Simulative Evaluation of a UMTS-based Car-to-Infrastructure Traffic Information System

(Invited Paper)

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***Abstract*—We developed a simulation framework for holistic analysis of complex UMTS-based Intelligent Transportation Systems (ITS). This framework couples simulation models of the UMTS link level, of higher network layers, and of road traffic. ITS are a hot topic in the communications society. Currently, research is primarily focusing on setting up Vehicular Ad Hoc Networks (VANETs) based on WLAN technology. However, VANETs are heavily dependent on high market penetration or infrastructure support. Third-generation (3G) networks might complement these efforts. They are already widely deployed and can serve as the basis for Car-to-Infrastructure (C2I) applications. Based on our simulation framework, we evaluated a UMTS-based Traffic Information Systems (TISs) in a typical highway scenario in which information about traffic jams needed to be communicated to other cars for optimized route planning. The network setup is fictional; however, it clearly outlines the capabilities of the simulation framework as the measurement results are consistent with reasonable expectations.**

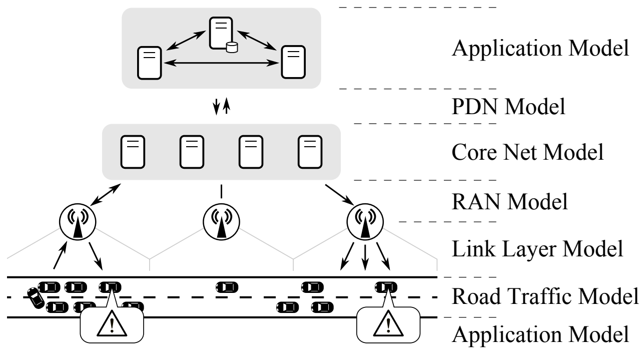


Fig. 1. Component model of the simulated UMTS-based Car-to-Infrastructure communication system

I. Introduction

Recently, the communications society intensified its focus on vehicular communication architectures and protocols. This includes scenarios such as safety applications, but primarily, these mechanisms are intended for use in general purpose Traffic Information Systems (TISs), e.g. for optimized route planning. Basically, two approaches are competing in this field: Car-to-Car (C2C) and Car-to-Infrastructure (C2I) communication architectures. Presently, mainly Wireless LAN (WLAN) is used in this domain. However, C2I applications require massive investments into a new infrastructure, e.g. along highways. C2C communication solutions address this problem by using the moving vehicles as a dynamic infrastructure established by Vehicular Ad Hoc Networks (VANETs). An example is the Self-Organizing Traffic Information System (SOTIS) approach [1]. Whereas it has been shown that this system works well even with a low density of SOTIS installations, new problem domains are opened, e.g. the increased end-to-end delay and the reduced quality or granularity of the available information. Furthermore, security is an aspect in terms of drivers' privacy and information security for closed user groups.

3G telecommunication networks, specifically UMTS, are a new player in this field [2], [3]. 3G approaches offer a couple of benefits for TIS applications. Compared to WLAN-based solutions, the perceived strengths and weaknesses of 3G networks are quite different. While, for example, the security of C2C networks cannot easily be guaranteed [4], there already are strong security measures in place to guarantee 3G networks' integrity, which can be re-used for C2I communication. As a second example, the distance between a message's sender and its intended receivers is almost a non-issue in 3G networks: its impact on the end-to-end delay is almost unnoticeable. On the other hand, even for short-distance messages the end-to-end delay is already quite high compared to that of direct radio links.

A key question asked about an infrastructure-based C2I communication system is therefore whether end-to-end delays will still be acceptable for common TIS applications. Another important question is whether such a system will scale better [5] than more traditional WLAN-based C2C solutions to accommodate high penetration rates, given that in this C2I solution all network traffic has to be routed through the available infrastructure. Both questions are at the core of the problems which hindered adoption of some of the early 2G-based approaches [6] to C2C and C2I communications via a cellular network proposed in the 1990s. Development of C2I solutions is now picking up again, with new approaches based on 3G networks.

Recent work in this field has mainly dealt with analytical evaluations of only some of such a communication system's aspects [3]. By means of an analytical model, the authors quantified the achievable performance in some realistic scenarios. In particular, the advantages of Multimedia Broadcast Multicast Service (MBMS) were studied, which is needed for efficient C2I services on top of the UMTS network.

Furthermore, experimental approaches have accomplished post-hoc analysis of implemented testbeds. In these setups, either detailed studies have been conducted [2] or complex extensible testbed architectures have been developed [7]. However, only the currently deployed UMTS versions could be tested and the size of the experiments was limited. Moreover, an evaluation of the environmental impact of TISs based on real-world experiments is infeasible, and even simulative studies on this topic are rare [8].

