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Simulation of V2X Applications with the iTETRIS system

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Abstract

The main task of the "iTETRIS" project which was co-funded by the European Commission was the development of a software system for the simulation of large-scale traffic management solutions based on vehicular communication (V2X). Several steps were taken to assure that the developed simulation system fits the current research and engineering needs, including the evaluation of a city's traffic problems, definition of performance metrics, development of V2X-enabled traffic management applications, and the extension of the simulators used within the developed simulation architecture. Within this report, the major results of the project will be presented. Most of these results were made freely available after the project's end.

Keywords: traffic management; vehicular communication; simulation;

1. Introduction

Vehicular communication (V2X) – the ability to exchange messages between vehicles and between vehicles and infrastructure – is a fast growing research topic highly assisted by the European Commission. The technology promises safer and cleaner mobility by increasing a vehicle's knowledge about its surroundings and by making more information about traffic available to the infrastructure. The development of solutions based on this technology requires proper simulation tools which allow predicting the impacts of the developed solutions before they are installed in the real world.

The iTETRIS project was co-funded by the European Commission and aimed at developing and implementing a software system for simulating vehicular communication and applications which are using V2X technology. The focus was to allow the simulation of large-scale traffic management applications – so-called efficiency applications – based on vehicular communications. Other types of applications using

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this technology, such as applications which aim on increasing vehicle safety or multimedia applications were not regarded within the project. Before implementing the simulation software itself, several steps were taken to assure it would fit the end-users needs.

The rest of this document is structured as following: first, a short introduction to the simulation of vehicular communication is given. Then, the steps taken for determining the end-user needs are described. Then, the implemented system is presented, followed by a summary on performed evaluations. The document ends with a summary.

2. V2X Simulation

While the idea of communicating vehicles goes back to 1939 and the GM “Futurama” World Fair (Hartenstein, Laberteaux, 2010), the allocation of new communication channels within USA, Japan, and European Union for vehicular communication, as well as available cheap Dedicated Short Range Communication (DSRC), or IEEE 802.11p hardware, raised new interest in vehicular communication. Not only potential applications of V2X technology have to be investigated, but also solutions to realize the communication between vehicles itself have to be developed, opening the research field to information and communication scientists and engineers.

Although V2X applications would preferably be developed and evaluated in real world environments, logistic, safety and monetary cost reasons make simulation-based evaluations a critical and necessary phase before deployment. Simulations also offer an easier reproducibility of results for the development of V2X applications, as well as the investigation of the benefit of a granular penetration of the V2X technology possible.

The first simulations performed in this area regarded only the communication part while the behavior of traffic participants was neglected. Computer network simulators such as ns-2 (ns-2, 2011) were used and extended by proper models for message propagation. The fact that the message senders/receivers (“nodes”) were moving was resembled using random movement on a 2D-plane or by moving them along simple road networks at a constant speed. The position changes were given to the network simulators as a list of coordinates at the simulation’s start and were replayed during the simulation’s run. These files describing the movement of a node (vehicle) through the network are called “trace files”.

The next step for gaining a larger degree of reality was to use traffic simulations for generating trace files (Karnadi, Mo, Lan, 2007). This procedure allowed including movement characteristics of vehicles into the simulation runs, including the dynamics of single vehicles as well as constraints posed by the infrastructure, such as halting in front of red lights. Additionally, most traffic simulation packages allow setting up real-world road networks so that the behavior in a certain, real-world scenario can be modeled.

Along with gaining more expertise in simulating vehicular communications, the wish to model not only the communication itself, but also the effects of applications which use the exchanged information grew (Sommer et al, 2008). As the effects manifest in driving behavior, such as lane changes, acceleration/deceleration, route changes, or in changes of the infrastructure, such as a prolonged green light time for most occupied roads, the simulation of these effects was not possible using predefined trace files. Instead, the changes in driver/infrastructure behavior had to be put back and incorporated into a traffic simulation for investigating the impact of these changes on traffic in later simulation steps.

Several systems which allow an interaction between a traffic simulator and a network simulator exist. Many of them were developed as a part of a doctoral thesis which puts some constraints on a long term applicability of these software solutions. The major problem is the lack of support for these tools after the end of the thesis within which they were developed. Additionally, these tools usually cover only the features needed within the thesis, making them applicable for only some part of possible V2X usage scenarios. At last, as the standardization of vehicular communication is progressing, they often use outdated assumptions about the communication characteristics. In contrast, iTETRIS was intended as a sustainable, up-to-date and supported V2X simulation environment.

