# Chapter 26: Simulative Performance Evaluation of Vehicular Networks

David Eckhoff, University of Erlangen, Dept. of Computer Science,
Martensstr. 3, 91058 Erlangen, Germany, david.eckhoff@fau.de
and
Christoph Sommer, University of Paderborn, Dept. of Computer Science,
Fürstenallee 11, 33102 Paderborn, Germany, sommer@ccs-labs.org

**Abstract**

In the last decade simulation has become the primary tool for the performance evaluation of vehicular network applications, technology, and protocols. Simulations can be a powerful tool to investigate large scale networks at low cost. However, both conducting simulations right – and conducting the right simulations – are crucial to obtaining meaningful results. First, the level of detail for a model has to be chosen carefully: too abstract and it may produce unrealistic results, too complex and it becomes computationally infeasible or requires too much or too fine grained data (which might only be sparsely available). Running, understanding, and evaluating a simulation is not trivial, and neither is creating new simulation models to represent new protocols or previously unaccounted environmental aspects. This chapter introduces the state of the art in the simulation of vehicular networks, details when and how different, complex real life effects should be captured in a simulation model and, ultimately, gives guidance on how to obtain meaningful simulation results.

**Index Terms**

None

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## I. INTRODUCTION

The performance assessment of vehicular network applications and protocols is a nontrivial challenge and can usually be approached using three different methodologies, namely analytical evaluation, Field Operational Tests (FOTs), and simulation. Their applicability depends on the type of performance evaluation, as each of them has distinct advantages and limitations, requiring researchers to carefully choose which method suits their needs best:

Mathematical analysis of vehicular networks can give valuable insights into the overall behavior, lower and upper bounds, and can generally help understand the designed system. System components are represented by analytical models, oftentimes based on probability distributions, and brought together to investigate the performance of the examined application or protocol. However, these analytical models often simplify the properties of vehicular networks (e.g., the mobility of vehicles) to keep the complexity of the problem at a manageable level; these simplifications can introduce inaccuracies leading to imprecise, inexact, or even incorrect results.

Testing the envisioned system in the field is probably the most straightforward approach and can offer many advantages. While simulations and analytical approaches can only account for effects that have been modeled beforehand, real-life testing can help discover problems and system properties that simply haven't been considered before. Based on data collected in the field, new empirical models can be developed for both analysis and simulation which can in return help validate the results from the field test itself. The major downsides of FOTs are high costs in terms of time and money (and the associated limited parameter space that can be explored), the use of only existing (possibly prototype) hardware, the difficulty to draw conclusions on the scalability of the envisioned system, and limited insights into underlying causes of observed behavior.

Simulation can be a powerful tool to investigate large scale networks at low cost, however, just as for the analytical approach, its outcome fully depends on the used models. When modeling complex components, e.g., multipath radio propagation or road traffic, simplifications have to be made to keep the simulation run time at a reasonable length. The level of detail for a model has to be carefully chosen: too abstract and it may produce unrealistic results, too complex and it becomes computationally infeasible or requires too much (possibly unavailable) data, or the available data at the required granularity is of much lower quality than coarser grained one.

In the last decade simulation has become the primary tool for the performance evaluation of vehicular network applications, technology, and protocols. There exist various publicly available open source simulation frameworks that make the setup and conduction of simulations easier and faster. Examples include Veins [1], iTETRIS [2], and VSimRTI [3]. However, running, understanding, and evaluating a simulation is not trivial, and neither is creating new simulation models to represent new protocols or previously unaccounted environmental aspects.

This chapter will give an overview of the state of the art in the simulation of vehicular networks, explaining when and how complex real life effects should be captured in a simulation model and how to obtain meaningful simulation results. Background information on individual topics can be found in textbooks on wireless communication [4] and simulation in general [5], books on simulation of road traffic in particular [6], as well as literature on model verification and validation of simulations [7].

## II. Mobility

The first thing that comes to mind when simulating vehicular networks is the actual mobility of the vehicles. Not only does the movement of vehicles heavily influence their network connectivity – it is also one of the main characteristics of Vehicular Ad Hoc Networks (VANETs). In this context a realistic mobility model is the basis of every scientifically sound performance evaluation.

In the beginning of VANET research, it was believed that VANETs are just an application for Mobile Ad Hoc Networks (MANETs), a field that has already been studied for years. However, it was soon found that the mobility patterns used in MANET simulation are not adequate to assess the system performance for VANETs. For example, random way point models were used in order to simulate urban vehicular mobility [8], but were soon shown to not correctly reflect traffic characteristics and are likely to produce incorrect results [9], [10]. In turn, after modeling the specific characteristics of vehicular movement (e.g., bound to streets, mixture of high/low-density areas, high relative speeds) it could be shown that the protocols and applications designed for general MANETs do not perform well in a vehicular context [11].