Simulation experiments of UMTS networks are usually done using proprietary models without focus on application in vehicular networks, e.g. in [9], and without incorporating realistic mobility models. Furthermore, such simulations are not using a holistic approach, i.e. they are not including all system aspects from the wireless links to the core 3G network as well as influence of the road traffic. Even for WLAN-based C2C approaches, it has been shown that coupled simulation of network communication and road traffic is necessary [10].

Comprehensive evaluations of such communication systems, using features which are still in the early planning stages, can, however, easily be performed if all components of such a system are modeled in sufficient detail and assembled into a simulative testbed. Therefore, we developed a new simulation framework that allows such a *holistic analysis* of complex 3G-based TISs. The simulation framework is based on a bidirectionally coupled environment for network simulation and road traffic microsimulation, which we developed and which we have also used for recent studies of VANET protocols [11].[1]

Our simulation framework will be used for the simulative evaluation of a planned real-world communication system, which is currently being designed in the Cooperative Cars (CoCar) project. The project is part of the German government-funded research initiative Aktiv[2], which encompasses research in the fields of traffic management, active vehicle safety, and cooperative systems.

In this paper, we show first simulation results for a typical highway scenario by using a fictional 3G network setup. The results clearly outline the capabilities of the simulation framework as the measurement results are consistent with reasonable expectations. Figure 1 depicts an overview of the CoCar communication system, along with the various models that have been integrated to form the testbed we will use for evaluations. Based on the example of the CoCar system, we describe in this paper each of the models the framework is composed of and detail how the models interact with each other.

The paper is structured as follows. First, section II introduces the application models. Then, section III gives an overview on the Public Data Network (PDN), Core Network, and Radio Access Network (RAN) models used. Section IV details the UMTS link layer model that was integrated with the simulator and section V introduces the road traffic model. We finally outline first results that we obtained in a proof-of-concept study, which focuses on the single use case of traffic jam warning exchange, and discuss the impact they will have on a real-world implementation (section VI).

[1] http://www7.informatik.uni-erlangen.de/veins/

[2] http://www.aktiv-online.org/

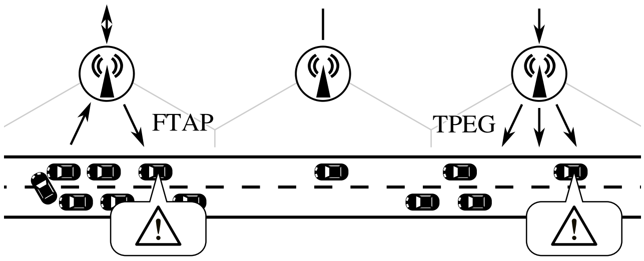


Fig. 2. Protocols used in the CoCar communication system

II. Application Models

The CoCar Traffic Information Center (TIC) and all CoCar clients, i.e. components of the simulative testbed at the network edge, are represented using detailed application-layer models of the respective services. All components send and act upon bit-precise representations of CoCar messages.

For the simulation of message transmissions, we used the OMNeT++ simulation framework [12]. OMNeT++ runs discrete, event-based simulations of communicating nodes on a wide variety of platforms and is free for academic use. It is getting increasingly popular in the field of network simulation. Scenarios in OMNeT++ are represented by a hierarchy of reusable modules written in C++. Modules' relationships and their communication links are stored as *Network Description* (NED) files and can be modeled graphically. Simulations are either run interactively, in a graphical environment, or are executed as command-line applications.

Three application-layer protocols have been specified to handle communication among vehicles in the CoCar system. As illustrated in Figure 2, two of these protocols are used for the exchange of traffic jam warnings and will be presented in this section. In the uplink, vehicles use the Fast Traffic Alert Protocol (FTAP) to send messages to the CoCar TIC via the UMTS Random Access Channel (RACH). FTAP messages are sent in a very compact, binary representation and fit into at most two Random Access Channel (RACH) frames. In the downlink, these messages are immediately reflected to all vehicles in the same cell, again using the FTAP protocol. In a second step, the TIC aggregates all received messages' contents to maintain a high-level view on traffic conditions. From this high-level view, a pool of CoCar messages based on the Transport Protocol Expert Group (TPEG) protocol is derived and is periodically multicast in the form of a TPEG carousel.

In order to obtain realistic results, the simulation model already uses a number of optimizations, such as microaggregation on the server side and client-side duplicate avoidance. Several parameters were introduced that allowed a fine-tuning of the application layer models' behavior to guarantee optimum performance. Among these configurable aspects are:

- Variable FTAP and TPEG message configurations to examine trade-offs between added security elements and system performance.
- Bandwidth caps to be observed by the TIC to examine the impact of CoCar transmissions on the core network vs. reduced delays.
- Freely-configurable message repeat intervals and validity timeouts to examine how best to balance network load and dissemination speeds.
- Architectural variants of the communication infrastructure, to help judge in what direction core network components of the UMTS should evolve.