3. iTETRIS Approach

For assuring that the developed simulation system will be capable to simulate modern V2X-based traffic management applications, the needs were evaluated, first. They included the determination and implementation of simulation scenarios, the development of metrics, as well as evaluation of possible traffic management applications. The named results will be described in detail in the following.

3.1. Scenarios

The first step in iTETRIS development was to investigate real-world traffic problems. The task was performed by the municipality of the city of Bologna who was one of the iTETRIS project partners. Four example areas were recognized and the problems arising in those areas were described. Additionally, proposals for traffic management solutions which may solve these problems were given. Table 1 gives a summary on these results.

Table 1. Chosen areas within the city of Bologna, together with traffic problems found within them and possible solutions.

Area	Problems	Solution/Strategy
“acosta”/”pasubio”	public transport vs. private event traffic	bus lanes management
“irnerio”	detectors down	identify malfunctioning detectors
	road yards	increase intersection capacities
		suggest alternative routes
“ringway”	only way to cross the city	increase intersection capacities
	congestions	suggest alternative routes
		allow low-emission vehicle to cross the inner ring
“highway/orbital”	congestions on orbital	suggest best orbital exit

Besides these descriptions, simulation scenarios for the microscopic traffic simulation “Vissim” (PTV, 2011a) and scenarios for the macroscopic traffic assignment tool “VISUM” (PTV, 2011b) were generated. Each of these scenarios describes the traffic within an area of the city, including the definition of the demand for the peak hour between 8:00am and 9:00am. Additionally, information about infrastructure, such as traffic lights, parking zones, or variable message signs, were given in form of shape files, intersection telemetries, and traffic light signal plans. These inputs were converted into the traffic simulation “SUMO” (Behrisch et al, 2011, Krajzewicz, 2011, DLR, 2011, see also section 4.2). Figure 1 shows the scenarios obtained from Vissim, Figure 2 the ones converted from VISUM.

Fig. 1. iTETRIS-scenarios extracted from Vissim: “a.costa", “pasubio”, “joined”.

Fig. 2. iTETRIS-scenarios extracted from VISUM: “irnerio”, “ringway”, “highway”. All cover parts of the city of Bologna, please note different scales.

3.2. Metrics

Well-defined metrics make simulation runs comparable. Even metrics which seem to be unambiguous can differ in their definition; see (Blokpoel, Krajzewicz, Nippold, 2010). The definition of metrics in iTETRIS put the focus on road-traffic related metrics available within a traffic simulation. They differ slightly from metrics used by traffic engineers, as a simulation has a complete knowledge about the state of the modeled network, while real-world measures are mostly incomplete.

At the very beginning, it was found that a distinction should be made between network-wide metrics and metrics for single intersections. Some major metrics, such as “average travel time” are very common for describing the performance of a solution on a city-wide level, but can hardly be applied to single intersections. On the contrary, the performance of a traffic light system at an intersection can be well described using values such as queue length which are rather useless on a city-wide level.

The metrics were developed by collecting metrics used by the project partners, first. 27 road network performance metrics and 15 intersection performance metrics were found. In a second step, the collected metrics were rated by the involved partners separately using five grades between ‘- -’ (irrelevant) and ‘+ +’ (needed). The overall ranking for each of the metrics was obtained by averaging the per-partner ranks. The metrics which were ranked most important – 16 network metrics and 11 intersection metrics – were then defined using “atomic” measures, such as current vehicle velocity, road length, etc. For example, the metric “travel time” is defined as:

$$P_s^{\text{travel time, mean}} = \frac{1}{n_s^{\text{vehs}}} \sum_{n=1}^{n_s^{\text{vehs}}} t_n^{\text{travel}} \quad (1)$$

using:

n_s^{vehs} (set of) vehicles simulated within scenario *s* (number of vehicles which entered the simulated area during the simulation run

t_{veh}^{depart} the time at which vehicle *veh* enters the simulated network (in [s])

t_{veh}^{arrival} the time at which vehicle *veh* leaves the simulated network (in [s]).

$t_{veh}^{\text{travel}} = t_{veh}^{\text{arrival}} - t_{veh}^{\text{depart}}$ the travel time of vehicle *veh* (in [s])

The complete list of defined metrics can be found in (Blokpoel, Krajzewicz, Nippold, 2010).

3.3. Applications

Based on the traffic management methods proposed after the evaluation of the traffic within the city of Bologna, applications which realize these methods using vehicular communication were specified. The specifications include the following applications: Traffic jam ahead detection (distributed method), Travel Time Estimation (Centralized), Bus lane management (with road recommendation), Limited Access Warning (Lane Closure / without Road Recommendation), Request-Based Personalized Navigation, Regulatory and contextual Speed Limit Information, Emergency Vehicle, Event Based Traffic Condition Notification, Traffic Light Adaptation by Traffic Management Centre, Identification of malfunctioning Loop Detectors, Induction Loop Replacement, Postpone departure Time for Road Network Balancing, Centralized Route Recommendation based on Travel Time Estimation, (Decentralized) Floating Car Data, Routing in Traffic Light controlled Network.

