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A survey on modeling and simulation of vehicular networks: Communications, mobility, and tools

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A R T I C L E I N F O

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A B S T R A C T

Simulation is a key tool for the design and evaluation of Intelligent Transport Systems (ITS) that take advantage of communication-capable vehicles in order to provide valuable safety, traffic management, and infotainment services. It is widely recognized that simulation results are only significant when realistic models are considered within the simulation toolchain. However, quite often research works on the subject are based on simplistic models unable to capture the unique characteristics of vehicular communication networks. If the implications of the assumptions made by the chosen models are not well understood, incorrect interpretations of simulation results will follow. In this paper, we survey the most significant simulation models for wireless signal propagation, dedicated short-range communication technologies, and vehicular mobility. The support that different simulation tools offer for such models is discussed, as well as the steps that must be undertaken to fine-tune the model parameters in order to gather realistic results. Moreover, we provide handy hints and references to help determine the most appropriate tools and models. We hope this article to help prospective collaborative ITS researchers and promote best simulation practices in order to obtain accurate results.

1. Introduction and motivation

In the last years, the development of collaborative Intelligent Transport Systems (ITS) has been a focus of deep study. Communication-capable vehicles enable a plethora of valuable services targeted at improving road safety, alleviating traffic congestion, and enhancing the overall driving experience [1]. To support these services, different standardization bodies have defined the networking architecture of ITS stations [2,3], including vehicles' on-board units (OBU) and infrastructure's road-side units (RSU). Multiple network interface cards of different communication technologies coexist within a same OBU or RSU to support different use cases. Thus, cellular or broadband wireless interfaces provide the vehicle with connectivity to the infrastructure network (V2I), while dedicated short-range communications (DSRC) in the 5.9 GHz frequency band allow for vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) data transfers. In these cases, vehicles form a vehicular ad hoc network (VANET) in which collaborative services can be deployed.

The design and evaluation of ITS services and communication protocols is cumbersome, given the scale of vehicular networks and their unique characteristics. Some small-scale testbeds have been deployed [4,5] as a proof of concept, but results from small experiments cannot be extrapolated to real networks. In very few cases, field operational tests (FOT) have been implemented to evaluate an ITS platform under real traffic conditions [6]. However, given the high amount of required resources to deploy a FOT, it is only an option for a limited number of researchers and practitioners on the field. As an alternative, **simulation models** feature a good trade-off between the realism of results and the flexibility of target networks under study. Not surprisingly, most research on VANET and collaborative ITS rely on simulation as the main tool for design and evaluation.

Different fields stitch together in the development of collaborative ITS, including wireless communications and civil traffic engineering. In order to gather significant simulation results, a good understanding of the different models involved is required. It is widely recognized that simplistic wireless communication models lead to unreasonable results that do not match reality [7]. In addition, vehicular mobility patterns greatly differ from other networking scenarios and they need specific models to capture the characteristics of vehicles' movements. Different mobility patterns have a distinct impact onto simulation results [8,9]. Therefore, an ITS researcher must be aware of the different models that can be

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employed for each aspect of the simulation environment and how model parameters should be tuned to obtain realistic results.

While, traditionally, mobility and network simulators have been developed by different communities for different end users, both tools merge in collaborative ITS. It is of paramount importance that simulations account for realistic vehicles' movements as generated by mobility simulators. Then, network simulators must provide realistic simulation of communication models as the vehicles move according to a given traffic pattern. In some cases, an ITS application influences the mobility of vehicles. For instance, a traffic management service might indicate some vehicles to follow an alternative route to avoid a congested road. To support such scenarios, integrated mobility and network simulations are necessary and can be provided by interfacing existing tools or developing new ones.

In this paper, we survey the most significant approaches for wireless modeling and mobility modeling in vehicular networks. Specifically, we describe the models that have been often employed to characterize wireless signal propagation (path loss and fading) in the absence or presence of obstacles, including the support provided in available simulation tools. Common configurations of models parameters for both highway and urban environments are provided when applicable. In addition, we cover the simulation models which are available for the simulation of IEEE 802.11p DSRC and related standards. Differences among them are outlined. Regarding vehicular mobility, we briefly review some of the many models that have been proposed for decades and provide references for fine-tune calibration of model parameters when high mobility accuracy is required. Furthermore, we summarize the main features of common mobility simulation tools and describe the process to obtain a realistic vehicular scenario. Finally, we discuss the available options for performing integrated mobility and network simulations. We hope this work to help prospective collaborative ITS researchers and promote best simulation practices in order to obtain accurate results.

