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Large-scale simulations and performance evaluation of connected cars - A V2V communication perspective

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ABSTRACT

Performance evaluation is integral to the vast majority of research on Vehicle-to-Vehicle (V2V) technology enabled connected cars. To validate ideas and concepts, researchers have been continuously striving towards the higher accuracy of simulation-based performance evaluation. However, many state-of-the-art network simulators lack comprehensive physical (PHY) layer models. More often, simplified representations of vehicular channel characteristics are used to achieve a trade-off between accuracy and performance. Vehicular channel modeling is a highly complex task because of its unique properties, for example, higher carrier frequency, rapid fluctuations in vehicular channels due to moving scatterers, and propagation in horizontal plane instead of a vertical plane with diffraction and reflection. Efficiently incorporating vehicular channel details into a single network simulator is infeasible; instead, a chain of simulation tools are used together. In this paper, we proposed a two-stage simulation framework which combines several layers of simulation tools into two distinct stages. During the first stage, a Geometry-based vehicular propagation model is used to characterize received signal strength among transmitter-receiver pairs. For this purpose, metropolitan area-wide 2.5D building geometry data and vehicular mobility traces are employed to represent the real-world environment. Subsequently, the output from the first stage is collected and fed as an input to the network simulator. Through extensive simulation-based studies, we analyze the difference between the proposed framework and standard propagation models implemented in the network simulator and their impact on the network-level performance metrics such as packet loss rate (PLR), throughput, latency, and jitter.

1. Introduction

The proliferation of the Internet of Things (IoT) and Connected Cars offer some interesting opportunities for the people to travel safely and conveniently. Vehicle-to-Vehicle (V2V) communication systems are at the center of modern connected cars and smarter cities and have been identified as an attractive solution to enhance road traffic conditions thereby contributing to achieving the goal of safer, cleaner, and more efficient and sustainable traffic management solutions. The potential applications of V2V technology include Intelligent Transportation Systems (ITS) and traffic telematics which allows vehicles

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to communicate with each other seamlessly. Hence, V2V communication is one of the most important todays research and development topics for the ITS innovations of tomorrow connected and smarter cities.

Most of the applied research in V2V communication systems relies either on testbed implementations or simulation-based performance evaluations [1]. Testbed deployments capture the surrounding environments of the vehicles more accurately and represent wireless channel characteristics in real-time. Therefore they provide large-scale network and protocol evaluation. However, due to their sheer cost and scalability issues, simulation is the widely used method to evaluate new protocols before the actual deployment. Moreover, many of the latest discrete-event simulation-based network simulators lack sophisticated propagation models that represent real vehicular channel characteristics, especially at the physical (PHY) layer of the network protocol stack. To bridge the gap between testbed and simulations, a detailed and flexible simulation framework which combines vehicular channel model, traffic generator, and network simulator is highly sought-after [1,2].

Vehicular channel modeling has been extensively studied and can be categorized into three types of models, i.e., stochastic, deterministic and geometry-based. In stochastic modeling approach, propagation characteristics are modeled by mean of analytical studies where the electromagnetic equations determine the path loss between any transmitter-receiver (TX-RX) pair. Lower computational complexity is achieved at the expense of imperfect realization of site-specific V2V communication scenarios. Deterministic approaches are capable of the modeling channel for specific V2V scenarios. However, the main disadvantage is the associated higher computational complexity. Finally, the geometry-based method combines the best from stochastic and deterministic channel modeling approaches and offer good accuracy-computational complexity mix [3]. The network simulators implement several propagation models, like Free-space, Two-Ray ground reflection, Log-distance, etc. Although these models are computationally inexpensive and relatively easier to implement, they are incapable of capturing the site-specific vehicular channel properties that could significantly impact the V2V performance evaluations.

The geometry-based channel models utilize information about the surrounding environment of the vehicles. The real-world environment information can be obtained from several sources, for example, in [4] and [5], authors used aerial or satellite images to reconstruct 3D building geometry information. Subsequently, ray-tracing is applied to determine the signal strength at each point of the constructed 3D terrain. Similarly, the propagation model studies given in [6,7] and [8] captures the propagation effects due to obstructing buildings by obtaining building geometry information from the globally available data source OpenStreetMap (OSM) [9]. Boban et al. in [10], further improved previous efforts by including building geometry information and vehicle mobility traces to determine the metropolitan area-wide received signal strength.

The focus of this paper is to assess the impact of real-world vehicular channel characteristics on simulation-based performance evaluations. We proposed a multi-phased simulation framework which combines several layers of simulation tools into two distinct stages. The first stage consists of three steps. During the first step, metropolitan area-wide 2.5D building geometry information is procured from commercial sources. Next, realistic vehicular mobility traces were generated at a city-wide scale. Thirdly, the building geometry data and mobility traces are then fed into the publicly available Geometry-based Propagation Model for V2V Communication (GEMV2) [10]. GEMV2 calculates the receiver signal strength among all the potential V2V communication pairs by taking into account obstruction caused by buildings and vehicles. In the second stage, the propagation path loss values from the GEMV2 are collected and assigned to all the corresponding communicating transmitter-receiver (TX-RX) pairs in the discrete-event network simulator ns-3 [11]. Through extensive simulations, there were two studies carried out. For this purpose, we presented a detailed case study for the city of Doha, Qatar. The first set of simulation results shows the impact of modeling line-of-sight (LOS) and non-line-of-signal (NLOS) links separately on received signal strength and a comparison with standard propagation models implemented in network simulators. The second study shows the impact of using realistic vehicular propagation modeling on network simulation-based performance evaluation. The results show a significant difference regarding network-level performance metrics such as packet loss rate (PLR), throughput, latency, and jitter.

The rest of this paper is organized as follows. The related work on vehicular channel modeling and simulation frameworks are described in Section 2. The proposed simulation framework is explained in Section 3, along with the description of the information required to build the realistic simulation scenario. The performance evaluation is presented in Section 4. To reflect on the limitations and the applicability of the proposed framework we included a discussion in Section 5. Finally, the paper is concluded in Section 6.

2. Related work

This section is divided into two parts. First, a brief overview of the V2V propagation modeling techniques is provided, which is followed by simulation framework for V2V ad hoc networks in the second part.

2.1. Studies on V2V propagation channel models

A wireless transmission path between a transmitter and a receiver vehicle can either have a direct line-of-sight (LOS) or a non-line-of-sight (NLOS) where the path is obstructed by buildings, foliage or even by other vehicles [10]. Studies on V2V propagation modeling considered different obstruction types, e.g., buildings, vehicles, and foliage using three existing techniques, i.e., stochastic, deterministic, and geometry-based.