III. Network Models

Three network elements are used to transmit messages received at the UMTS base stations, i.e. the NodeBs, to the communication system's TIC. All NodeBs are connected via the Radio Access Network (RAN) to the UMTS provider's core network components. These components relay messages via the core network to a Gateway GPRS Support Node (GGSN), where they are commonly re-framed for transmission over the Public Data Network (PDN) to their destination, the TIC.

Real-world algorithms for packet scheduling and optimization are the intellectual property of network operators and the actual network design varies widely between different implementations. In the simulative testbed, both the RAN and the core network components are therefore simulated at an abstract level: All base stations were transparently connected to a node representing the GGSN and the processes of message scheduling and transmission were reproduced using statistical models of the RAN and core network.

However, all protocol adaption and re-framing at this gateway node was performed using the well-tested models of the OMNeT++ *INET Framework* extension for Internet models. The *INET Framework* provides a set of OMNeT++ modules that represent various layers of the Internet protocol suite, e.g. the TCP, UDP, IPv4, and ARP protocols. This made it possible to simulate the link between gateway and TIC using detailed models of an Ethernet link, as well as the network cards and all protocol layers up to the transport layer.

Nodes representing UMTS base stations were distributed in the simulated area to approximate realistic coverage of different geographic regions.

IV. Link Layer Model

Realistic simulation of UMTS channels was made possible by performing extensive simulations of packet transmissions using a dedicated link level simulator, then deriving from this study a set of statistical models for the implemented simulative testbed.

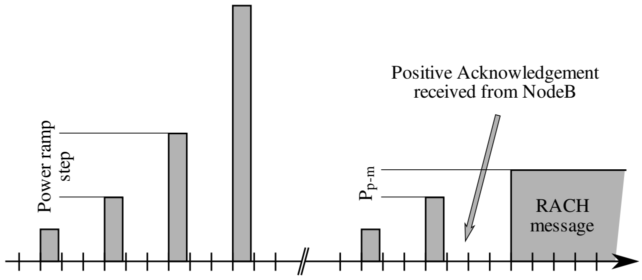


Fig. 3. Access procedure on RACH: One failed, one successful attempt

Actually performing all signal processing tasks that take place on the UMTS physical layer for every single network connection is unfeasible in terms of CPU usage and memory consumption. Instead, performance measures should ideally be modeled on a higher level.

A separate set of simulation results has been obtained for each investigated combination of input parameters. Subsequently, the results of these simulation experiments were used to derive distribution functions for all involved statistic variables. Whenever a transmission is triggered, the relevant performance figures are generated according to the currently active model, which in turn depends on various system parameters.

Since the model has a dependency on the vehicle speed, which is a continuous figure, it is not possible to simulate for all conceivable combinations in advance. Instead, we choose two available models that are closest to the desired velocity to interpolate the required value.

A. Random Access Channel (RACH)

The RACH is a common uplink transport channel that can be used by mobile terminals to request the establishment of a dedicated channel. It can also be used to transmit small amounts of user data, which is the feature we will primarily focus on. Figure 3 illustrates the RACH access procedure. RACH preambles, consisting of 16 repetitions of a spreading sequence of length $256\,\mathrm{chips}$, are sent with increasing transmit power as long as no positive acknowledgment is received from the NodeB or until the predefined maximum number of preambles is reached. In the latter case, the physical layer access procedure terminates unsuccessfully but another set of preambles can be sent when signaled from the MAC layer.

The slotted aloha scheme is used to access the air interface, which means preambles can only be transmitted at fixed points in time, called access slots in UMTS. Two radio frames ($20\,\mathrm{ms}$) consist of 15 access slots, which amounts to $^4\!/_3\,\mathrm{ms}$ per access slot. The Access Service Class (ASC) for a given service (here: CoCar FTAP) defines the set of sub-channels that is assigned to it. The sub-channel defines the concrete locations of the access slots that a service is allowed to transmit in. Note that an ASC can contain more than one sub-channel, thus reducing the time between two consecutive access attempts. [13]

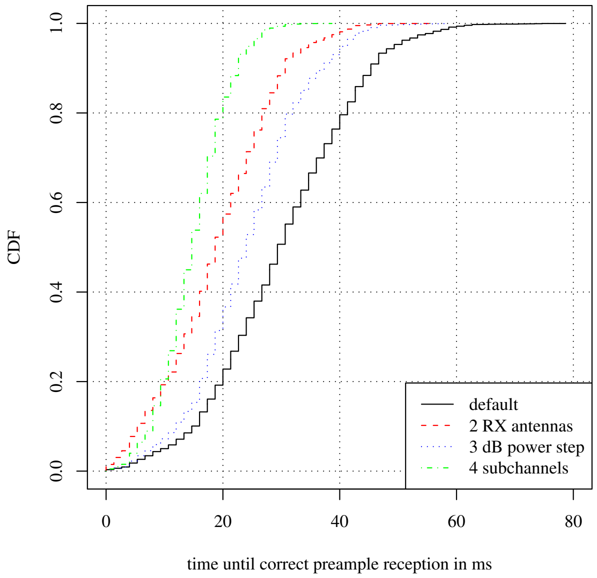


Fig. 4. CDF of the random access procedure duration for the default set of parameters (c_0=$-6\,\mathrm{dB}$, $2\,\mathrm{dB}$ power step, 1 RX antenna, 2 RACH subchannels), compared to alternative parametrizations

