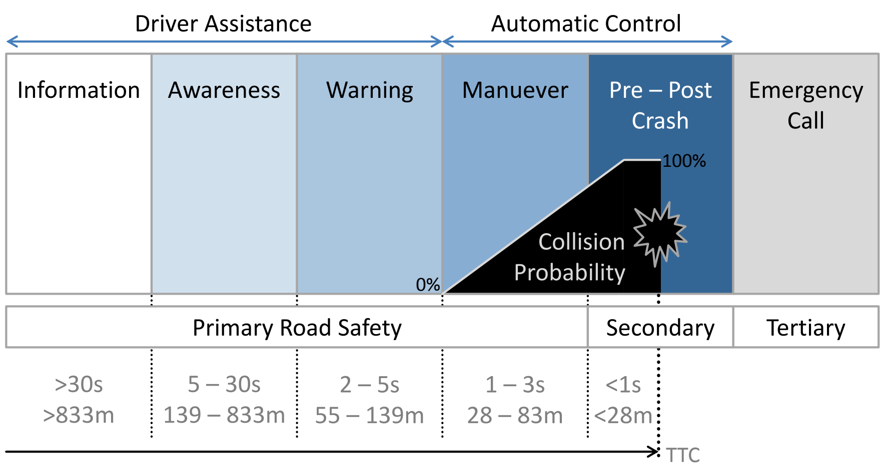


Figure 1.6. *Distance zones of the ETSI road safety application model (based on [ETS 13])*

Figure 1.6 shows the constraints of CAM-based safety and efficiency applications. It shows the position of the different information zones in relation to the time to a possible incident, using the metric of the TTC (time to collision). All values for the TTC should be accepted with caution as exact values are indeed very difficult to define. Even according to the ETSI, the given values are not finalized and are mainly intended as examples [ETS 13]. Figure 1.6 includes additional values for the distance towards the incident to get a better sense of the related spatial dimensions. These values are simply calculated for the TTC of the individual zones, in a situation where two vehicles approach each other with a constant speed of 50 km/h

(13.89 m/s). Different situations (e.g. different movement constellations or vehicle speeds) would obviously lead to other values here.

The leftmost zone of the model contains all applications for driver Information. Such applications have the most relaxed timing requirements in this model and no critical safety relevance, yet the highest distance to the situation. In fact, these applications conform most likely to the traffic efficiency applications from the classification in section 1.2. There is a smooth transition from safety to efficiency applications, as there is also between the individual safety applications with soft and hard timing constraints. The next zones for Awareness, to inform the driver about road hazards, and for Warning, to signal possible collision risks, still contain applications for driver assistance. The Maneuver zone is characterized by an increasing collision probability and a TTC that is below the reaction time of most drivers. Hence, this zone is the last one that contains primary road safety applications to avoid collisions. However, collision avoidance and stabilization would only be possible with the active engagement of the vehicle's automatic control systems. Additionally, the model also contains secondary safety applications in the zone where the collision probability reaches 100 % and a crash is inevitable. Finally, tertiary e-call applications aim for safety relevant actions after the incident takes place.

1.5.1. *Evaluation metrics*

The application and hence the communication performance in the simulation scenario should be evaluated with two distinct metrics.

1.5.1.1. *Safety metric*

For safety use cases, it is particularly relevant that the periodically transmitted information (in CAMs) reaches the destined receivers in time. Conventional approaches to analyze only the packet delivery ratio (PDR), meaning the successfully received messages out of all sent messages, or the transmission latency, meaning the delay from the sending attempt to the reception, deliver only a limited informative value for this issue. The combination of both metrics evaluates the time period between two successfully received messages from an according sender. This metric is known under several synonyms as Consecutive CAM Period (CCP) [PRO 14d], Inter Reception Time [ELB 06], Inter-Packet Gap or Update Delay [KLO 12].

The CCP could be represented with the following equation 1.1, where $n-1$ and n are two subsequently received messages and t_r is the time of reception:

$$CCP(n) = t_r(n) - t_r(n-1) \quad [1.1]$$

According to this definition, the CCP initially depends on the sending rate f_s and the communication quality, which is actually the property that should be measured.