Another fact that complicates the modeling of vehicular mobility is that there exist various mobility patterns, dictated, e.g., by the road network, time of day, or population density. For example, on a freeway or highway the mobility is 1-dimensional, while in urban scenarios it is mostly 2-dimensional with grid-like street layouts in many American cities and seemingly random streets in European cities. Also, in rush-hour traffic a considerably larger amount of cars drive in one direction than the other; in high population areas streets are more likely to be clogged and average velocities are therefore lower. Further, the presence of traffic lights changes traffic flows considerably. These properties make it hard to create one general mobility model to generate traffic to be used in the simulation of vehicular networks.

One approach to circumvent this problem is the use of traces. Gathered by equipping vehicles with GPS receivers and a logging device, an entry in a trace file usually consists of a timestamp, a GPS coordinate, (heading, speed) and a vehicle ID. This trace file can then be played back to simulate road traffic. While the realism of the generated mobility pattern is as high as possible, there are several drawbacks of the trace-driven approach. Creating these traces is a cost-intensive task, as a considerable amount of vehicles have to be equipped in order to represent real traffic. The maximum simulated traffic density is therefore always bound by the number of equipped vehicles that generated the trace. Simply cloning vehicles in the trace may circumvent this issue, but will just decrease the realism of the simulated traffic. There are several publicly available traces (e.g., [12]–[15]) that can be used to simulate urban mobility. Many of them are generated using public vehicles such as taxies or busses, which introduces a new problem: the mobility of these vehicles is atypical and may not represent regular traffic, in other words, applications evaluated using a taxi trace can only be shown to work for taxies and nothing more; general conclusions might be invalid. Another problem can arise from the resolution of the used trace file: Oftentimes, the resolution is in the range from 1 s to even 1 min per entry, requiring the movement in-between to be (linearly) interpolated, introducing inaccuracies and unrealistic movement. Combined with error-prone GPS readings, the played back trajectory can considerably differ from the original one, again resulting in unrealistic traffic and hence network topologies.

These drawbacks led to the conclusion that there is a need for traffic simulators that are able to generate realistic traffic that can be used as an input for vehicular network simulation. Popular examples include SUMO[16] and VISSIM[17], both developed by traffic scientists. They can be classified as microscopic traffic simulators, meaning that each vehicle in the simulation is simulated individually, whereas the perspective of a macroscopic simulation lies on traffic flows to investigate the traffic system as a whole. In microscopic simulators, vehicles are assigned routes through a predefined road network, with acceleration and deceleration of a vehicle being determined by a car-following model that, amongst others, takes into account the current speed and the distance and speed of the leading vehicle(s). Examples of car-following models include but are not limited to Wiedemann [18], Krauss [19], and IDM [20], [21]. Lane-change models are tightly connected with car-following models to capture decisions on whether and when a vehicle changes lanes [22]. Sample input parameters of these models are the maximum speed and the smallest acceptable gap (in terms of time or space) between vehicles and they range in complexity up to the level of politeness of a driver [23].

For realisitic traffic, however, it is not sufficient to simulate microscopic mobility. Lower-quality map data (e.g., consisting only of a few roads, not considering the number of lanes, access and turn restrictions, speed limits, traffic lights, etc.) can lead to unrealistic car clusters and road utilization [24]. Results produced in these scenarios significantly differ from results produced with real map data (cf. Figure 1). Further, when additionally adding obstacles such as houses (full-featured simulation) that heavily influence radio propagation [25] the simulation metrics (in this case, the neighbor count of a vehicle) again change considerably. To increase the quality of the used map, publicly available crowd-sourced geodata can be utilized, for example obtained from the OpenStreetMap project [26].

In general it can be said that realistic underlying map data is an important requirement to produce meaningful simulation results. Unfortunately, high quality map data alone is not sufficient. Another important factor is *traffic demand*, the route assignment for the individual vehicles. Randomly assigned origin and destination pairs combined with a microscopic traffic simulator will produce realistic microscopic traffic but unrealistic traffic flows [27]. Demand models that account for different types of areas such as residential or industrial as well as population densities in these areas (along with a trip planning model) are able to produce more realistic origin and destination pairs making it possible to simulate typical city traffic flows [28].

Last but not least, it is important to account for border effects of the simulated road network. A good way to do this is to define a so-called Region of Interest and only investigate vehicles within this region but to simulate traffic in a larger area around this region, as shown in Figure 2. Otherwise, roads on the border of the simulate road network are likely to be less frequented as they are seldom part of a shortest path through the network.