In the absence of LOS, diffraction and reflection of radio signals allow NLOS reception due to the presence of buildings. There are some studies that looked into the impact of building on the received power strength. These studies mostly deterministic, include variety of scenarios from a single building [12–14] to narrow or wider intersections with different number of surrounding buildings [15,16]. In [12] authors performed the measurement-based verification of the theory of diffraction (UoD) around a single isolated corner of a building. The results show that the reflection and diffraction from the building wall contribute significantly towards relative signal amplitude at 1823 MHz frequency band. [13] and [14] describe propagation models for multiple urban corners. Both models were able to decide on different link types such as LOS, NLOS, and nLOS (near LOS) by using geometry details of buildings and road topology layout. Results obtained from [15] and [16] show that buildings, surrounding the intersections cause multiple propagation paths and contribute significantly towards the received power. Geometry-based propagation modeling is an important technique that takes building obstructions into account by mean of geometric parameters and simplified representation of building layout. In [17], an NLOS propagation path loss model is presented specifically derived for V2V communication at the 5.9 GHz frequency band. The authors in [18] augmented geometry-based stochastic propagation model for V2V with measurements based study to parameterize the generic model. The proposed model captures the V2V propagation characteristics to considerable accuracy while keeping the computational complexity lower. [6] provides an intermediate solution between deterministic and stochastic modeling techniques to capture the shadowing effect caused by the obstructing buildings. The model relies mainly on the commonly available building outline data and is less computationally intense. The authors in [5] put further emphasis on the realism and accuracy of channel modeling in V2V communication, especially the density and location of scatters distribution and their fading effects. In [4] and [5], authors used aerial or satellite images to reconstruct building geometry information. Subsequently, deterministic and geometry-based modeling techniques are applied to determine the signal strength of the constructed terrain.

Most of the previous research efforts on propagation modeling dealt with static obstructions, neglecting the cases where surrounding vehicles contribute towards the signal attenuation. To this end, some propagation models studied the impact of vehicles between the TX-RX vehicles on the V2V communication performance. The measurement campaigns are complimented by stochastic results to understand the interplay among propagation properties and vehicles. [19] and [20] indicate that in comparison with LOS condition, the NLOS due to vehicle obstruction significantly attenuates the signal. Some papers studied the impact of shadowing in V2V communications. [21] used three-way knife-edge model to study the impact of shadowing on inter-vehicle communication. [22] proposed scalable propagation model that included both large and small-scale fading by using vehicle location and road topology map information. Similarly, [23] proposed a semi-empirical shadow fading model based on measurements. The paper concludes that on average obstruction due to vehicle results in 10dB additional loss. The main focus of empirical studies is to cover a variety of environments, such as urban, rural and highways. [24] proposed an empirical study focused on characterizing the delay spread for three types of areas. In [25], authors conducted several field tests to characterize the impact of obstruction caused by vehicles. The results indicate the importance of NLOS through vehicle blockage that contributes diffracted signal paths to the receiver. Another empirical model [26] signifies vehicles as an obstruction based on an extensive measurement study collected from over 200 locations. Finally, [27] include a measurement-based study to quantify the effect of various propagation conditions on Vehicle-to-Infrastructure (V2I) communication in several urban environments with different terrain elevations and traffic flow variations.

More recently, Boban et al. [10] presented a detailed study on the attenuation of radio waves induced by all three main types of obstruction such as building, foliage, and vehicles in the V2V networking scenario. The proposed framework calculates different propagation mechanisms for each type of link by employing geometry-based channel modeling approaches. The empirical measurements were obtained from a variety of environments such as open space, urban and suburban highways. The geometry-based V2V channel model makes use of a real-world representation of obstructions to calculate different propagation mechanisms such as reflection, diffraction, scattering, etc.

2.2. Studies on V2V simulation frameworks

Related work also covers simulation frameworks for vehicular ad hoc networks (VANETs). There is a bulk of work done on joint simulations between microscopic vehicular traffic generators e.g., SUMO (Simulation of Urban Mobility) [28] and network simulators e.g., ns-2 and ns-3 [11]. The realism in simulations is achieved by mean of unidirectional [29] or bidirectional [30] incorporation of mobility traces from the traffic generators into vehicular networking simulations. Examples of integrated simulators include Veins [30], iTETRIS [31], VSimRTI [32], VanetMobiSim [33], ISP [34], HiTSim [35], Traffic and Network Simulation Environment (TraNS) [36]. However, incorporating vehicular traffic traces in network simulations is just one aspect of realistic performance evaluation of V2V communications. Most of the integrated frameworks rely on existing propagation models which are available with the network simulators. These built-in models make several assumptions to achieve simplicity and provide only the aggregated impact of the vehicle's surrounding environment on the network performance.

To mitigate the limitations of incorporating physical (PHY) layer details in network simulator another technique is to deal with link-level and system-level simulations separately and combine their collective impact on the overall performance by mean of a common interface [1]. The central idea is to extract relevant information from the link-level simulations and include it in system-level simulations. This approach has been extensively applied in the context of cellular and mobile networks [37,38]. There are two approaches to implementing the common interface, i.e., online and offline. The online approach [2,14,39] is similar to several other propagation model implementations where the network simulator implements complex electromagnetic equations into the simulator. Although fast, the online approach increases the complexity of joint simulator while making the overall technique less flexible. In the offline approach, [40] different characteristics from the traffic network are extracted and provided to the network simulator.

Network simulators use several propagation models to assign path loss values among all potential transmitter-receiver (TX-RX) pairs. Numerous studies [41–43] highlighted the importance of propagation model selection and their impact on network simulation accuracy. Earlier, the significance of geometry-based propagation models [10] was highlighted that uses site-specific information and geometrical details of the surrounding buildings and vehicles to characterize and model different types of links. Depending on the surroundings, the presence or absence of a certain type of obstruction such as buildings, foliage and vehicles may result in different path loss experienced by the vehicles at different locations.

Contributions: We proposed a novel two-stage simulation framework which combines multiple layers of simulation tools into two distinct stages. The first stage distinguishes LOS links from NLOS link types in a realistic V2V communication environment. The second stage performs packet-level simulation under varying vehicular traffic conditions. Finally, the selected channel propagation modeling techniques are evaluated regarding several network-level performance metrics such as Packet Loss Rate (PLR), throughput, latency, and jitter. The first stage identifies and collects information that is required to create a realistic simulation environment. It includes the necessary steps to process and combine data from diverse sources such as building geometry data and vehicular mobility traces. We implemented a metropolitan-area-wide reference scenario using a case study for the city of Doha, Qatar. Geometry-based V2V channel modeling technique (GEMV2) [10] is employed to obtain a site-specific characterization of received signal strength for the given simulation scenario.

As for the second stage, network simulator ns-3 is utilized to perform packet-level simulations and performance evaluation. We implemented an offline interface between the two stages that process and format the output from the first stage and incorporated the results into the network simulator. Finally, extensive performance evaluation is carried out for the given simulation scenario. Firstly, a comparison between geometry-based and traditional propagation models implemented in ns-3 is given. Secondly, packet-level evaluation of the channel modeling methods is provided using the protocol stack compliant with IEEE 802.11 standard [44] for vehicular communications. This paper involves intensive efforts on framework implementation and integration. To the best of our knowledge, none of the previous studies came up with such a detailed simulation framework that could quantify the impact of different channel modeling techniques on the network-level performance metrics in the realistic vehicular environment.