In the case of ad hoc communication with single-hop broadcast of messages to the neighbors in the communication range, packet losses due to fading or shadowing would lead to an increased CCP compared to the sending rate. Hence, the CCP is qualified to measure burst errors. In the case of communication over a cellular network, packet losses are mitigated by methods of (hybrid) ARQ with message retransmissions on the different layers. However, this approach could result in higher transmission latencies than the sending rate. On the receiver side, this aspect denotes out-of-order delivery for the individual packets. The CCP is also qualified to measure this case, which leads to an increased CCP, as only the most recent updates are useful for the safety applications.

With the given definition, the sole CCP has some minor drawbacks. First, the range of the CCP is in the interval of $[\frac{1}{f_s}, \infty)$. Particularly in cases where the CCP has high values, the potential receiver never receiving updates from the sender, could have two causes. It could either depict critical burst errors. However, the two nodes could also be located far away enough from each other to be anyway out of communication range and thus most probably also out of mutual relevance. Second, the CCP actually measures the supported real-time capability for the certain use cases and the use cases could have very different requirements towards this reaction time.

Hence, the evaluation of the CCP should primarily consider all CCP time spans t_{ccp} where the node i is in the relevance area t_R of a regarded sender and where the t_{ccp} is smaller than or equal to the real-time requirement τ plus a short time difference δ_t. This short time difference accounts for tolerable jitters in the message transmission. The Safe Time Ratio (STR) is the result when this value is normalized with the time span where the nodes are in the relevance area. It is described in (equation 1.2):

$$STR_i(\tau) = \frac{\sum \{t_{ccp}(i) | t_{ccp}(i) \in t_R \wedge t_{ccp}(i) \le \tau + \delta_t\}}{\sum t_R} \qquad [1.2]$$

The name Safe Time Ratio (STR) was coined in related work [SEG 14]. The definition of the STR shows similarities to the calculation of cumulative distribution function (CDF) of the distribution of the CCP as it considers all measures less than or equal to a specific value. Actually, the complementary CDF is used in the literature for the measurement of unreliable periods [KLO 12].

1.5.1.2. *Efficiency metric*

Due to a higher distance horizon towards the traffic situation, efficiency use cases have more delay-tolerant characteristics. The quality of information reception could be calculated with a mean squared error metric regarding the received information, according to equation 1.3. This metric considers the deviation of the perceived information data $\hat{D}(i)$ at the individual vehicle node i in comparison to the data of the actual reference situation D. For better scalability, the MSE is normalized with the norm of the reference data D:

$$MSE_i = \mathbb{E}\left[\frac{1}{\|D\|^2}\left\|\hat{D}(i) - D\right\|^2\right] \qquad [1.3]$$

For the simulated applications, we use the current speed from the transmitted CAMs as well as Floating Car Data (FCD) messages as representative parameters of the information. For the simulation, the reference data D directly depends on the generated mobility pattern from the traffic simulator.

1.5.2. *Simulation set-up*

One particular aim of the simulation is the presentation of the features of our introduced cellular simulator VSimRTI_Cell. Thus, this simulator is part of the simulation set-up. In general, the set-up includes the following simulators for the different domains:

Traffic: the microscopic traffic simulator SUMO [KRA 12] simulates a realistic mobility pattern for the vehicles in the scenario;

Application: the VSimRTI internal simulator VSimRTI_App serves as a data generator for the communication messages and hosts the application logic for message reception and maintenance of a local dynamic map (LDM);

Ad hoc communication: the well-known network simulator OMNeT++ [VAR 08] simulates the IEEE 802.11p based communication stack and realistic radio propagation with fading and shadowing characteristics;

Cellular communication: the VSimRTI_Cell simulator, introduced in section 1.4, will simulate the transmission over the cellular network.

1.5.2.1. *Traffic simulation*

The scenario to be simulated is shown in Figure 1.7. It is located in an inner-city environment in Berlin (Germany). The scenario includes 30 reference vehicles overall to be equipped with the applications and the communication technologies. Only these reference vehicles are considered for the result evaluation. The vehicles are spawned into the simulation on ten different routes, although the routes could partially overlap. This means on each route at least three vehicles enable a sufficient grade of measurement coverage. The vehicles do not perform any reactions to the traffic situation like changing their route. The main intention is to drive their route and exchange information.