For determining the implementation requirements of the iTETRIS simulation system under development, each of these applications was defined on a fine scale by giving:

- a tabular description including the type of messages used by this application, the actors involved, the type of the required network, the needed communication range, transmission frequency, the message expiry time, as well as further information about how this application should be evaluated
- a component diagram showing the structures which should be simulated assigning them to the involved simulators
- a sequence diagram showing the behavior of the real-world components
- a sequence diagram showing the behavior of the simulation components
- the resulting high-level requirements to the involved simulators

4. iTETRIS Simulation System

4.1. Network Simulator: ns-3

Within initial tests, the network simulator ns-2 and its successor ns-3 (ns-3, 2011) were compared. The tests showed ns-3 to be more stable when simulating a large number of nodes which made it preferable to ns-2 for large-scale evaluations.

Within iTETRIS, major changes to ns-3 were implemented. For making it interoperable with the complete simulation system, ns-3 was extended by a socket-based communication interface which allows to trigger the simulation of sending a V2X message, to retrieve the information about received messages, and which allows to trigger a simulation step. As ns-3 is originally used for simulating wired IPv4 and IPv6 networks, further extensions were necessary to allow the simulation of messages sent via a V2X wireless channel. These extensions have been realized by implementing a further communication stack which lives besides the existing stacks for IPv4 and IPv6 communication within ns-3. Figure 3 shows the implemented architecture and its components, revealing the also implemented communication channels 802.11p, UMTS, WiMAX, and DVB and the ability to simulate different message routing protocols. The iCS is the iTETRIS Control System, which will be further discussed in section 4.3.

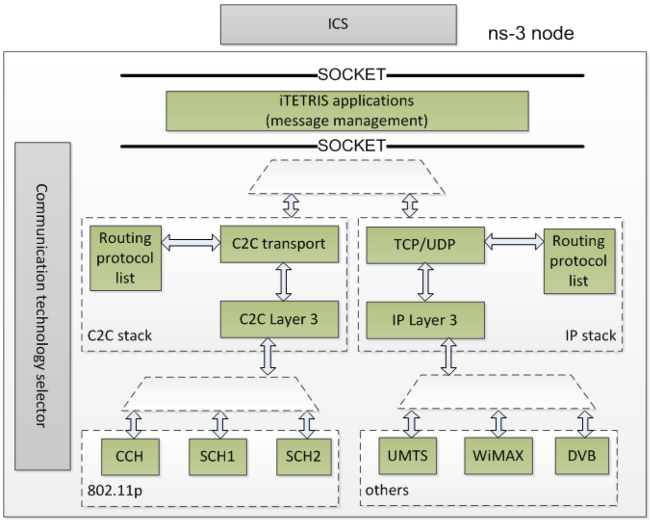

Fig. 3. ns-3 V2X stack architecture and components, where C2C stands for Car-2-Car, and CCH, SCH, stands for Control CHannel and Service CHannel, respectively.

Additionally, different propagation models have been included into ns-3, showing the need to use modern propagation models such as WINNER (WINNER, 2007) which regard obstacles between communication nodes such as buildings.

4.2. Traffic Simulator: SUMO

The traffic simulation package “Simulation of Urban Mobility” is a development of the Institute of Transportation Systems at the German Aerospace Center. The work on this road traffic simulation started in 2001. SUMO was meant to be released as open source from the very beginning, and a first public version was released in 2002. Besides the traffic simulation itself, the SUMO package includes a set of further tools for importing and generating road networks as well as for importing, converting and generating traffic demand. SUMO is capable of modeling and simulating road traffic including public transport, different traffic light types and multi-lane traffic.

SUMO has already developed into a popular tool within the vehicular communication simulation community. After being used for generating trace files, an extension implemented mainly by the University of Lübeck named “TraCI” (“Traffic Control Interface”) allowed to use SUMO in a loop with an external network simulation application by coupling both using a socket connection. This extension allows to retrieve the positions of simulated vehicles, but also to influence them by giving them commands for lane changing, speed adaptation, etc. Currently, SUMO is used in conjunction with different communication simulators using different middleware solutions.

Several extensions have been made to SUMO within the iTETRIS project. The major ones will be discussed in the following.