Following these steps, current simulators can generate quite realistic mobility patterns [15]. For the simulation of a Intelligent Transportation System (ITS), however, it is essential that future simulators account for all of its participants. Current efforts include the integration of public transport such as busses and trains as well as cyclists and pedestrians. Also, vehicles that are currently not driving may need to be modeled as they can be utilized for various vehicular network applications [29], [30]. Even the mobility of driving vehicles will change as electric vehicles and car sharing will likely play an important role in future transportation systems. At a microscopic scale, future mobility models have to be able to include atypical driving behavior, as this is an important requirement for the investigation of safety applications. It is an inherent property of most car-following models that they do not allow accidents, however, without these critical situations (e.g., red light/right of way violations, too small safety gaps, speeding) the benefit of safety applications can only be approximated vaguely through other metrics.

Further, there is a definite need for high quality reference scenarios to be used as input for the evaluation of vehicular networks as they would certainly help increase the trustworthiness and reproducibility of simulation results.

## III. Wireless Communication

In the context of vehicular networks, discrete event simulation of communication has become the most established simulation method. The basic concept is to not change the simulation behavior based on continuous equations like it is done in continuous simulation, but to only do so at discrete point in times, so called events. For example, to model the continuous transmission of a packet in a discrete event simulator, one approach would be to create events where the system changes, namely at the start and at the end of the transmission. The simulation maintains an ordered event queue, where events are inserted and processed based upon their associated time. The simulation clock is always instantly advanced to the time of the next event, and will therefore advance faster or slower, based on the events in the queue. State variables are updated in an event and future events are determined and inserted into the queue. The simulation will end if either the event queue is empty or the simulation clock has reached a predefined limit. The simulators most used in the vehicular networking community are OMNeT++ [31], ns-2 and ns-3 [32], and JiST/SWANS [33].

### *A. Channel Modeling and Physical Layer*

When examining wireless communication between vehicles, the wireless channel itself plays an important role in the performance of the envisioned application. This error-prone, chaotic channel is usually hard to predict [34] and there exist various ways to model it within a simulation environment. The most straightforward approach is the use of a unit disc model, Equation (1), where the packet success probability $p_{\text{succ}}$ is a boolean function of the distance $d$ between sender and receiver: if the receiver is within a predefined range $R$ of the sender the packet can be decoded, otherwise it will be lost.

$$p_{\text{succ}} = \begin{cases} 1 & \text{if } d \leq R, \\ 0 & \text{if } d > R. \end{cases} \tag{1}$$

While this is a very abstract channel model that can produce incorrect results when the performance of the examined application is highly dependent on the reception of single packets, it might be appropriate for macroscopic simulations.

For microscopic simulations the state of the art is the use of channel models to determine the receive power $P_r$. As shown in Equation (2), $P_r$ depends on the transmit power $P_t$, the antenna gains of both the sender and receiver antenna ($G_t$ and $G_t$, respectively), and on the sum of all attenuation components $L$, which can account for slow-fading, fast-fading or probabilistic attenuation effects.

$$P_r[\text{dBm}] = P_t[\text{dBm}] + G_t[\text{dB}] + G_r[\text{dB}] - \sum L_i[\text{dB}] \tag{2}$$

In this context, power levels $P$ are usually given in dBm (decibel milliwatt), that is, the power ratio referenced to one milliwatt. The conversion from milliwatts to dBm can therefore be done as shown in Equation (3). Attenuation levels are given in dB to describe their effect on the signal as the ratio of input to output intensity (cf. Equation (4)). An attenuation of $< 0$ dB would therefore amplify the signal.

$$P[\text{dBm}] = 10 \log_{10} \frac{P[\text{mW}]}{1\text{mW}} \tag{3}$$

$$L[\text{dB}] = 10 \log_{10} \frac{P_{in}[\text{mW}]}{P_{out}[\text{mW}]} \tag{4}$$

A widely used path loss model to capture the effect of decreasing signal strength over distance is the free-space path loss model (or, more precisely, an empirical adaptation thereof) which only depends on the distance $d$, the wave length in meters $\lambda$ and a path loss exponent $\alpha$ (usually set to 2, but can be changed according to the environment [4]).

$$L_{freespace,emp}[\text{dB}] = 10 \log_{10} \left( \frac{16\pi^2 d^\alpha}{\lambda^\alpha} \right) \tag{5}$$