3. Two-stage simulation framework for V2V ad hoc network

Emulating realistic vehicle surrounding environment requires a variety of information from multiple sources. Moreover due to the complexity involved in implementing vehicular channel modeling for large-scale network simulations it is not possible for a single simulator to evaluate the performance of the entire system. Instead, several layers of simulators and the intermediate tools are used together. To this end, a layer of two simulators, i.e., geometry-based propagation model and network simulator along with a tool-chain of utility software have been combined by mean of an offline interface. The proposed simulation framework consists of two distinct stages. In the first stage, received signal strength value is calculated for all the potential TX-RX communication pairs in the presence of realistic 2.5D building geometry and vehicular mobility trace data. The measurements are then processed offline and stored locally for use in the latter stage. The second stage combines the path loss values with an abstract propagation model implemented within the network simulator. One of the advantages of using two-stage approach is that it allows the first stage, i.e., propagation modeling to be implemented independent of the second stage, i.e., network simulation and vice versa. Secondly, it hides the complexity and the implementation details and therefore adds more flexibility to the overall simulation framework. Thirdly, promotes re-usability by employing experimentally validated tools and techniques. Finally, it improves the accuracy of network-level performance evaluation.

3.1. Stage 1: environment data and geometry-based propagation model

To model the real-world surrounding environment in an urban V2V communication scenario, geometry-based propagation models require building geometry information, outlines of the vehicles and their mobility traces.

3.1.1. 2.5D building geometry data

The 2.5D building geometry data has been procured commercially for an area of approximately 140 sq. km. Within the city of Doha, Qatar. Building geometry data is obtained for the selected part of Doha in a vector form where each building is represented by a closed 2D polygon with accompanying height information. The raw geometry data has to be converted to the required XML format, to use with the Geometry-based Propagation Model (GEMV2) [10]. The raw building geometry information consists of both metadata and binary data which together describe the object feature information in the respective area. The data is provided in the form of a pixel-map, and all the values are written as a binary stream. The binary stream is then Base64 encoded and outputted in ASCII format. Finally, the XML formatted output is obtained to use in the subsequent step by the geometry-based propagation model. The geometry data is used to calculate diffractions and reflections off the building outlines, as described in the subsequent subsection.

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[1] RMSI-http://www.rmsi.com/telecom/

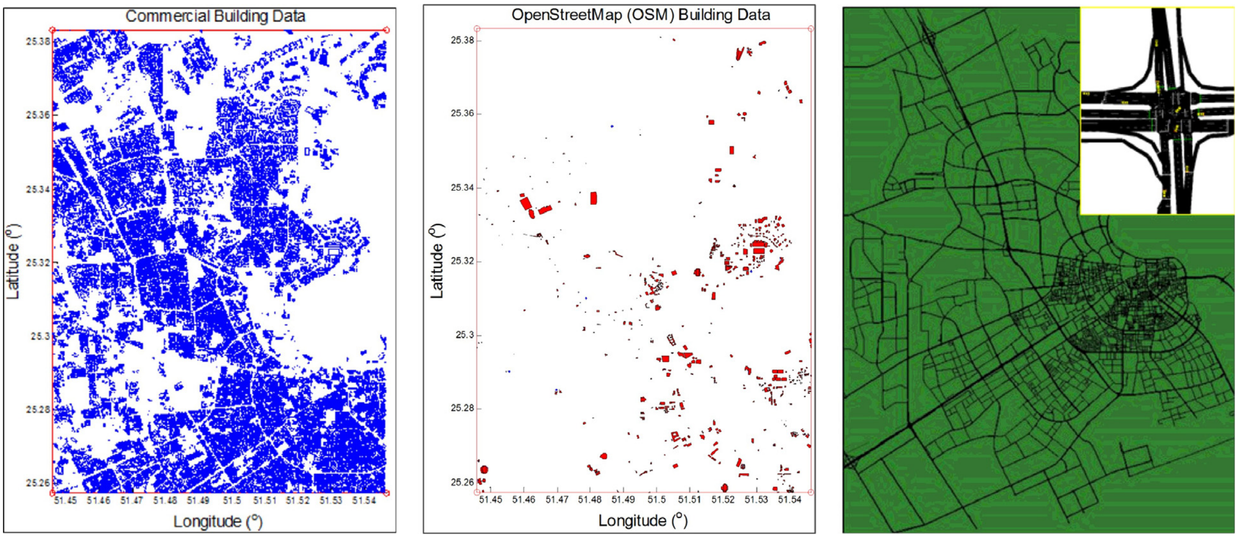

Fig. 1. (a) Building geometry information procured from a commercial source.[1] (b) Building geometry information obtained from OpenStreetMap (OSM) [9]. (c) Road infrastructure map obtained from OpenStreetMap (OSM) [9] and displayed in SUMO-GUI [28]. Inset figure shows the vehicular traffic near an intersection.

The proposed simulation framework is independent of the geometry data sources as far it complies with the data format as required by GEMV2. The GEMV2 propagation model requires geo-data to be formatted in .osm or .pbf file format. The raw building geometry binary data is processed and converted into the desirable file format. OpenStreetMap (OSM) [9] provides open-source and free worldwide map data. Mainly volunteers around the world contribute and collaborate to create and maintain the geographical information system (GIS). OpenStreetMap data finds its usage in many applications. However, the quality of data varies significantly throughout the world. In the context of vehicular ad hoc networks the OpenStreetMap data has been utilized and compared with commercially available geo-data. For example, authors in [7], utilized OpenStreetMap data for V2V propagation modeling in the urban scenarios. They reported the significant impact of available information in the geographic database on the accuracy of performance evaluation. As for the simulated reference scenario, the geo-data for Doha is incomplete with either most of the building layout information missing or partially drawn. Fig. 1(a) and (b) compares the building geometry data set for the selected area within the city of Doha, Qatar from commercial source and OSM.

3.1.2. Vehicular mobility trace data

To generate mobility traces at city-wide scale over real road infrastructure map, the SUMO [28] is utilized. The road network layout for the selected Doha area is extracted from the OpenStreetMap. OSM provides worldwide maps through an extensive network of contributors and large user base. For this purpose, the OSM file format has to go through several necessary conversion steps before it is combined with randomly generated trips and route information. The road network information in NETMAP file format and the route information produce vehicular mobility patterns in Floating Car Data (FCD) format. The microscopic-level mobility traces where movement patterns for each vehicle are modeled has its routes, and move throughout the selected part of the urban area in Doha. To be able to use the FCD data with network simulator like ns-2/ns-3 [11], OMNET++ [45], etc. the mobility trace has to be exported in the required format using the *TraceExporter* utility available with the SUMO distributions. Fig. 1(c) illustrates the extracted road topology from OpenStreetMap and the mobility scenario in SUMO-GUI.