1) Simulations: The simulation results (Figure 4) depict the distributions of the delay times that can be expected for various RACH parameter settings. Specifically, the delays consist of the time that passes between message generation in the mobile terminal, the subsequent power ramping phase, and the correct detection of the access preamble by the NodeB. Table I shows the parameters that were used in the overall performance evaluation. The solid black line of Figure 4 represents those default parameters, whereas the other curves were generated by varying a single parameter each. All simulation use the ITU Vehicular B power delay profile for modeling multipath fading. Transmission times for data are not included in the figures. Since these are deterministic values, they can be added as a constant factor as needed.

2) Conclusions: The simulation studies show that the access times for the RACH can be influenced by a number of operator-chosen parameters.

The *number of sub-channels* that is available for a particular service determines the frequency of the allowed access attempts and therefore the capacity of the Random Access Channel. Increasing the number of RACH sub-channels has shown to yield a linear gain in latency, at no additional cost. However, note that the amount of sub-channels is finite.

The *power step size* must be chosen rather carefully. For a single user, a larger step size will increase the probability of each preamble to be successfully detected by the NodeB. However, in a typical multi-user scenario, the interference caused by each access attempt's final preamble will negatively affect the transmission of all other users, thus increasing delay times. As a trade-off, a power step size of $2\,\mathrm{dB}$ is recommended here.

TABLE I
DEFAULT SET OF PARAMETERS FOR RACH

Spreading Factor	32
No. of receive antennas	1
Vehicle speed	$0 \ldots 130\,\mathrm{km/h}$
Power step	$2\,\mathrm{dB}$
No. of sub-channels	2
Size of message	$70\,\mathrm{byte}$

Finally, the number of receive antennas of the NodeB is taken into account. As can be seen from Figure 4, NodeBs equipped with antenna arrays will be able to achieve a considerable gain in detection performance, which can greatly reduce delay times on the air interface.

3) Example: Consider the parameters shown in Table I for the realization of a RACH. The solid black curve (labeled *default*) in Figure 4 depicts the delay distribution for this specific set of parameters. Obviously, $90\,\%$ of all access procedures take about $55\,\mathrm{ms}$ or less to complete. Using a spreading factor of 32 results in a data rate of $120\,\mathrm{kbit/s}$ on the physical layer, or $150\,\mathrm{byte/frame}$. The duration of a frame is $10\,\mathrm{ms}$.

Taking into account the channel coding and overhead from the higher protocol layers, we find that the $70\,\mathrm{byte}$ message cannot be transmitted during one frame but must be split into two. Subsequently the total delay for $90\,\%$ of all access procedures amounts to:

$$45\,\mathrm{ms} + 2 \cdot 10\,\mathrm{ms} = 65\,\mathrm{ms}. \tag{1}$$

Messages that do not fit into two radio frames would have to be split further and a new access procedure is required after each two consecutive frames, which will again increase the time to complete the data transmission.

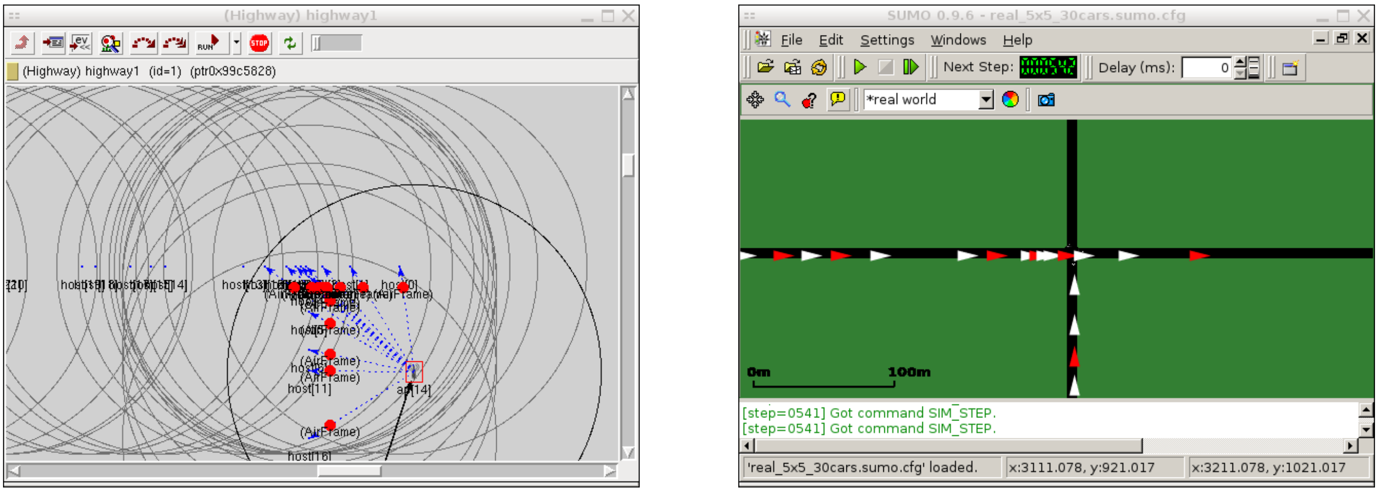
B. Forward Access Channel (FACH)