This model has been shown to often overestimate and underestimate the measured power level in the context of vehicular communication [25], [35]. The reason for that is a second strong component, namely the reflection of the signal from the ground as illustrated in Figure 3. This effect is called two-ray interference [36] and leads to constructive and destructive self-interference effects caused by a phase difference $\varphi$. This phase difference between the line-of-sight and the reflection component depends on the length of the two rays, $d_{\text{los}}$ and $d_{\text{ref}}$, and the wavelength $\lambda$ and can be given as:

$$\varphi = 2\pi \frac{d_{\text{los}} - d_{\text{ref}}}{\lambda}. \tag{6}$$

Distances can be derived from the sender and receiver antenna heights $h_t$ and $h_r$ and the distance $d$ as $d_{\text{los}} = \sqrt{d^2 + (h_{\text{t}} - h_{\text{r}})^2}$, and $d_{\text{ref}} = \sqrt{d^2 + (h_{\text{t}} + h_{\text{r}})^2}$.

Lastly, the reflection coefficient $\Gamma_\perp$ depends on a fixed $\varepsilon_{\text{r}}$ and the incidence angle $\theta_{\text{i}}$. The needed sine and cosine of $\theta_{\text{i}}$ can be derived via simple geometry ($\sin\theta_{\text{i}} = (h_{\text{t}} + h_{\text{r}})\,/d_{\text{ref}}$ and $\cos\theta_{\text{i}} = d/d_{\text{ref}},$). This leads to:

$$\Gamma_\perp = \frac{\sin\theta_{\text{i}} - \sqrt{\varepsilon_{\text{r}} - \cos^2\theta_{\text{i}}}}{\sin\theta_{\text{i}} + \sqrt{\varepsilon_{\text{r}} - \cos^2\theta_{\text{i}}}}. \tag{7}$$

Using the phase difference and the reflection coefficient we can model two-ray interference as a path loss component $L_{\text{tri}}$[dB].

$$L_{\text{tri}}[\text{dB}] = 10\log_{10}\left(4\pi\frac{d}{\lambda}\left|1 + \Gamma_\perp e^{i\varphi}\right|^{-1}\right)^2 \tag{8}$$

It should be noted that this two-ray interference model is easily confused with a much simplified version, the simplified two-ray ground model (although the *simplified* is often omitted). This model was derived for cellular communication, assuming large distances together with perfect polarization and reflection. It assumes that below a break-even distance $d_c$ radio propagation follows the free-space path loss model (path loss proportional to $d^2$) – and that above $d_c$ it follows a path loss proportional to $d^4$. For typical values of vehicular networks $d_c \approx 886.6\,\text{m}$, so for all reasonable distances this simplified two-ray ground model will work just like a free-space path loss model.

Figure 4 illustrates the difference between the free-space model (i.e., $\alpha = 2$), the simplified two-ray ground model, and the two-ray interference model, highlighting the inapplicability of the simplified two-ray ground model.

Radio propagation is also influenced by obstacles such as houses, pedestrians, trees, or other vehicles that attenuate the signal. The line of sight between sender and receiver may be blocked, hence lowering the received power. This effect is usually referred to as shadowing. If transmission attempts can be assumed independent and uncorrelated in time (on the order of seconds) and space (on the order of tens of meters), the effect of obstacle shadowing can be modeled purely stochastic, for example using the log-normal shadowing as shown in Equation (9) [37]. It uses a normal distributed random variable $X$ with variance $\sigma$ to determine the attenuation of the signal.

$$L_{lognorm}[dB] = 10\log_{10}(X_\sigma) \tag{9}$$

When transmissions are made within a short period of time or the geometric conditions do not change between transmissions, however, purely stochastic models cannot be used. In these cases, models have to be deployed that take into account the exact positions of obstacles such as buildings [25], [38], [39] and vehicles [40], [41] to derive the level of attenuation caused by shadowing.

To account for small scale fast fading effects, additional fading models that take the power level determined by a deterministic propagation model as input can be applied. Popular examples include Rayleigh Fading [42] which models fading based on two uncorrelated Gaussian random variables, Rician Fading [43] that takes the existence of a strong line-of-sight component into account, and Nakagami-m [44] which models multipath fading based on $m$ paths and has been shown to produce realistic results for the simulation of vehicular networks.