3.1.3. Description of the GEMV2 propagation model

For the first stage, (GEMV2) [10] has been utilized. GEMV2 provides a geometry-based, efficient propagation model for V2V communications. GEMV2 treads through the crossroad of deterministic and stochastic channel modeling techniques. GEMV2 propagation model can distinguish and measure channel characteristics of three different types of links by taking into account buildings and vehicles position along with their geometry outlines information. (1) Line-of-sight (LOS), (2) Non-line-of-sight, obstructed by buildings (NLOSb) and (3) Non-line-of-sight, obstructed by vehicles (NLOSv).

Propagation models for wireless communication incorporate three propagation mechanisms, i.e., reflection, diffraction, and scattering. These propagation mechanisms occur in two distinct manners depending on the relative location of the transmitter and receivers (1) large-scale and (2) small-scale fading. Since the GEMV2 model provides channel characterization of three link types namely LOS, NLOSb and NLOSv, therefore, each type handles these three mechanisms differently. The model introduces two propagation mechanisms for each link type. (1) Large-scale signal variation is calculated deterministically and models the effect related to path loss and large-scale fading. (2) Small-scale signal variation is calculated

Table 1
Propagation models and parameter values for LOS, NLOSv and NLOSb links.

Link type	Large-scale variation	Small-scale variation
LOS	Two-ray Ground Reflection with reflection coefficients	(σ_{min} = 3.3 dB, σ_{max} = 5.2 dB)
NLOSv	Horizontal and vertical multiple knife edge diffraction	(σ_{min} = 3.8 dB, σ_{max} = 5.3 dB)
NLOSb	Single interaction reflection and diffraction and Log-distance pathloss	(σ_{min} = 0 dB, σ_{max} = 6.8 dB)

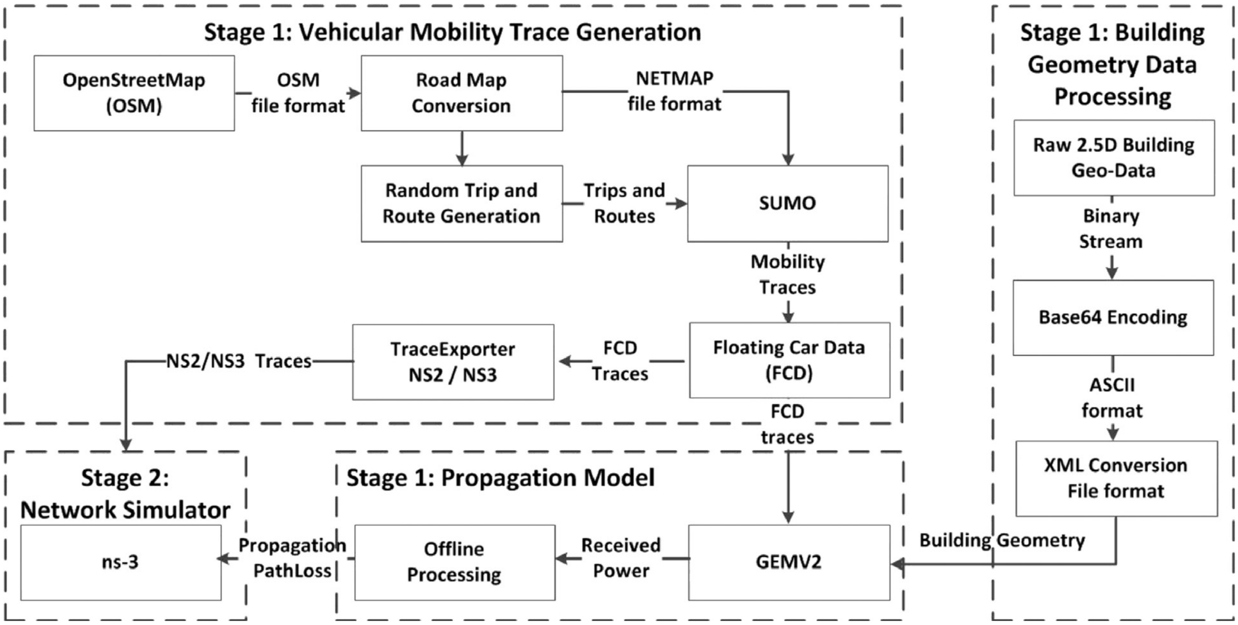

Fig. 2. Two-stage simulation framework: stage 1, environment (2.5D geometry and vehicular mobility traces) data and geometry-based propagation model.

stochastically and models the effect by combining multipath due to diffractions, reflections, and scattering, and Doppler spread. GEMV2 applies different propagation models for calculating large-scale variations based on the link type, i.e., LOS, NLOSv, and NLOSb. The small-scale variation is calculated by using zero-mean normal distribution along with the minimum and maximum standard deviation, i.e., (σ_{min}, σ_{max}) obtained using an elaborate method based on the extensive experimental dataset. These values are extracted and experimentally validated for all three types of links in different environments like open space, urban, highway and under different traffic densities.

- For LOS links, the received power is mainly defined by the large-scale signal variation which is calculated by using Two-ray ground reflection with reflection coefficients selected according to the antenna heights. The small-scale variation is a zero-mean normal distribution with minimum standard deviation obtained from the open-space environment and maximum deviation from downtown environment given by (σ_{min} = 3.3 dB, σ_{max} = 5.2 dB).
- For NLOSv links, multiple-knife edge diffraction is used to calculate large-scale variation. The small-scale variation is a zero-mean normal distribution with minimum standard deviation obtained from highway environment and maximum deviation from downtown environment given by (σ_{min} = 3.8 dB, σ_{max} = 5.3 dB).
- For the NLOSb links, the maximum between Log distance path loss model and single-interaction reflection/diffraction off the building is used to calculate large-scale variation. We chose the later case, and the small-scale variation is a zero-mean normal distribution with minimum standard deviation set to 0 and maximum deviation from the downtown environment is used given by (σ_{min} = 0 dB, σ_{max} = 6.8 dB). Table 1, summarizes the channel models used and the parameters settings for estimating received the signal power of LOS, NLOSv and NLOSb link types.

The accuracy of GEMV2 model has been compared and validated against the empirical dataset. In [10], Boban et. al. performed measurements studies with IEEE 802.11p standard compliant hardware platform. The measurement campaign considers various environments under different traffic to obtain the values for the minimum and maximum standard deviation, i.e., (σ_{min}, σ_{max}). For example, in LOS and NLOSv cases the σ_{min} is selected from the least variable environments open space and highway, respectively. As for the NLOSb case, the σ_{min} is set to 0 because GEMV2 estimates reflection and refraction from the single-interaction rays off the building geometrical layout. For all link types, σ_{max} is based the measurements collected in a downtown environment. More details on GEMV2 working and implementation is given in [10].