The UMTS Forward Access Channel (FACH) is a UMTS common downlink transport channel. Messages that are sent by the NodeB using the FACH can be received by all mobile stations in a cell. It can be used for multicast transmission of messages via the UTMS Multimedia Broadcast Multicast Service (MBMS).

In the FACH simulation model we used, transmission of a message of size n on this channel takes:

$$t = \left\lceil \frac{n}{40\,\mathrm{byte}} \right\rceil \cdot 10\,\mathrm{ms} \tag{2}$$

This is because messages are transmitted on the FACH in discrete slots of $10\,\mathrm{ms}$ each. Implementers of the FACH can choose between a number of different slot formats, detailed in [13]. This results in different spreading factors being used and different channel bit rates being available for transmissions. In our evaluations, we assumed a FACH parametrization that allowed $40\,\mathrm{byte}$ of data to be sent in one frame.



(a) Event-based network simulation

(b) Road traffic microsimulation

Fig. 5. Screenshots of simulators' GUI versions running network and road traffic simulations in parallel

V. Road Traffic Model

One of the goals of the simulator was measuring the impact of the CoCar communication system on the road traffic. The choice of the mobility model has been shown to influence the outcome of simulations to a large degree [14]. Simulations were hence based on the Vehicles in Network Simulation (Veins) framework, which allows a realistic node mobility model to be employed [10].

Traffic simulation in the high level simulator is performed by coupling with the running simulation a dedicated traffic simulator, SUMO [15], which uses the microscopic traffic model of Stefan Krauss [16] and is developed by German research organizations DLR and ZAIK. Both simulators exchange state information at run time, allowing not only vehicle movement to influence the network layout, but also network events to e.g. change routing decisions of drivers and, hence, influence vehicle movement. Figure 5 shows screenshots of both simulators running such a bi-directionally coupled simulation of traffic streams merging at an intersection.

Serving as communication scenario of the proof-of-concept evaluation was traffic in the area of a large motorway interchange next to Frankfurt Airport. This region, where two major German motorways (A3 and A5) and one large trunk road (B43) connect, was chosen because of its overlap with the testbed of the German research initiative *SIM-TD* and because of the challenges it poses to routing and traffic optimization.

Figure 6 gives an overview of this region, which spans approximately $10\,\mathrm{km} \times 10\,\mathrm{km}$. In this area, all traffic on roads classified as "Autobahn", "Schnellstrasse", and "Bundestrasse" (motorway, trunk road, and primary road) was simulated.

The mobility models of simulated vehicles were configured to model two distinct vehicle classes, loosely representing cars and trucks, their parameters set to the values given in Table II. This parameter set lead to a diverse mix of vehicles participating in the scenario, which in turn lead to very dynamic traffic patterns emerging during simulations. A

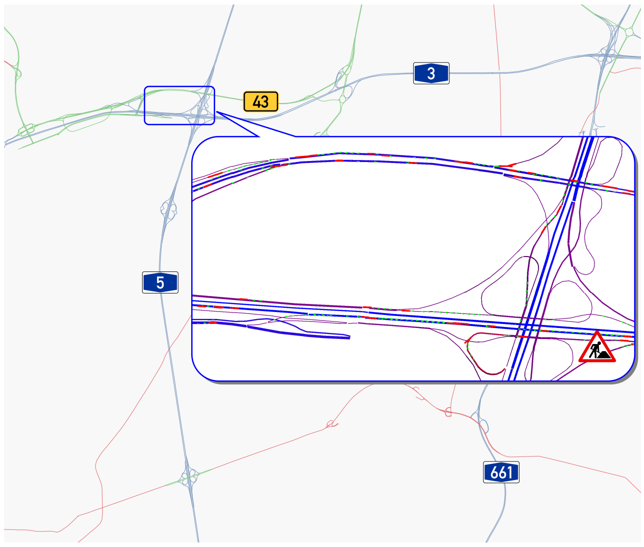


Fig. 6. Road map of the $10\,\mathrm{km} \times 10\,\mathrm{km}$ simulation scenario and GUI screenshot of the traffic simulator, showing a section of the motorway interchange during the simulation

lane-precise road network model was employed, based on data available via the OpenStreetMap[3] project.