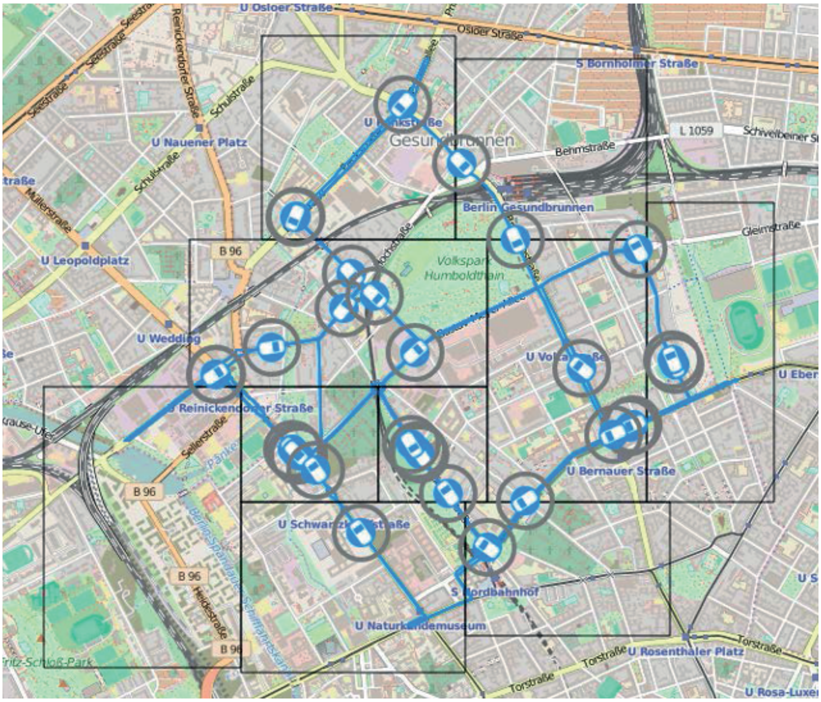


Figure 1.7. *Simulation scenario with routes of individual vehicles and cellular regions. For a color version of this figure, see www.iste.co.uk/hilt/transportation.zip*

1.5.2.2. *Application simulation*

The application logic is separated into three individual parts to be deployed on the vehicles and one application for a traffic efficiency server on the Internet. However, the simulated applications will not influence the traffic behavior with active route changing or similar actions:

VehicleMainModule implements the basic application facilities and should be equipped on the vehicle in every variation. It collects the sensor, location, speed and direction data to be included in the CAMs. Moreover, it maintains the LDM from sensor data as well as received messages from the ad hoc and cellular network. More specifically, the LDM implements a data matching of the information to a grid with geographic pixels;

VehicleAdhocModule uses the data from the VehicleMainModule and communicates it via IEEE 802.11p. It implements two different messages to be periodically disseminated. The CAMs only include the most recent local sensor data.

The FCD messages summarize the information in the LDM and map it to the central point of a geographic pixel before dissemination. Thus, it has two main parameters for the regular sending period of the CAMs and the FCD messages;

VehicleCellModule is the analogous component to the VehicleAdhocModule to communicate over the cellular network. This module supports an additional configuration for the local CAM destination area to be processed by the GEO in the cellular network. Moreover, it additionally sends CAMs per unicast to the Traffic Server. However, this application does not send FCD messages as they are managed centrally by the ServerModule;

ServerModule is the application on the server and maintains a central map with the same configuration as the LDM. It collects traffic information of the CAMs from the registered vehicles and periodically disseminates FCD messages back to the vehicles.

Table 1.1 outlines the specific configurations for the most important parameters of the individual application modules. Some parameters apply for multiple application modules.

Parameter	Application module	Value
LDM Grid Size	VehicleMainModule, ServerModule	20×20 pixels
LDM Pixel Side Length	VehicleMainModule, ServerModule	200 m
CAM Interval	VehicleAdhocModule, VehicleCellModule	100 ms
CAM Geo Radius	VehicleCellModule	695 m
CAM2Server Interval	VehicleCellModule	1 s
FCD Interval	VehicleAdhocModule, ServerModule	10 s

Table 1.1. *Simulation parameters for the application modules*

1.5.2.3. *Communication simulation*

The communication networks are simulated by OMNeT++ (ad hoc) and VSimRTI_Cell (cellular).