Fig. 2 shows the schematic of proposed two-stage simulation model. The first stage mainly consists of three building blocks. (1) Building geometry data processing: the raw data procured from commercial sources has to process and converted into the required file format. (2) Mobility trace generation: using OpenStreetMap [9] and SUMO [28] and (3) Geometry-based Propagation model i.e., GEMV2 [10]. The building geometry data in XML format and the vehicle mobility traces are fed into the GEMV2 simulator. GEMV2 runs the experiment and generates output in terms of received power level between all the potential TX-RX pairs. The offline processing block arranges the GEMV2 output by link type, propagation path loss value, and distance among all the communicating pairs. The framework uses this information as an input to the network simulator during the execution of subsequent stage. Network simulator, i.e., ns-3 [11] is the only constituent building block of the second stage, describe next in more details.

3.2. Stage 2: network simulations

The network simulators provide a global or aggregated performance perspective of several vehicles involved in the experiments. With network stack implemented, the evaluation of network-level performance metrics can incorporate the impact of packet collisions and queuing delays at the transmitters and receivers. For V2V communication performance evaluations, network simulators (like ns-3) are capable of simulating a large number of vehicles in an ad hoc environment. Network simulators are capable of calculating path loss by employing propagation loss models like two-ray ground reflection, log-distance, etc. Although these propagation models do consider lossy wireless environment by mean of estimating path loss exponent, the problem is that they do not fully reflect the surrounding environment of the vehicles. In this paper, we mainly focused on how to combine realistic vehicular propagation models with network simulator and investigate V2V performance evaluation from the application point of view.

The network simulator, ns-3 [11] is utilized to evaluate the impact of propagation model selection in a discrete-event network simulator. In ns-3, several different propagation channel models can be used for packet-level simulations. These propagation models can be categorized into three groups [46].

- Propagation models like Friis, log-distance, three-log distance, and two-ray ground reflection calculates the path loss deterministically over the distance between the TX-RX pairs. Such models mostly rely on the distance, transmission power, reference distance and path loss exponent information to calculate the signal strength at the receiver end.
- Another class of propagation models termed as abstract models in [46], do not implement equations required to calculate propagation losses instead these models such as fixed, matrix, random and maximal range can be configured with fixed path loss values.
- Finally, the third class includes fading model like Nakagami and Jakes that are *chained* with the deterministic and abstract channel models to incorporate the impact of mobile fading in the simulations.

In this study, a simple Matrix propagation model is used, and its performance is compared with several other deterministic channel models under similar V2V communication scenarios and networking parameters. In Matrix propagation model the propagation loss is fixed between each TX-RX pair. The simulation scenario consists of several vehicles and their positions in the simulated area were obtained from the SUMO. The offline processing block of the first stage arranges the path loss information in a matrix like the tabular format where each entry contains information like time step, transmitter identity, receiver identity, link type, and propagation path loss value between the TX-RX pair. The propagation path loss values were obtained from the realistic GEMV2 propagation model. All these entries are sorted on the time step field.

The network simulation employs the static technique, i.e.; each iteration corresponded to a simulation instance build on top of the previous one, i.e., “snapshots” were taken of the overall scenario in the V2V ad hoc network. In the static technique, the complete experiment run is divided into distinct time steps, and each iteration of the experiment corresponds to a single time step. At the start of each time step or iteration, the system-level simulator reads position and corresponding propagation path loss information for each TX-RX pairs. These values were obtained from the previous step and fetched from the local disk. So unlike other deterministic propagation modeling techniques which calculate the received signal power as the function of different parameters such as distance and path loss exponents, this value can be extracted offline from the GEMV2. The served vehicular network applications set different parameters such as required beaconing frequency, data rate, and throughput latency budget. As for the physical (PHY) and MAC layers, vehicles follow IEEE 802.11 [44] standard for vehicular communications and are configured with an application which sends periodic Cooperative Awareness Message (CAM) [47]. The application used a beaconing frequency of 10 Hz which is typical of several applications. This process continues until all the time steps are executed. Fig. 3 summarizes the Stage 2 in a flowchart diagram representation.

4. Performance evaluation

4.1. Simulation environment

For performance evaluation, we have emulated a typical urban reference scenario near the Old Airport region and its surrounding area in Doha, Qatar. The selected region covers 3.2 sq. km. of the area with approximate maximum and minimum bounding box given by (25.27°, 051.54°) and (25.26°, 051.52°) coordinates, respectively. The selected region, in general, is characterized as dense with heterogeneous building heights which comprise of several wider intersections which are major crossroad with up to four lanes in each direction and narrower street canyons as well. The mobility traces comprises five

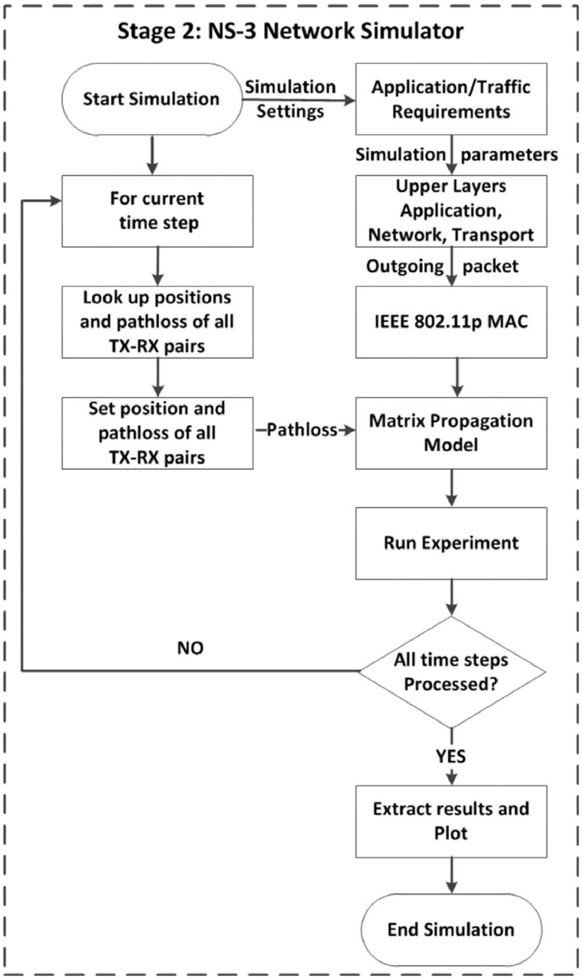

Fig. 3. Two-stage simulation framework: Stage 2, The schematic of network simulation using ns-3.

hundred vehicles over the period of simulation duration. Each vehicle follows a precomputed route between the randomly selected source and destination. The average speed of the vehicle is selected within the range of 20 km/h and 60 km/h.