Traffic flows of 2000 vehicles were set up in the east-west and west-east directions of motorway A3, keeping the number of simulated cars at a manageable level, but at the same time allowing for a multitude of alternative routes, e.g. along trunk road B43.

Realistic movement of cars was achieved by first iteratively pre-computing routes for all vehicles until a steady state regarding route selection was achieved. The mobility scenario was then modified by adding an artificial traffic obstruction, namely the closing of two out of three lanes at the motorway interchange, preceded by a short section of motorway that

[3]http://www.openstreetmap.org/

TABLE II
ROAD TRAFFIC MICROSIMULATION PARAMETERS AND THEIR VALUES

Parameter	Car	Truck
Fraction of vehicles	80 %	20 %
Mobility model	Krauss	Krauss
Maximum speed	$35 \dots 70\,\mathrm{m/s}$	$22 \dots 28\,\mathrm{m/s}$
Maximum acceleration	$2.60\,\mathrm{m/s^2}$	$1.30\,\mathrm{m/s^2}$
Desired deceleration	$4.5\,\mathrm{m/s^2}$	$4.0\,\mathrm{m/s^2}$
Assumed length	$5\,\mathrm{m}$	$15\,\mathrm{m}$
Driver imperfection σ	0.5	0.75

imposed a $60\,\mathrm{km/h}$ speed limit on all vehicles. No adjustment of pre-computed routes was performed for this modified scenario, so all vehicles started out unaware of the presence of the obstruction.

Vehicles could then use the CoCar communication system to exchange information about perceived traffic jams, causing all receivers of such a warning to adjust their routes to avoid affected roads.

VI. Performance Evaluation

Based on the introduced simulation framework, we outline selected results obtained from a proof-of-concept study modeling interworking scenarios of communications and road traffic. This section further describes the impact the CoCar communication system might have on the environment and on the network infrastructure, as well as on CoCar users' mobility and safety. In particular, we provide answers to the following questions:

- Will the long detours increase vehicle emissions? How high are CO_2 emissions?
- How much strain will different system configurations put on the network infrastructure? What is the network load on the air interface and on the core network?
- How timely will vehicles learn about a new event, either in the immediate vicinity or at an arbitrary location? What end-to-end delay can be expected for messages received via FTAP or via TPEG?

Multiple simulation runs were carried out and the results evaluated using R [17]. They are shown as empirical Cumulative Distribution Functions (CDFs), plotting for a range of values the probabilities of a measure yielding at most a specific one. Hence, the median of a measure will be associated with a CDF value of 0.5, or e.g. the first quartile with a value of 0.25.

A. Impact on Road Traffic

Figure 7 shows the results of the first evaluation, examining the impact of the CoCar communication system on the environment. It plots the CDF of all vehicles' total amount of CO_2 emitted during their travel from start to destination, independent of the length of their route. As can be seen, activating the CoCar communication system in simulations did not lead to an increase in participants' CO_2 emissions, as could be assumed based on the much longer detours that vehicles would now routinely take to reach their destination. Instead, a slight decrease was observed – from a total of $3780\,\mathrm{kg}$ to a total of $3740\,\mathrm{kg}$. This is also indicative of a smoother traffic flow.

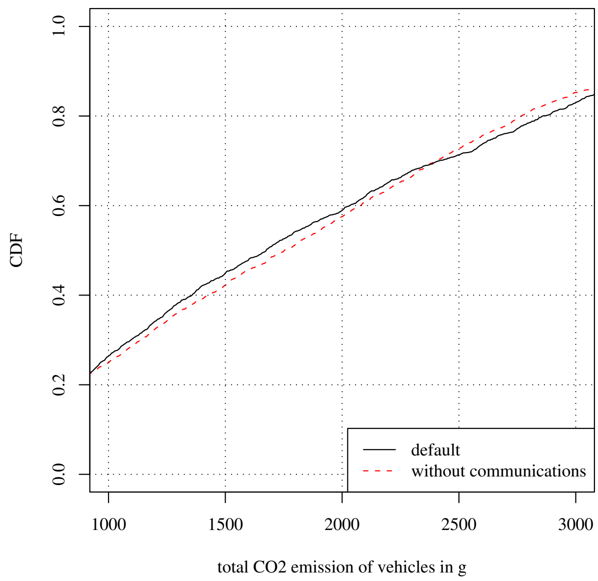


Fig. 7. Impact of the CoCar communication system on road traffic: Quantiles of vehicles' CO_2 emissions.