OMNeT++ uses the advanced communication models for the site-specific propagation, particularly shadowing characteristics [PRO 14c]. Moreover, OMNeT++ simulates the IEEE 802.11p based communication stack with the parameterization from Table 1.2. The given models for MAC and PHY layers respect all important aspects such as hidden terminals.

VSimRTI_Cell simulates the different cellular regions, shown as black rectangles in Figure 1.7. The region locations and expansions conform to data from OpenCellID (http://opencellid.org). All regions possess equal parameterizations for the communication properties. The configuration is presented in Table 1.2. It assumes an up-to-date HSPA network with capacity and delay properties to be in-line with recent measurements [SER 09, PRO 09, TEN 10]. The Traffic Server is located in a specific region with the properties of the overall network to simulate a well-connected Internet server.

IEEE 802.11p parameter	Value
Carrier Frequency	5.9 GHz
Bitrate	6 Mbit/s
TxPower	50 mW
RxSensitivity	–85 dBm
ThermalNoise	–94 dBm
AntennaGains	0 dBm
Cellular parameter	**Value**
Region UL Capacity	28.0 MBit/s
Region DL Capacity	42.2 MBit/s
Region DelayModel	GammaSpeedDelay
Region UL/DL minDelay	40 ms
Region UL/DL expDelay	150 ms
Network UL/DL Capacity	100 MBit/s
Network DelayModel	SimpleRandomDelay
Network UL/DL minDelay	10 ms
Network UL/DL maxDelay	30 ms
Network UL/DL delaySteps	3

Table 1.2. *Simulation parameters for the communication properties*

1.5.2.4. *Simulation variations*

For the subsequent simulation series, we investigate three different scenarios where all reference vehicles in the simulation are equipped with a variation of the application modules:

ad hoc VehicleMainModule + VehicleAdhocModule

cellular VehicleMainModule + VehicleCellModule

hybrid VehicleMainModule + VehicleAdhocModule + VehicleCellModule

The Internet-based traffic server is equipped in all scenarios with the ServerModule. However, in the ad hoc scenario, it never receives any messages.

1.5.3. *Simulation results*

In the following, we first analyze the safety capabilities of the different communication approaches with the help of the presented metric of the safe time ratio (STR). Afterwards, we evaluate the mean squared error (MSE) to measure the quality of the general information dissemination over a longer range in the whole scenario. Most traffic efficiency applications are usually based on such a dissemination principle.

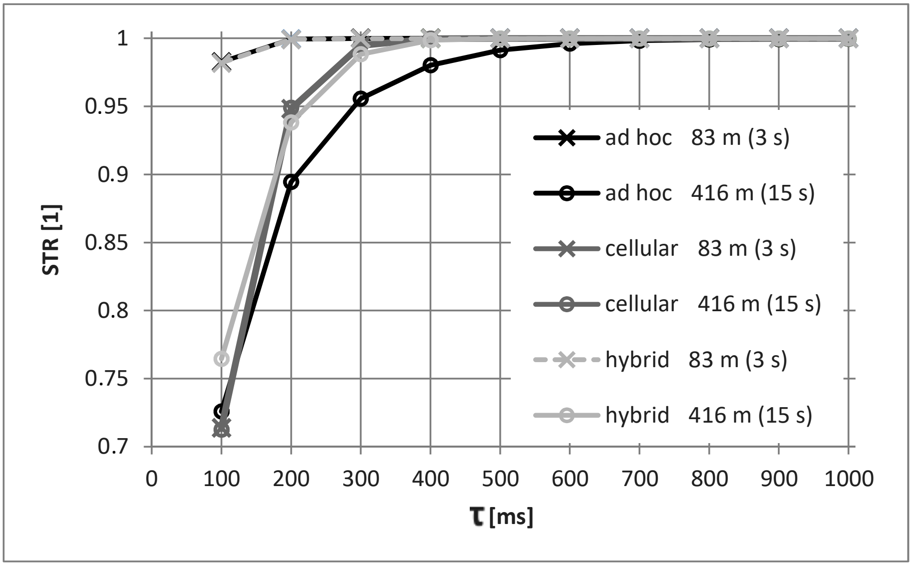


Figure 1.8. *Results for safety metric STR for different equipment settings and relevance areas*