The network simulator implements a number of threshold parameters that determine whether a frame is received successfully at the receivers end, in presence multiple transmitters. For this purpose mainly two parameters EnergyDetectionThreshold and CCAModelThreshold are used with the values set to −80 and −82, respectively. These values are according to the IEEE 802.11 [44] standard. The CCAModelThreshold is used to determine whether a receiver detects a frame. If a frame is received with the signal strength less than CCAModelThreshold value, the frame is discarded at the PHY layer. The signal strength has to be stronger than the EnergyDetectionThreshold value to receive the incoming frame correctly. Otherwise, the frame is considered corrupted and discarded at the MAC layer. Finally, in the case where multiple frames arrive simultaneously, the SNR value is calculated and compared with another parameter CPThresh value. Here, the SINR (dB) is given as the ratio between the receiving frames signal strength to the sum of other frames signal strengths and the Noise. The value of CPThresh and Nosie is set to be 4 dB and −99 dBm, respectively as given in [49]. The receiving frames are considered correct if the SINR is larger than CPThresh. Otherwise, all frame are discarded. The other source of performance degradation includes path loss and channel fading. In the network simulator, while the path loss is estimated using GEMV2, the impact of channel fading is incorporated by chaining the abstract propagation model with the Nakagami-m Channel model. We measured the PLR, by analyzing the sequence numbers of received packets in each receiver log file for each simulation time instance. The parameter MaxRange (maximum range) is defined as the threshold distance (in meters) between a sender and the receiver, outside which it is assumed that the packets can not be decoded properly at the receiver independent of its received SINR. The given values of transmission range radii for each link type are based on transmission power, receiver sensitivity threshold and the nearby environment [10]. The simulation parameter and their values from both GEMV2 and ns-3 are given in Table 2.

Table 2
Simulation parameters and values.

Parameters	Values
Number of vehicles	500
Beacon transmission frequency	10 Hz
Antenna type	Omni-directional
Frequency	5.89 GHz
Packet size	512 bytes
Channel bandwidth	10 MHz
Transmission power	18 dBm
Data rate	6 Mbps
Energy detection threshold	−80 dBm
CcaMode1threshold	−82 dBm
Simulation duration	300 s
Max. range (LOS links)	500 m
Max. range (NLOSv links)	400 m
Max. range (NLOSb links)	300 m
Simulation area	3.2 sq. km
Propagation models	**Parameter values**
Log distance	Exponent: 2.9 Reference distance: 1 m Reference loss: 47.8423 dB
Two ray ground reflection	System loss: 1 Minimum distance: 0.5 m Height above Z: 1.5 m
Nakagami-m	Distances: 80 m, 200 m Exponents: 0.25, 0.75, 0.75

The main focus of this section is to evaluate the impact of GEMV2 and other standard propagation models available with ns-3 [11] on network-level performance metrics. There were two studies conducted,

1. Comparison between geometry-based propagation model and models implemented in ns-3, in terms of received signal power (dBm), packet loss (PL), and effective communication range.
2. Evaluation regarding several network-level performance metrics such as PLR, throughput, latency and jitter in the presence of interference from multiple transmitter-receiver vehicles.

Following metrics are used to measure the impact of propagation models on network-level performance.

1. Packet Loss Rate (PLR) is defined as the ratio between the number of packets lost by all the indented one-hop receivers to the total number of packets transmitted. In our simulation, the one-hop receivers include all the vehicles that are within the transmission range of a transmitting vehicle.
2. Throughput, defined as the total received bytes at the destination, averaged over the total simulation time.
3. Receive time is defined as the time spend on actually receiving the packets accumulated over 1000 ms (1 s) window and averaged over total simulation time.
4. Latency, given as the sum of all end-to-end delays for all received packets, averaged over a total number of packets received.
5. Jitter is the difference between delays of two consecutive packets.

4.2. Simulation study

4.2.1. Comparative study of propagation models in vehicular environment

Network simulations for the selected urban region of Doha, Qatar was performed along with the given parameters settings. At first, received signal power characterization among all the potential communicating pairs was carried out using GEMV2. Fig. 4 shows the Google Earth visualization of the received power calculated by the GEMV2 propagation model. The building geometry is outlined in white color whereas the line colors represent received signal strength. The colors of the lines representing links between TX-RX pairs show received power relative to the maximum received power in dBm during the simulations. The maximum received power observed during the simulation instance was −22 dBm.

As shown in Fig. 5, the difference in received power between the LOS and NLOSv and NLOSb type link signifies the fact that both vehicle and building obstructions cause a significant reduction in the received signal power (dBm). The comparison among propagation models regarding received power shows considerable differences as well. These results are obtained using the GEMV2 and ns-3 simulators with the settings described in the previous sub-section. The LOS type links in GEMV2 are modeled using the Two-ray ground reflection technique however the implementation details differ from that of ns-3. The ns-3 implementation of Two-ray ground reflection model assumes that the distance between the communicating pair is

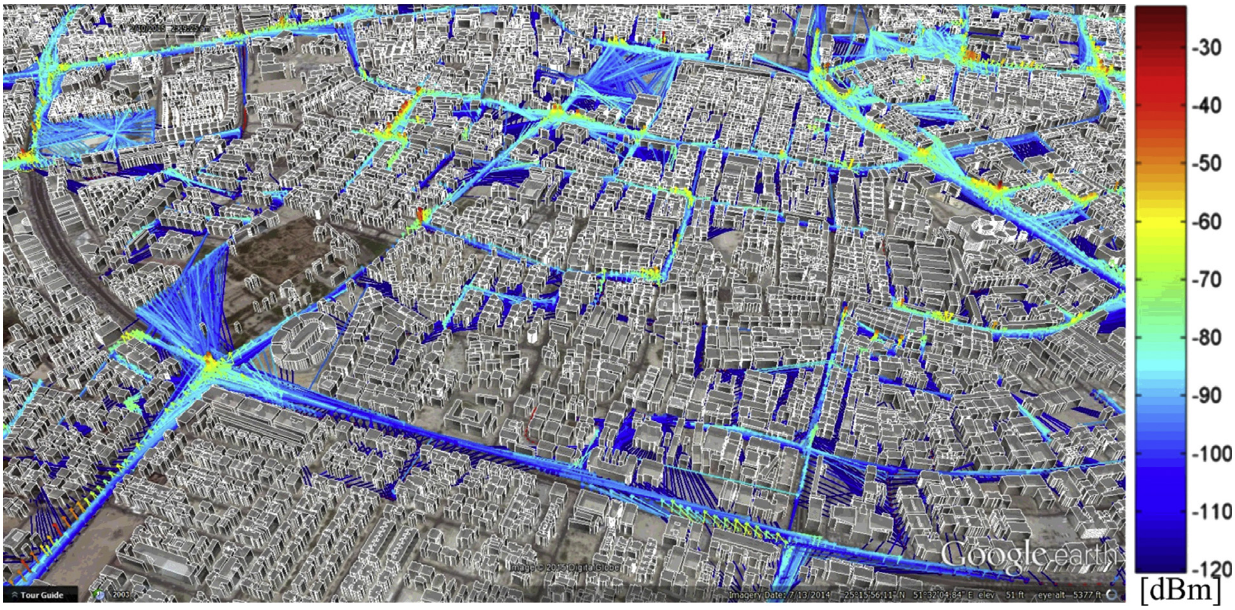

Fig. 4. Google Earth visualization of an urban V2V scenario with a number of transmit-receive pairs in the city of Doha, Qatar. The white color represents building outlines and the colormap shows received signal strength in dBm which is calculated using GEMV2 [10].