When the receive power level $P_i$ of a packet $i$ has been determined the simulation has to decide whether the packet is decodable. This is usually done evaluating the Signal-to-Interference-plus-Noise Ratio (SINR) by dividing by the sum of the power levels of all other packets on the channel plus the background noise $N$:

$$\text{SINR}(i)[\text{dB}] = 10\log_{10}\left(\frac{P_i[\text{mW}]}{N[\text{mW}] + \sum_{i\neq j} P_j[\text{mW}]}\right) \tag{10}$$

The SINR allows to compute the bit error probability, i.e., the probability of failing to decode one bit. This probability depends on the used modulation (QPSK, BSK, QAM, ...) and can also be derived from empirical data [45]. In the case of QPSK and under the assumption of an Additive White Gaussian Noise (AWGN) channel it can be given by:

$$\text{BER} = \frac{1}{2}\,\text{erfc}(\sqrt{\text{SINR[dB]}}) \tag{11}$$

The probability whether a packet can be decoded successfully is therefore computed by $p_{\text{succ}} = (1 - \text{BER})^{\text{PacketLength[bits]}}$. In network simulations, the decision of whether or not a packet is received is then commonly made by drawing a random number $v \in [0, 1)$ and comparing it against $p_{\text{succ}}$ to determine the final decision: The packet is handed over to the MAC layer if $v \leq p_{\text{succ}}$.

### *B. MAC Layer*

Going up the communication stack, the MAC layer's responsibilities include determining whether the channel is busy, when to actually access the channel, reacting to a failed transmission, congestion control, scheduling packets coming from upper layers, and many more. The MAC layer receives packets from higher layers such as the network layer, or, if these are absent, directly from the application layer and hands it over to the PHY layer for transmission. The decision when to actually give the packet to the PHY layer is determined by Quality of Service (QoS) policies (scheduling, prioritizing, etc.) implemented in the MAC layer.

A simple approach in simulation would be to combine the unit disk model with an idealized MAC layer that always assumes the channel idle, has zero processing and transmission delay, and disregards collisions. While this simplification seems to be too unrealistic, it can be valid when the actual performance (e.g., in terms of latency or throughput) of the MAC layer does not play an important role. The major reason to assume an idealized MAC layer is the performance of the simulation itself: When looking at large scale networks with thousands of vehicles, the time needed to run the simulation can be unreasonably long.

However, when the examined application has specific requirements in terms of latency, throughput, or packet success rates these models become invalid and a realistic MAC layer model is needed to investigate their performance properly. In the context of inter-vehicle communication this relates to almost everything related to traffic safety [46], to virtual traffic lights [47], or to platooning [48].

For direct WiFi-based communication between vehicles, IEEE recently approved the 802.11p amendment [49] incorporated into the 802.11-2012 [50] standard. This document describes the PHY and MAC layer and adds to the IEEE WAVE family of standards that defines the operation of ITS. Additional MAC layer operations are defined in IEEE 1609.4-2010 [51]. Although the straight forward choice is to use this MAC layer also in simulation, vehicular networks are often examined using existing models of similar protocols, namely, IEEE 802.11b, IEEE 802.11a, or an adapted version of these [52]. While, on a larger scale, this can be expected to yield comparable results, it has been shown that this methodology is invalid in many cases and can produce results that are significantly different from simulations tested with a full-featured 802.11p model [53].

The use of multiple channels in IEEE WAVE (or ETSI ITS G5 in Europe [54]) requires the MAC layer to choose a channel for communication [55]. This affects throughput and channel busy times, and therefore also latency. Moreover, when the number of transmitters is smaller than the number of channels (which is most likely the case in vehicular networks), there is a chance that messages sent by close-by vehicles are not detected. These effects would be completely neglected by single-channel MAC layer models. QoS mechanisms such as the Enhanced Distributed Channel Access (EDCA) subsystem with multiple internal queues where packets are enqueued according to their priority play an important role in the performance of overlying applications. Not only do these queues have inter-frame spacings of different length but also can high priority packets overtake and therefore block lower priority ones, resulting in higher latency and lower throughput.

From this we conclude, that the MAC layer used in packet-level simulation should almost always be a model of the MAC layer used in the examined network. Of course, this does not only apply for 802.11 based technology but for all kinds of communication networks including cellular technology such as UMTS/LTE/LTE-A.

While detailed functional modeling is a required property for the meaningfulness and reproducibility of the carried-out simulations, it is certainly not sufficient: MAC layers come with a vast set of parameters that can be changed accordingly, with many of them having a big influence on the actual performance. These settings should therefore be chosen according to current trends and recommendations and always be included in simulation studies. For example, although 802.11p allows datarates from 3 Mbit to 27 Mbit, FOTs commonly follow a recommendation to primarily use a rate of 6 Mbit. Also, fixed transmission powers that lead to an unreasonable small or large communication radius should be avoided.

Unfortunately, even if all these steps have been followed, reproducibility cannot be guaranteed. A study conducted for a related discipline, Wireless Sensor Networks (WSNs), which investigated the comparability among IEEE 802.15.4 and IEEE 802.11 models used in different network simulators revealed that, although all these models claimed to follow the standard, the simulation outcomes were alarmingly different for each one of them [56]. Creating a simulation model from a MAC layer standard is a nontrivial, error-prone task, especially when statements in the standards are ambiguous. Ideally, the used models should therefore be open-source, well documented, widely used and possibly peer-reviewed. Further, a worrying trend in recent publications in the field of vehicular networking can be observed: potentially owing to the rising complexity of simulations and small available space for papers, an increasingly smaller number of publications could be found to give the necessary details of employed models, their parameterization, and the scenario that was evaluated [52], [57].

