Networking Simulation for Intelligent Transportation Systems
Networking Simulation for Intelligent Transportation Systems

High Mobile Wireless Nodes

Edited by

Benoit Hilt
Marion Berbineau
Alexey Vinel
Alain Pirovano
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Preface

Nowadays, network simulation has become more affordable than real-world experiments and the least-expensive mean for the evaluation of networking propositions for Intelligent Transportation Systems. This requires that, for purposes of accuracy, simulation software adapts to the simulated field. Which, for the case of ITS, results in integration of realistic mobility, wireless communication environments, and protocol mechanisms that are as precise as possible.

However, every simulation user should be aware of the fact that simulation only represents the functioning of the real world in a limited way.

In this book, we show how simulation can be used in several domains of ITS, ranging from vehicular to railway and aircraft communication networks, with appropriate examples. In the 10 chapters of this book, several levels of the communication models and the technologies of ITS communication are addressed. This ranges from channel modeling to traffic generation, including access layer and routing.

In Chapter 1, Robert Proztmann et al. address the scalability of vehicular communication technologies on the basis of IEEE802.11p when mixed with LTE technology. They present a multi-aspect simulation environment called VSimRTI, a comprehensive framework that connects various simulation tools together to cover all aspects needed for a proper evaluation of new cooperative mobility solutions for ITS.

In Chapter 2, Christian Pinedo et al. address the challenges associated with the interaction of the Internet of Things (IoT) and the ITS domain. They aim to provide guidelines on modeling these smart, low-cost, near-field wireless objects and on how to integrate their behavior in traditional network Discrete Event Simulation (DES) tools.
In Chapter 3, Fabien Garcia et al. analyze the current traffic regulations in different airspaces. They lay out the constraints in aircraft movement as well as the different types of mobility models and their respective merits. They finally present traffic traces’ extraction, enhancement and filtering, leading to new developments on cooperative trajectory studies as a new trend.

In Chapter 4, Christophe Guerber et al. deal with data exchanges between on-board and ground systems. They explain how simulation can be a solution to assess the performances of aeronautical communication architectures and protocols through the examples of communication technologies such as VHF Data Link (VDL) and Aeronautical Mobile-Satellite Service (AMSS).

In Chapter 5, Patrick Sondi et al. propose, in the context of the European Rail Traffic Management System (ERTMS), a virtual laboratory based on co-simulation. It relies on two existing tools: an ERTMS simulator implementing the functional subsystem (ETCS) and an OPNET simulator that enables the modeling of the whole telecommunication subsystem, namely the GSM-R (Global System for Mobile Communications’ Railways). They also address the evolution from co-simulation to multi-modeling in order to directly connect the models and avoid the problems related to heterogeneity of simulators.

In Chapter 6, Herve Boeglen et al. show the effects encountered when WiFi frames are transmitted over the air. They provide a channel simulation solution, which is a trade-off between computing time and realism. The source code for ns-3 of this solution is provided in an appendix.

In Chapter 7, Justinian Rosca et al. present a platform that flexibly integrates a traffic simulator with a communication simulator, thus providing an ideal platform for co-simulating transportation system applications. The communication models can be tuned on the basis of real-world measurements in scenarios such as urban, residential and highway traffic.

In Chapter 8, Marco Gramaglia et al. focus on the representation of road traffic for the simulation of highway vehicular networks based on V2V communication technologies and present an original, fine-tuned, measurement-based mobility model.

In Chapter 9, Sebastien Bindel et al. explore the Link Quality Estimators (LQE) in the context of VANET. They propose a metric (F-ETX) that automatically adapts to the link quality and provides a trade-off between the dynamicity and accuracy of Link Quality assessment.
In Chapter 10, Nader Mbarek et al. show how to adapt the Autonomic Computing paradigm to ITS and in particular to Vehicular Ad hoc Networks (VANETs) in order to enhance the performance of communications in such changing environments. The design of a QoS-based broadcasting protocol is presented as a usage case.

We hope that this multi-purpose book will help the reader to move a step forward in their understanding and/or current work in the domain of network simulation for Intelligent Transportation Systems.

Benoit HILT
Marion BERBINEAU
Alexey VINEL
Alain PIROVANO
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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
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](image)

### 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](image)

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 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.
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 \((\text{minDelay}, \text{maxDelay})\) 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 \([\text{minDelay}, \text{maxDelay}]\);

*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