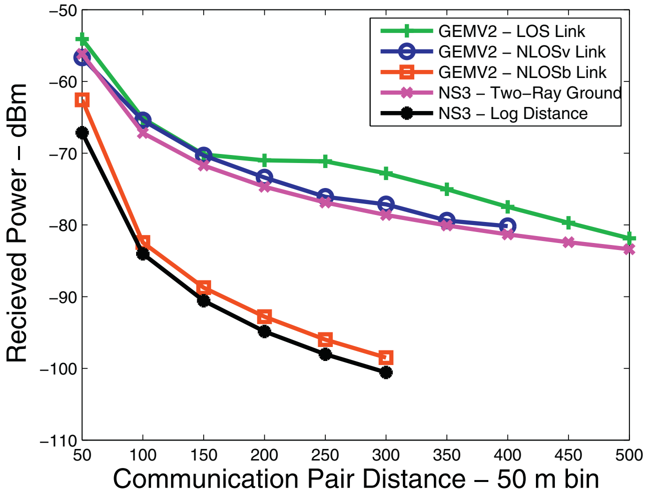

Fig. 5. Received signal power - dBm vs. Communication pair distance - m for LOS, NLOSv and NLOSb type links in GEMV2 and common propagation models in ns-3.

too large as compared with their antenna heights and considers the path difference between LOS and ground-reflected rays very small, thus assumes the existence of LOS rays only. Taking into account the ground-reflected rays results −2 dBm to −6 dBm difference regarding received power. Similarly, GEMV2 calculates the maximum between log-distance path loss and the single interaction reflections and diffractions off buildings to model NLOSb links. Whereas the log-distance implementation of ns-3 simply generalized the urban environment by mean of path loss exponent which is set to 2.9. The buildings surrounding the vehicles cause multiple propagation paths and contribute reasonably to the received power. Since the vehicles are surrounded by realistic representation of the environment in terms 2.5D building geometry, on average the received signal power differ between −2 dBm and −4 dBm. As for the NLOSv link types, GEMV2 utilizes three-way knife-edge model to study the impact of diffraction on inter-vehicle communication. The result shows that NLOSv due to vehicle obstruction significantly attenuate the signal causing packet loss to increase as the distance between sender and receiver increases.

The differences in propagation model implementations have a profound impact on the packet loss and effective communication range, as well. Packet Loss (%) and effective communication range (m) are measured based on the receivers minimum sensitivity threshold value of -82dBm for the data rate of 6 Mbps as given in [44,48]. For each communicating pair within the given maximum range, the received signal power is compared against the sensitivity threshold to determine

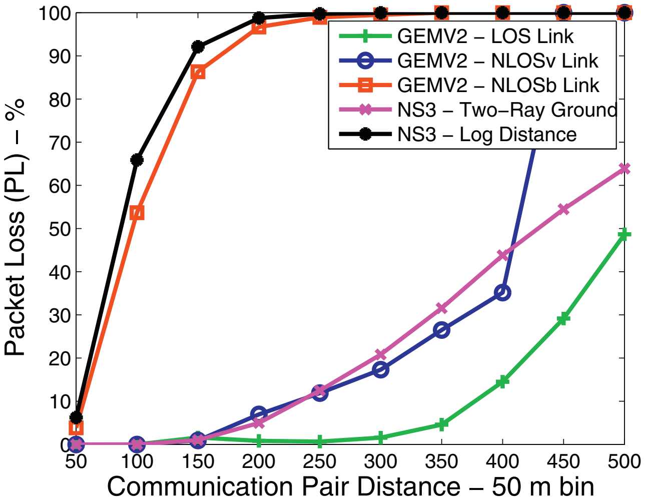

Fig. 6. Packet Loss (PL) - % vs. communication pair distance - m for LOS, NLOSv and NLOSb type links in GEMV2 and common propagation models in ns-3.

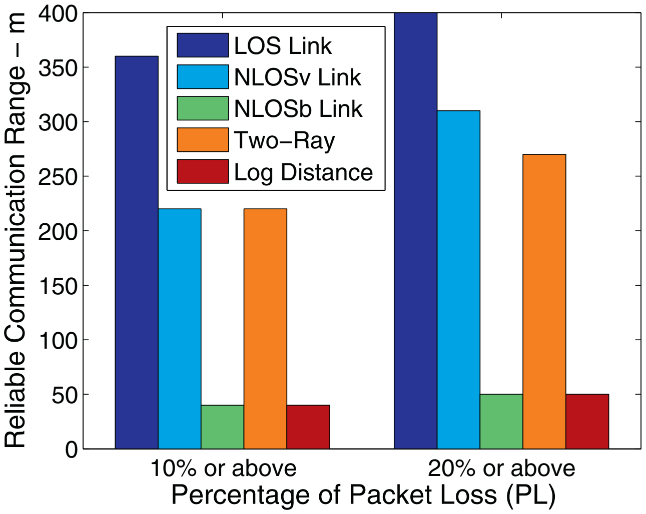

Fig. 7. Reliable communication range - m for LOS, NLOSv and NLOSb type links in GEMV2 and common propagation models in ns-3.

whether a packet is delivered successfully. Fig. 6 shows that as the distance separating transmitter-receiver increases, the packet loss increases. For all the propagation models, most of the packets were delivered at shorter distances, however as the distance increases the PL increases as well. LOS links sustain lower packet loss even at longer distances (up to 400m) between the communicating pairs, however, in NLOSv and NLOSb cases there is a significant increase in packet loss as the distance reaches 300m and 50m, respectively. The performance difference in terms of PL between Log-distance and NLOSb is marginal. While the relative performance difference between Two-ray ground reflection and LOS is comparable to distance up to 200 m, however, the gap grows significantly with the increase in distance.

Fig. 7 show the reliable communication range, calculated as the maximum distance at which the PL is less or equal to 10%. The maximum range set for LOS, NLOSv and NLOSb type link are 500 m, 400 m, and 300 m, respectively. The discrete components from vehicles and building obstructions and scattering causes reliable communication range to decrease significantly. For LOS, NLOSv, and NLOSb link types the reliable communication range is observed to be as low as 28%, 45% and 87% of the maximum transmission range, respectively. The effective communication ranges for the most common propagation models are also plotted. On average Log-distance propagation model and NLOSb type links perform comparably. The comparison between the ns-3 implementation of two-ray ground reflection and LOS model in GEMV2 shows that the later sustain higher effective transmission range. Using further relaxed packet loss of up to 20% results in an increase in reliable ranges for all propagation models in comparison with that of 10%.