The reminder of this paper is organized as follows. Section 2 is focused on wireless signals modeling and simulation tools in the context of vehicular networks. Simulation models for DSRC technologies are reviewed in Section 3. In Section 4, we survey some significant vehicular mobility models and different traffic simulation packages. The steps to set up a realistic vehicular scenario are also discussed. Section 5 deals with coupled network and mobility simulations to account for ITS services that influence the behavior of traffic flows. Finally, Section 6 concludes this article.

2. Vehicular wireless communication

Understanding the implications of our chosen communication models is key to design appropriate simulation experiments and get insight from their results. In this section we review the most relevant models for vehicular communication systems, as well as the different tools that support them. We highlight the main take-aways that a prospective ITS researcher must keep in mind when conducting a simulation-based study. In addition, valuable information and handy references to help design experiments with different degrees of realism are provided.

2.1. Modeling of wireless links

When modeling a wireless ad hoc network, one of the first questions we have to answer is when we can state that a node[1] u is able to communicate with another node v. In such case, we say that a link exists from u to v.[2]

The simplest approach to model a wireless link is derived from a *Uniform Disk Graph* (UDG). All nodes are assumed to feature a communication range of radius r. In this way, a bidirectional link between u and v exists if and only if $|u, v| \leqslant r$, where $|\cdot|$ denotes the Euclidean distance. Note that a UDG represents an ideal network in the sense that perfect communication occurs up to r distance units from the source. This model does not have into account reception errors which might be provoked by radio interferences. It has been often employed in the literature since it provides a rough estimation of network connectivity in a simple way. However, it is well known that real wireless links do not follow this ideal model at all [11].

In order to capture the characteristics of realistic wireless links, signal propagation must be accurately defined (Section 2.2). This determines how signal power dissipates as a function of the distance. In the absence of interferences, the receiver will be able to decode the wireless signal, and therefore reconstruct the original message, whenever the *signal to noise ratio* (SNR) satisfies the following condition:

$$SNR = \frac{S}{N} \geqslant \beta,$$

where S is the received signal power, N is the noise power, and β is a threshold dependent on the sensitivity of the wireless decoder. Noise represents the undesired random disturbance of a useful information signal.

Since wireless medium is shared by the nodes in an ad hoc network, transmissions from a node interfere with concurrent communications between different nodes. This may cause great disturbance in the resulting signal, so that receivers would not be able to decode the message. In such case, we say that a *collision* has occurred. Thus, in the most general case, correct reception of a message by a node must satisfy that the *signal to interference-noise ratio* (SINR) holds the following requirement:

$$SINR = \frac{S}{I + N} \geqslant \beta,$$

where I is the cumulative power of interfering signals. Next we describe some of the commonly employed propagation models for wireless signals, so that the SINR for a given receiver can be computed.

2.2. Modeling of wireless signal propagation

As we have seen in the previous subsection, the signal strength at the receiver is lower than when it leaves the transmitter. Several factors contribute to this phenomenon, such as the natural power dissipation as the signal expands, the presence of obstacles which reflect, diffract and scatter the original signal, and the existence of multiple paths which may lead to signal cancellation at the receiver. The mean signal strength at the receiver as a function of the distance from the transmitter can be estimated by *large-scale* propagation models, while rapid fluctuations of the signal at the wavelength scale is better represented by *small-scale* fading models. The following subsections briefly review the most representative models that are relevant to vehicular wireless communications. They can be classified according to different criteria [12]. In Fig. 1, we distinguish among (i) deterministic vs stochastic models, (ii) large-scale path loss vs small-scale fading models, and (iii) whether obstacles (surrounding buildings, the vehicles themselves) are

[1] Throughout this paper, 'node' can be exchanged with 'vehicle' or 'RSU'.

[2] We assume that nodes employ omni-directional antennas. This is the most common scenario, although works on vehicular ad hoc networks with directional antennas have also been undertaken [10].