### *C. Network Layer and higher*

The IEEE and ETSI standards define mechanisms for the use of IP-based communication over the 802.11p link in vehicular networks, however, most of the envisioned applications do not require these higher layers. Therefore, simulations of vehicular ad-hoc networks often use a three-layer stack (PHY/MAC/APP), commonly relying on lightweight niche protocols such as the WAVE Short Message Protocol (WSMP). For cellular communication this is different, as many centralized services (e.g., traffic information systems, location based services) are only reachable via IP. For the simulation of many vehicular network applications it is not necessary to fully simulate the network layer, but it is sufficient to abstract from it using delay characteristics of the communication link [58]. Similar assumptions hold for the wired communication between Roadside Units (RSUs) (and possibly some centralized server), as it does most likely not require a full-featured communication model of the network and transport layer in order to produce meaningful results for the investigation of most vehicular network applications. However, especially in the case of cellular links, empirical values for the delay can be hard to obtain and are also likely to not be constant or static.

In the field of vehicle-to-vehicle communication and especially in the research community, deployed mechanisms for higher layers include geonetworking, delay tolerant networks, or even peer-to-peer networks [59]. When investigating an application that relies on one of these mechanisms, these layers usually need to be modeled as well. This can be complicated when the scale of the simulation does not suffice to fully represent the characteristics of the underlying layer: a peer-to-peer network consisting of thousands of vehicles spread over a large area may behave completely different than one only consisting of a hundred close-by vehicles.

Abstractions made for these layers have to be investigated very carefully as they can significantly affect the simulation outcome.

An application running on the on-board unit of an IEEE 802.11p enabled vehicle does not only have specific constraints in terms of computation time and available memory, but is also likely to compete with other applications running on the same on-board unit. For example, vehicles are assumed to broadcast their current status with a frequency of up to 10 Hz in both the WAVE and ETSI ITS G5 system. This alone can generate considerable network load, causing packet collisions and higher latencies [60]. Furthermore, cross-layer mechanisms such as security policies or congestion control (as standardized in ETSI ITS G5) can influence the performance of the application layer by introducing security overhead or by limiting the packet generation rate. Ignoring these constraints by taking an isolated view on the envisioned application can lead to an overestimation that does not hold when investigating the system as a whole.

A future trend of vehicular networks is the move from focusing on just a single technology to designing systems that can make use of multiple different technologies, creating *heterogeneous vehicular networks* with mixed network stacks. Two opposing tendencies can be identified [61]. One pushes for a more and more generalized network stack that abstracts away from lower layers to decouple applications from the employed technology, aiming to provide an *always best connected* experience to upper layers. The other follows a *best of both worlds* approach, exposing information and control of lower layers to applications to selectively use the best fitting technology for a particular task, e.g., short range radio for near field information exchange in clusters and cellular networks for interconnecting these.

## IV. Coupling Mobility and Network Simulators

Reflecting on the high level of complexity required for an accurate simulation of both road traffic and network traffic, it is clear that, on their own, neither traditional road traffic simulators (common in the domain of transportation and traffic engineering) nor traditional network traffic simulators (common in the domain of applied computer science) can fulfill the requirements of both. One possible approach is to simulate vehicle movement in a road traffic simulator, record a trace file of mobility information, then replay the trace file in a network traffic simulator. However, this approach cannot capture the influence that many in-vehicle applications (most notably traffic safety and efficiency applications) will have on road traffic and driver behavior. Thus, the current state of the art in vehicular network research is bidirectionally coupled simulation. Here, two dedicated simulators, a road traffic simulator and a network traffic simulator, each developed and maintained by experts in their respective fields, are employed. Both simulators are running the same simulation and are continuously exchanging state information. The road traffic simulator governs node movement and, thus, topology dynamics in the network traffic simulation; the network traffic simulator feeds back control and sensor data to the road traffic simulation.

Such exchanged information items might include: *Node position and speed* for network topology and radio propagation calculation, *local and remote sensor data* for cooperative adaptive cruise control and platooning, *travel time information* for route (re-)planning, or *signal phase and timing* for green light optimal speed advisory.