4.2.1. Pollutant and Noise Emission Modeling

iTETRIS put a strong emphasis on allowing to measure the environmental effects of the developed V2X applications. This requirement necessitated an extension of the traffic simulation by models for pollutant and noise emission as well as for fuel consumption. It was assumed that an existing model should be re-used. An initial evaluation of available models resulted in a list of 15 models for pollutant emission / fuel consumption and 5 models for noise emission. The variety of the found models was very large, especially within pollutant emission models, ranging between coarse, macroscopic models which need only the driven distances and road types as input and very fine-grained emission models which require parameter as engine displacement, air conditioner parameter etc. In order to find a model which fit our needs, the input needed by the found models was put against parameters of the vehicles simulated in SUMO. Also, it was verified that the desired output values – the emission of the pollutants CO, CO_2, NO_x, PM_x, and HC as well as fuel consumption – could be computed by the model. After this comparison, it was decided to use the HBEFA database (INFRAS, 2011) as an input for the emission model. This database includes emissions for 130 classes of vehicles. The values stored in the database were extracted for each HBEFA emission class individually and fitted to a basic energy consumption function (M. Treiber, A. Kesting, C. Thiemann, 2008).

As the number of vehicle classes stored in the HBEFA database is very large, the obtained curves were clustered in order to join similar HBEFA vehicle classes. This reduction of modeled classes was done to simplify the process of setting up a simulation. The implementation allows the retrieval of pollutant emission values as well as the fuel consumption for each vehicle in each simulation step. It also allows aggregated outputs per vehicle, per edge or per lane over chosen time intervals.

The HARMONOISE (R. Nota and R. Barelds and H. van Leeuwen, 2005) model was used for modeling a vehicle's noise emission. The implementation allows aggregated outputs per edge or per lane over chosen time intervals.

4.2.2. Interfaces to external Applications

As stated before, SUMO allows an external application to connect to a simulation and to interact with the simulation using "TraCI". Within iTETRIS, the number of possible interactions was increased. Now, almost all simulated artifacts can be accessed and influenced, including traffic lights, vehicles, vehicle types, vehicle routes, induction loops, etc. as well as the parts the network is made of, namely lanes, edges roads, and intersections.

4.2.3. Sub-Second Simulation Time Steps

One major feature wanted by the V2X simulation community was the ability to run the traffic simulation with time steps below 1s. Two reasons motivate this: i) the fact that the processes simulated by communication simulations are very fine-grained in time and ii) the wish to simulate safety-related applications which need smaller time steps as the triggered actions influence vehicle dynamics on a fine-grained time scale, too.

To meet these requirements, SUMO's simulation core was reworked to milliseconds as internal time measure instead of seconds. The actual step time for a simulation step can be configured at the start of simulation and may be a value between 1 and 1000ms. The default was kept by 1s.

4.3. The iTETRIS Control System (iCS)

To coordinate both simulators, ns-3, and SUMO a third component is needed. This third component is the iTETRIS Control System (iCS), developed within iTETRIS. It is responsible for starting both simulators, for starting the traffic management applications to simulate, for synchronizing all these external applications, and for passing information between them, as depicted in Figure 4. Although other architectures for coupling simulations exist, it was decided to use basic TCP/IP socket connections. This has some advantages, such as the possibility to use a simple communication protocol, or the possibility to keep the interface simple allowing the adaptation of other communication and/or traffic simulations to the system more easily.

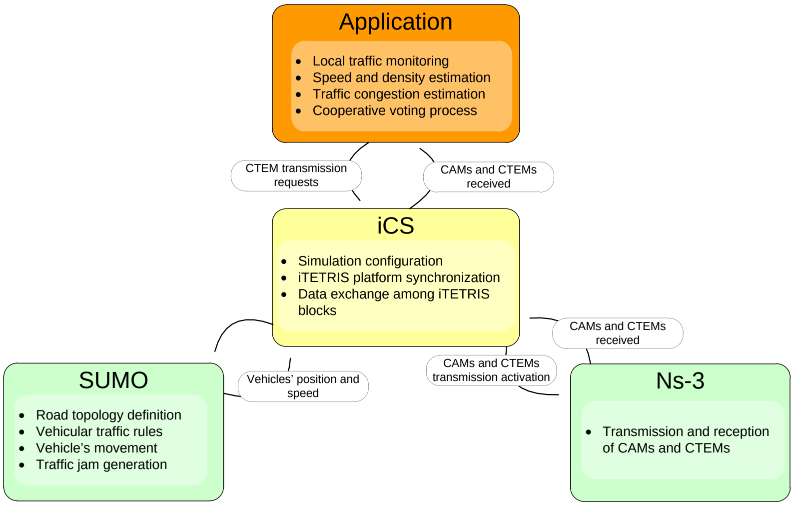

Fig. 4. The complete simulation execution system, including the used simulators, the simulated application(s) and the control instance. CAMs are Cooperative Awareness Messages, whereas CTEM are Cooperative Traffic Environment Messages.