1.5.3.1. *Safety metric*

The results for the STR are presented in Figure 1.8. The graph shows the STR's dependency on the real-time requirement τ. They include two variations: first, they show the communication technologies (ad hoc, black; cellular, dark gray; hybrid, light gray). Second, each access technology graph is presented with two different parameters for the relevance area time (t_R). In our evaluation, we define the relevance area according to the linear distance between the two vehicles. However, it could also incorporate further parameters as a converging trajectory, the same road or even lane etc. to limit the area to a more restricted set of relevant vehicles (e.g. eliminate vehicles in the opposite direction on a motorway). The linear distance, nonetheless, includes the most demanding properties. We selected a near-field relevance area of 83 m (line marker "x"), which addresses, according to Figure 1.6, use cases in the zone between Maneuver and Warning. For instance, the Intersection Collision Warning or the Electronic Brake Light Warning would be in this area. The second relevance area of 416 m (line marker "o") is in the middle of the Awareness zone from 1.6 and accounts for safety use cases with a slightly longer horizon, such as the Approaching Emergency Vehicle Warning.

The results for the ad hoc case in the near-field relevance area show that the STR already starts with a sufficiently high value of 98 % even for the most demanding τ of 100 ms. It quickly converges towards 100 % with a more relaxed τ. This is a result of the good communication properties of the direct IEEE 802.11p broadcasting with very short delays in the order of low ms and the low packet losses over short distances. The figures change for the medium field relevance area of 416 m, which should still be well within the limits of the communication range of our IEEE 802.11p configuration (with the parameters of transmission power, receiver sensitivity, etc.). However, the results reveal the known PHY Layer issues of increased packet loss due to fading, shadowing and also MAC layer coordination issues such as collisions due to the hidden terminal problem. Even in our moderate scenario, we could measure burst errors of spans longer than seven consecutive CAMs, resulting in the STR graph only converging toward 100 % at a τ of 700 ms. For higher relevance areas, the figures would turn out even more critical.

For the cellular case, both STR graphs show an equal trend, which is independent from the relevance distance. This reflects the expectation value of the underlying models of the regions with sufficient capacities to deliver all transmitted CAMs with the given delay distribution. We can see that there is a certain probability that messages are received out-of-order when particular messages, for example, take a longer way through the network with a higher latency. As the considered safety use cases mainly require the most recent updates of the CAMs only, older messages are dropped and neglected for the CCP and STR evaluation. This means, even when the data throughput of cellular networks is acceptable, the delay limits the performance of the use cases with real-time requirements less than 400 ms. This could be critical especially for use cases in the near-field relevance area of 83 m, where ad hoc communication shows its advantages of short latencies. If the future 5th generation of cellular networks can reduce latencies to the required scale, they could be a serious alternative for safety use cases.

For now, the hybrid approach to sending CAMs via ad hoc and cellular networks could be used as a migration path. The hybrid approach shows a similar trend to the cellular approach for the higher relevance distance of 416 m in supporting use cases with a τ of 400 ms fully with 100 %. It even starts at higher figures for the most demanding τ of 100 ms as the reception of short-delay ad hoc messages improves the performance. For the near-field relevance distance of 83 m, the ad hoc transmission appears to be dominating. Due to this, the hybrid approach delivers a more equal result compared to the ad hoc approach.