It is further possible to interconnect multiple road traffic and multiple network traffic simulators, each focusing on a particular region of the simulated scenario, or each looking at the simulated scenario at a different scale. This makes it possible to perform coarse grained simulation of a scenario on a global scale, with more finer grained simulations encompassing different models (or even different modeling approaches) for a particular region of interest. Such bidirectional coupling of simulators requires that all affected simulations share the same view on both past states and the current state of the simulation. In the easiest case this is achieved by making sure that at any given time only one simulator is active, synchronizing state information at the end of dedicated time steps and interpolating between steps as needed. Such an approach works well if most of a simulation's processing time is spent for one part of the simulation. In general, this is the case for vehicular network simulation, as highly detailed network simulation consumes several orders of magnitude more computational power than even the most complex car-following and lane-change models. Still, if performance is an issue, optimization techniques such as optimistic synchronization [62] can be employed.

Several coupled vehicular network simulators are under active development today – and more are added to cater to specific use cases.

The one with the longest track record is the Veins open source vehicular network simulation framework [63]. It is built on the OMNeT++ network simulation kernel and the SUMO road traffic simulator, adding a suite of models that are specific to vehicular network simulation (such as channel models, physical and mac layers). Veins is designed to serve as a flexible basis for developing custom simulations. Also of note is the iTetris program, which was funded by the European Commission to build a platform for the evaluation of solutions based on ETSI ITS G5. It integrates a complete ETSI ITS G5 stack with the ns-3 network simulation kernel and the SUMO road traffic simulator and is available for free to members of the iTetris community. Lastly, VSimRTI goes one step further in the modularization of individual simulators. It is not targeted towards a specific simulation kernel, but provides a generalized and open source framework for coupling different simulators. Adapters to VSimRTI exist for all major network and road traffic simulators.

Multiple future research directions of coupled simulations can be identified. One aspect that has often received only cursory treatment [64] is the impact of human driver behavior on vehicular networks; moving away from the assumption that supplying information to a *node* in the network ultimately means anything more than just informing the driver – who might or might not choose to react on this information, or who might chose to act on this information in a less than optimal way.

A second aspect can be identified in the ever closer integration of vehicular networking into cars. This requires a much closer investigation of in-car networks and their interplay with vehicular networks, not just in terms of changes in delay, latency, or in means for better data fusion and aggregation, but also with respect to security and privacy.

Another future research direction is the investigation – and ultimately the incorporation – of new mobility patterns that will emerge precisely because of vehicular networks, brought about by applications such as platooning or smart traffic lights.

## V. Performance Evaluation

In general, best practices for the simulative performance evaluation of vehicular networks agree very much with those of computer networks in general – a topic that has received ample coverage in the literature [5], [7], [65] and knowledge of which we assume here. Some peculiarities, however, require special attention.

First, vehicular network simulations do not lend themselves well to steady state simulation: oftentimes, the impact of (and reaction to) a singular event needs to be investigated or a single message traced through the network. Still, even for terminating simulations, it is important to ensure that initial conditions are close to what would be considered the steady state of an undisturbed system. Thus, accurately detecting (and discarding) transient simulation phase(s) is particularly important.

Secondly, guaranteeing multiple independent replications of vehicular network simulations is not as easy as varying pseudorandom number generator seeds. There is a paradigm shift when investigating the performance of vehicular networks applications combined with traffic mobility. The effect of randomness on the communication side of the simulation is often negligible compared to the effect different traffic patterns have on the simulation outcome. Although choosing different seed values for the traffic simulator will generate new mobility, the impact of changing the scenario itself (e.g., different time of day, different street network, new routes) is likely to be considerably stronger. From this it follows that countless repetitions of the network communication without changing the underlying mobility will still give results possibly very specific to one certain scenario.

Aside from the actual conducting of the simulation study, using the right representation/visualization of results is just as important. In the field of vehicular communication, it is still rather common to find figures showing mean values of collected samples. Just like in related disciplines, giving information on the standard deviation or the confidence intervals can give valuable insights and help evaluate important properties of the system. While this can be perfectly fine, for example, when the samples are normally distributed and the variance is known to be very small, the opposite is routinely the case in vehicular network simulations. Imagine a bipolar distribution of the samples: this plot would then show the average performance lying in-between the two peaks of the distribution, although maybe not a single sample was even near this value. Especially in decentralized, distributed networks such as vehicular networks, fairness is often a fundamental requirement. If a system performs very well for *some* vehicles at the cost of degrading the performance for others, this should be presented in the results. There are several methods to visualize fairness, including simple scatter plots, histograms, or the plotting of empirical Cumulative Distribution Functions (CDFs).