When run, the iCS starts the involved simulators and the applications to simulate, first. As soon as all simulators are ready, connections to them are established, and the simulation loop begins. The iCS simulation loop works as follows. At first, a simulation step of ns-3 is executed which simulated the exchange of V2X messages. The information about received messages is sent back to the iCS. In the next step, one step in SUMO is executed, moving vehicles through the road network and sending back the information about the simulated equipped vehicles' movement. Both data, the exchanged messages as well as the vehicle movements are then passed to the simulated applications and one step of the applications is executed. Finally, the information about vehicle positions and about messages to schedule for being send is given to ns-3. This concludes one iteration of the iCS loop and the next one starts.

5. Evaluation Results

The final step of the project was the usage of the obtained simulation system for evaluating message forwarding protocols as well as for evaluating traffic management applications.

The following message forwarding protocols were evaluated: Abiding GeoCast, Bi-Zone Broadcast Protocol (BZB), Contention based forwarding (CBF), Distributed and real time communications road connectivity discovery through vehicular ad hoc networks (DiRCoD), Greedy Perimeter Stateless Routing (GPSR), LANE-based vehicular density estimation Routing Protocol (LANE-RP), MobCast: Keep-alive for a geographical area, Multi hop vehicular broadcasting (MHVB), Movement Prediction-based Routing (MOPR), Spatially Aware Routing (SAR), Mapless road topology awareness, OPportunistic-driven adaptive RAdio resource Management (OPRAM), Reliable Distant-Neighbors Detection Variant (REDNET), Application layer congestion control policy, Information-centric Probabilistic Casting (iPC), and Road Topology-Oriented Contention-based Forwarding schemes (TOPOCBF). Most of these protocols combine some known methods, for keeping the message alive and for bringing it to the intended destination, such as rebroadcasting, store and forward, forwarding based on road topology, transmission power control, radio link reliability, etc. The evaluation shows that all of these methods bring benefits by increasing the protocol's robustness in congested and in sparse networks, even if messages are duplicated. Additionally, the evaluations show that a combination of such methods is needed if the scenario is varying in vehicle density, road type, or road density.

Nine traffic management applications were evaluated, partially reusing the descriptions mentioned in section 3.3. The results can be found in (iTETRIS, 2011a, Bauza, Gozalvez, Sanchez-Soriano, 2010, or Bieker, Krajzewicz, 2011) and can be summarized as following:

- heartbeat messages sent by V2X-equipped vehicles can be used to increase the knowledge about the state of the network though conventional, local measurements of traffic flow have to be replaced by other information, such as travel times on a global level or local vehicle velocities,
- conventional detectors, such as induction loops can be partially replaced by V2X communication if larger penetration rates are given,
- the V2X technology can be used for prioritizing vehicles, for example emergency vehicles,
- when developing V2X applications, one has to take into regard the penetration rate, as naïve applications may tend to degrade in performance with an increasing penetration rate.

6. Summary

The preparation work done in iTETRIS put the development of the simulation on a stable ground, assuring that the system will be applicable to real-world problems and engineer ideas. Additionally, traffic scenarios usable within the next project steps were obtained together with further information about the traffic of the city of Bologna. The developed measures allow the comparison of results obtained across different simulation runs.

Both simulators chosen were extended for being capable to perform simulations of modern vehicular communication, including the embedding of modern message propagation models, protocol stacks, and message forwarding protocols within the communication simulator ns-3, and environmental outputs, interoperability APIs, and sub-second time steps within the traffic simulator SUMO. Further components needed for the simulation of vehicular communication were embedded into the instance needed for coupling simulators named "iCS".

The obtained simulation system's usability has been proven by evaluating different message forwarding protocols and different traffic management applications. The results of simulating the latter prove a large potential of vehicular communication for traffic management, but also the need to develop traffic management application to a degree of high maturity before installing them in the real world.

Most of the results obtained during the project, including documents, data, and extensions to the involved simulators as well as the software coupling them were made available to the public under the general public license (GPL). Please note that not all of the achieved results could be presented here. Others can be requested at the project's web pages (iTETRIS, 2011b).

It should be stated, that both, communication and traffic models, are still a matter of scientific research. With the currently starting field operational tests (FOTs), such as DRIVE C2X, SCORE@F, or simTD, additional data will get available which will allow to further improved these models.

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