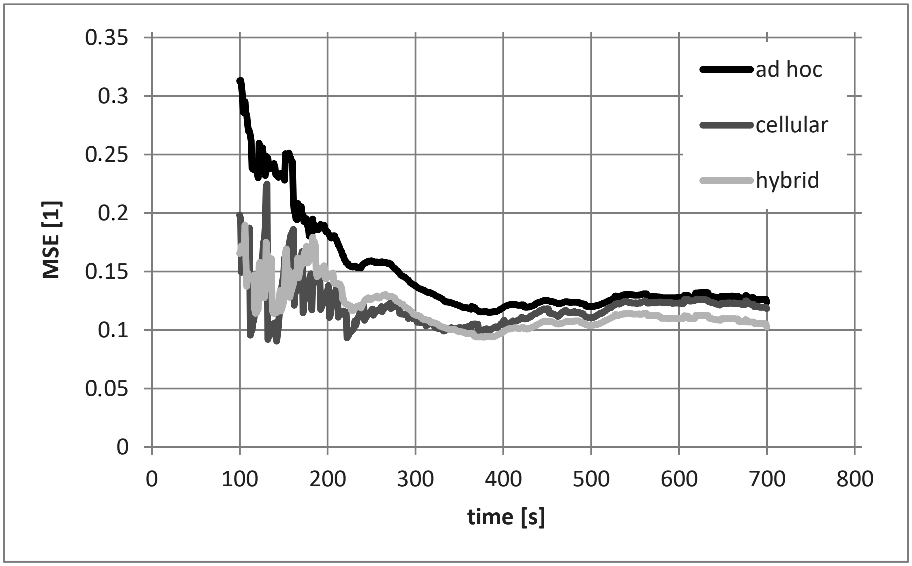


Figure 1.9. *Results for efficiency metric MSE for different equipment settings*

1.5.3.2. *Efficiency metric*

Figure 1.9 shows the development of the normalized MSE on the vehicles during the simulation time. It includes three graphs for the three different communication approaches (ad hoc, black; cellular, dark gray; hybrid, light gray). We cut away the very early and final phases of the simulation, when many vehicles still have to enter or, respectively, have already left the simulation. However, it is still worth examining the transition phases which would depict situations where the vehicles and thus the traffic information are not well distributed, but concentrated locally. Such situations may for instance appear temporarily in low traffic periods or in the early stage of system introduction when the penetration rate is generally low.

The trend of all graphs shows that the MSE generally decreases over the simulation time. It very slightly increases in the final phase when the first vehicles leave the simulation. We can see that the ad hoc approach, despite the short possible communication range, even reaches similar figures for a later simulation time compared to the other approaches. Our information handling algorithm which is based on the LDM actually implements a typical store-and-forward semantic. This approach collects information and carries it with the movement of the vehicle to later retransmit the summarized information. This is a very efficient method to increase the dissemination area for more delay-tolerant information. However, the black graph for ad hoc communication takes a longer time span to decrease as the vehicles have to drive for a certain amount of time to meet and exchange the information they have collected on their way. In comparison, the graphs for the cellular and hybrid approaches already start at fairly lower MSE values in the beginning of the simulation. This is due to the fact that the Traffic Server can quickly mirror the perceived traffic information back to the equipped vehicles. In the later simulation time, the hybrid approach slightly outperforms the cellular approach.

In summary, it could be stated that the cellular approach in this time period already delivers sufficient results for information dissemination. The hybrid approach, with additional messages over ad hoc communication, may still improve the redundancy. Nonetheless, our presented information handling application is still very simple and could be still improved with more advanced techniques for data aggregation, e.g. from the field of machine learning. However, this was out of scope of the presented evaluation.

1.6. Conclusion

Ad hoc networks based on IEEE 802.11p enable a decentralized information exchange among vehicles, and among vehicles and infrastructure units. Since the limited communication range and the lack of deterministic quality of service are a challenge for the scalability of ad hoc networks, some new approaches try to overcome these drawbacks by using cellular networks for the information exchange among vehicles. However, although cellular networks enable a nearly unlimited communication range, the architecture of these networks can involve a delay in information transmission which might violate the strong requirements of many safety applications. To reduce the drawbacks of both networks types, an intelligent combination of vehicular ad hoc networks and cellular networks could help. However, detailed analyses are needed to evaluate in which cases pure ad hoc networks, pure cellular networks or a combination of both would be the best. To give the research community a powerful tool for these evaluations, we have developed the novel cellular communication simulator VSimRTI_Cell. This lightweight tool models a level of abstraction of cellular networks and allows the simulation of large scenarios. Due to the coupling of VSimRTI_Cell to the existing simulation framework VSimRTI, this extended framework is predestined for the modeling of ad hoc networks and cellular networks. Our simulation study, presented in this work, gives an example to show how the research in this area can be addressed.

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