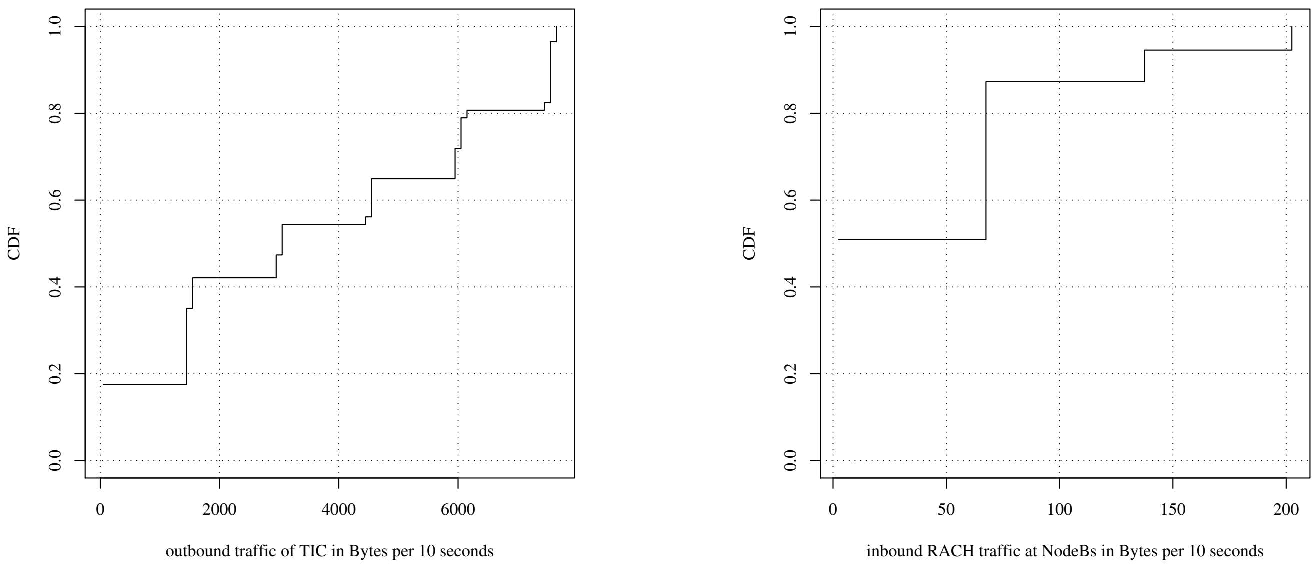
B. Impact on Network Traffic

Aside from the impact the CoCar communication system might have on road traffic, it is just as important to know how the rollout of such a system could affect existing services, in particular with regard to the allocation of bandwidth to the CoCar system.

Figure 8 illustrates the impact of the CoCar system on network traffic – both in the core network and on the air interface. Fig. 8a shows an example of the bandwidth used by the CoCar system, plotted as a CDF of the number of Bytes sent by the TIC to the core network within $10\,\mathrm{s}$ intervals. As can be expected, the relations between message size, carousel size, and allocated maximum bandwidth lead to a very bursty traffic pattern. The median of network load yielded $2.5\,\mathrm{kbit/s}$, peak load was at only $6\,\mathrm{kbit/s}$.

Fig. 8b displays a similar plot, but illustrates the number of Bytes sent by all CoCar clients via the air interface, i.e. on the RACH. Here, client-side duplicate avoidance lead to an even more sparse utilization of the available channel, with bandwidth utilization peaking at under $0.2\,\mathrm{kbit/s}$ and a median value near $0\,\mathrm{kbit/s}$.