Finally, in order to assess the performance of, e.g., a safety application or a new channel access scheme, it has to be clear which metrics define their actual performance. Oftentimes the properties of the evaluated system can be divided into three parts: timeliness, efficiency, and robustness. It is easy to alter a scheme that has good balance between these three to become better in one department by sacrificing performance in another. An example would be a MAC protocol that greatly reduces the number of collisions (robustness) but at the same time increases the latency (timeliness) and throughput (efficiency). Selectively presenting metrics that only cover one (or two) of these fields would then give the misleading conclusion that the new scheme outperforms the older one.

Some applications might even require new metrics in order to be evaluated properly, metrics not found in the context of classic wireless network simulation. For example, traffic safety applications can be assessed with regard to the number of prevented traffic accidents, while privacy mechanisms can be evaluated by measuring the time a vehicle can be tracked through the network by some kind of adversary. Table I gives an overview on selected metrics to consider, depending on the context of the evaluated system. Naturally, observing such high level metrics can only give indications of the true performance of the system given an appropriate level of detail of the mobility and communication models. Along with the reproducibility of simulations, this is one of the major research challenges the vehicular network community has to tackle.

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# LIST OF FIGURES

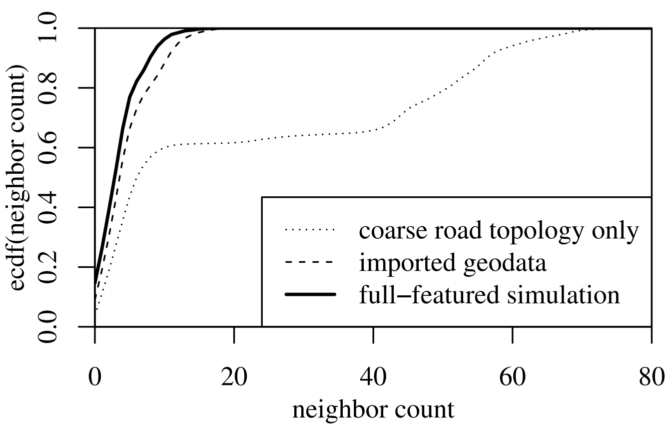


Figure 1. Impact of the quality of the used map data on the outcome of a simulation, based on results from [24].

Figure 2. A Region of Interest (big square, within a city scale road network) including buildings

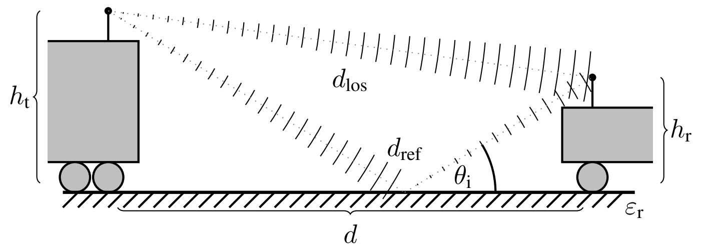


Figure 3. Illustration of the two-ray interference model: ground reflection causes distance-dependent constructive and destructive signal interference at the receiver.

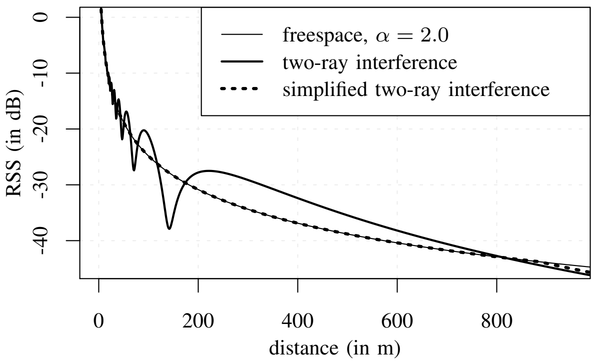


Figure 4. Model comparison for the Free-space model using different $\alpha$ values and the Two-Ray Interference model. For $d_c < 866.6\,\mathrm{m}$, results for $\alpha = 2.0$ and for the simplified Two-Ray Ground model are identical.

# List of Tables

Table I
SAMPLE LOW LEVEL AND HIGH LEVEL METRICS FOR THE SIMULATIVE PERFORMANCE EVALUATION OF VEHICULAR NETWORKS.

| Context | Example metrics |
|---|---|
| MAC Layer Protocols | Throughput, Channel Busy Times, Collisions, Packet Error Rates, Latency |
| Data Dissemination | Delay, Dissemination Range, Communication Overhead, Coverage |
| Safety | Timeliness, Accident Count |
| Privacy | Tracking Time, Anonymity Set Size, Entropy |
| Security | Overhead (Communication and Computation) |
| Environmental Applications | $CO_2$ Emissions, Fuel Consumption |
| Traffic Information Systems | Travel Time, Stop Count, Stop Lengths |