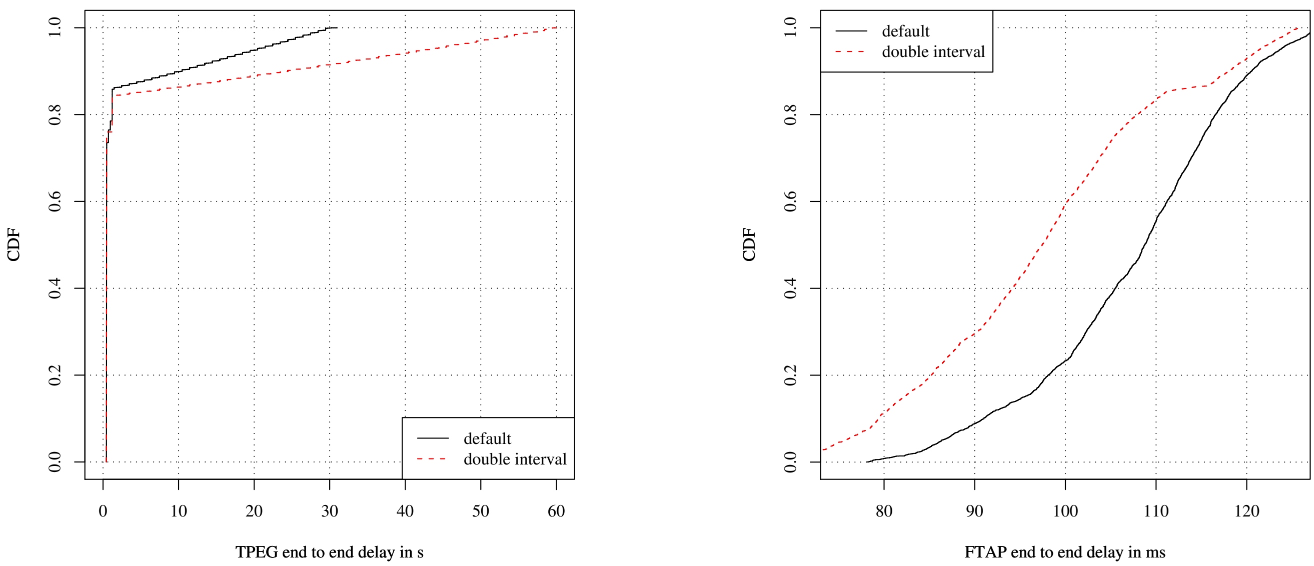
Even when keeping in mind that the measures recorded in this simulation only reflect the quantity of data transmitted for an area of less than $10\,\mathrm{km} \times 10\,\mathrm{km}$, these figures appear promising. In the end, most of the accumulated data is only relevant for the area it was recorded in and, hence, need not be transmitted globally.



(a) Downlink to vehicles

(b) Uplink to TIC

Fig. 8. Impact of the CoCar communication system on network traffic



(a) Messages via TPEG

(b) Messages via FTAP

Fig. 9. End-to-end delay of CoCar messages, depending on the means of delivery

C. End-to-End Delays

From an end user perspective, one of the most important measures to be recorded for the CoCar communication system is that of end-to-end delays. Often, the end-to-end delay is the one key figure that determines whether certain applications are feasible in a system – or if they simply cannot be realized because information would not reach its addressees in time.

These measures are plotted in Figure 9 for the TPEG and FTAP message types and for two different parameter sets, illustrating the trade-off between on the one hand reducing delay in the direct vicinity of traffic incidents, and on the other hand increasing the delay that wide-range dissemination of information will suffer.

Fig. 9a displays the delay between a warning message being sent by one vehicle and its associated TPEG traffic information message being received by another. Not counted is the time for cars that have not yet entered the simulation area and are as such fundamentally unable to receive any message. Also explicitly not reflected in this figure are messages containing information that was already known to cars, e.g. because they had been received via FTAP by the time a TPEG message was received.

As can be seen for $75\,\%$ of messages the end-to-end delay still lies under $1\,\mathrm{s}$. However, for $10\,\%$ of messages it took up to one complete carousel repetition interval until they were received by all vehicles. In the baseline scenario, this means that messages may take up to slightly over $30\,\mathrm{s}$, in the case of doubled warning intervals slightly over $60\,\mathrm{s}$, until wide-area dissemination of a message is complete.

Similarly, Fig. 9b displays the delay between a warning message being sent by one vehicle and the reflected FTAP message being received by vehicles in the same cell. Once again, this measure only includes transmissions for cars that had already entered the simulation area and which had already been informed about the particular congestion.

As can be seen, good parametrization of the system could result in average near-field communications delays of approximately $100\,\mathrm{ms}$ and in both evaluated parametrizations a $95\,\%$ quantile of under $125\,\mathrm{ms}$ – values that are well under the human reaction time.

VII. Conclusion

Based on a proof-of-concept study, we presented in this paper a comprehensive simulation framework to help in the design and evaluation of upcoming, UMTS-based C2I communication systems. Such 3G approaches might complement recent efforts to establish VANET-based Intelligent Transportation Systems such as TIS applications – basically because they are already widely deployed and provide capabilities such as inherent security measures and low latency communication, which are needed in the intended scenario. The simulative evaluation was not limited by currently-implemented UMTS infrastructure and thus able to use forthcoming technologies. We described in detail the individual models our simulations were composed of and how these models interacted to form the framework.

The study demonstrated the capabilities of such an UMTS-based C2I communication system. The deployment of the planned TIS could be shown to have no negative impact on the environment. In fact, calculated emission levels were even lower while the TIS was active. Further results of the performed evaluation indicate much lower delay times and a much lighter network load than can be achieved with currently-implemented UMTS infrastructure. Bringing about an almost unnoticeable use of uplink capacity, the proof-of-concept evaluation of a C2I communication system yielded near-field communications delays of well under the human reaction time and wide-area delays that easily surpass those of conventional C2C communication systems.

Acknowledgment

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