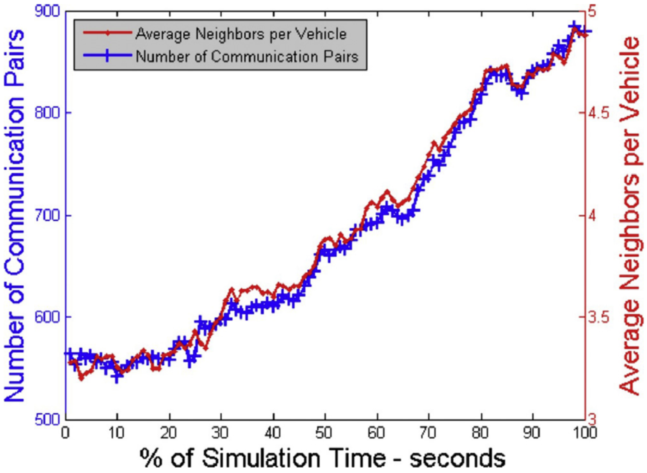

Fig. 8. Total number of communication pairs and average neighbors per vehicle vs. % of simulation time.

4.2.2. Impact of propagation models on network-level performance metrics

Next, the impact of incorporating the line-of-sight and non-line-of-sight path loss modeling and fading on the network-level performance metrics in ns-3 is described. The output regarding path loss from the MATLAB based implementation of the GEMV2 is supplied as an input to the Matrix propagation model in ns-3. To consider the impact of fading on the highways and urban environments stochastic channel model (Nakagami-m model) is applied on top of the given path loss models. In ns-3 this can be done by chaining the propagation loss models together so that each acts on the packet to closely represent the wireless communication channel in an urban community. Moreover, the performance is accessed with most commonly used PHY and MAC layer parameter setting in the vehicular networking environment as described in the simulation setup section. Fig. 9 through Fig. 13 show the simulation results in terms of network-level performance metrics such as packet loss rate (PLR), throughput, receive time, latency and jitter.

The simulation scenario emulates safety application that relies on the periodic broadcast of warring/awareness messages with the beaconing frequency [50] or update rate [51] of 10 Hz. Moreover, to account for interferences among vehicles during the simulation, the total number of communication pairs and an average number of neighbors per vehicle are increased as the simulation progresses as shown in Fig. 8. The Fig. 8 shows that to avoid cold start effect a warm-up time which constitutes the initial 20% of total simulation time was introduced. During this warm-up time, fewer communication pairs were made part of the simulation scenario thus avoiding a very large number of vehicles in a short period [52]. The rest of the curve shows that once a steady number of vehicles is achieved (after the warm-up time elapsed) a consistent number of communication pairs and neighbor density were introduced during the simulations in every step of the simulation time. Finally, the simulation includes a large number random routes, thanks to the utilities such as randomTrips.py and randomRoutes.py that are part of the SUMO distribution.

Fig. 9 shows that as the simulation progresses the PLR increases for all three types of communication links. There are two main contributing factors for higher packet losses, firstly, the inter-vehicle distances and secondly the increase in vehicle density. The reliable communication among the communicating pairs is achieved at shorter distances. The LOS, NLOSv, and NLOSb link types maintain reasonable packet loss rate, i.e., up to 10% at communication distances of only 360 m, 220 m, and 40 m, respectively. The PLR go up as the receiving vehicles leave the line-of-sight segment. In the case of non-line-of-sight link types, there are significant packet losses at the higher distances between the communicating pairs. Taking a closer look at the PLR curves progression, it can be observed that the PLR remains at relatively lower levels, for example, 5% in the case of LOS type links. As the simulation progresses, the vehicular density increase as new vehicles are injected into the experimental setup and therefore average neighborhood size increases as well. Vehicles nearby each other tend to compete for the common channel resulting in higher packet losses due to contention.

Fig. 10 shows the impact of lower packet delivery on achievable throughput. Throughput decreases for all three types of communication links. The LOS links were able to retain significant throughput for longer distance among the communicating vehicles whereas overall NLOSv and NLOSb links were able to manage up to 95% and 90% of the throughput achieved by the LOS links. These results are further supported by average packet reception time given in Fig. 11. The time each vehicle spent on receiving packet decreases as the simulation progress which leads to lower throughput for each link types. The percentage decrease regarding packet reception time for NLOSv type links is observed to be between 4% to 20% as the simulation time increases. A close observation of the simulations reveals that an NLOSb type link typically has epochs with NLOS and LOS conditions. The duration of these epochs varies depending on the surrounding environment and speed of the vehicles. Considering the average speed between 20 to 60 km/h of the vehicles and a surrounding urban environment, leave less time of reliable packet reception in the scenario.

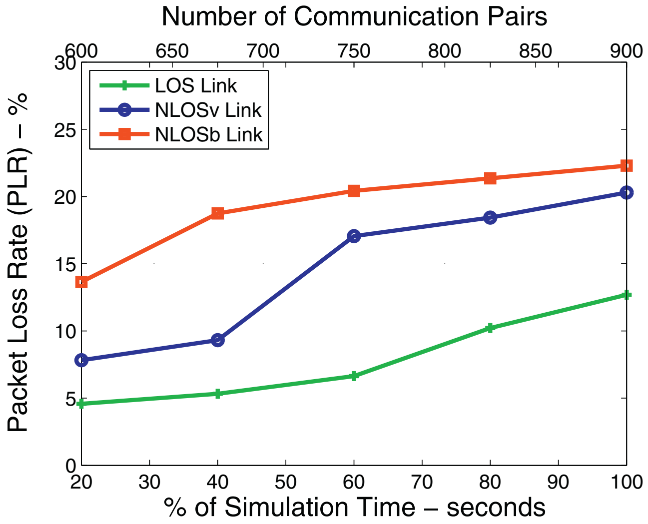

Fig. 9. Performance in terms of Packet Loss Rate (PLR) - % vs. % of simulation time.

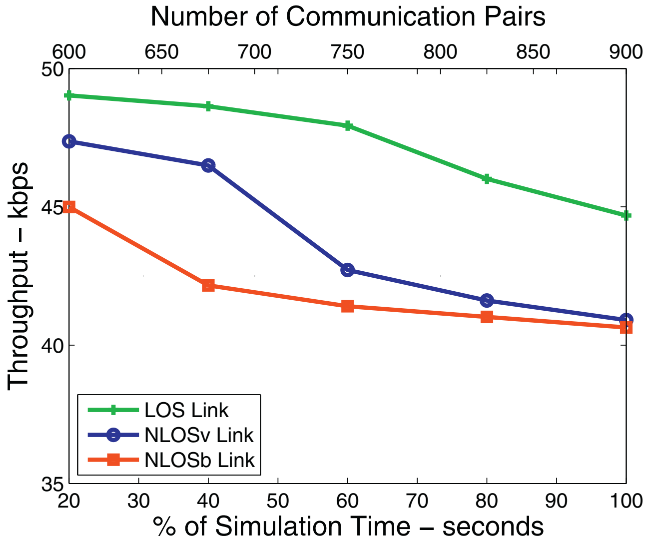

Fig. 10. Performance in terms of throughput - kbps vs. % of simulation time.

Figs. 12 and 13 show the performance regarding latency and jitter, respectively. On average LOS, NLOSv and NLOSb type links experience 74ms, 120ms, and 50ms of latency, respectively. For LOS and NLOSv link types the latency increases considerably as the vehicle neighborhood size increases. However, for the NLOSb links, the latency increases slightly as the simulations progress. Similar trends are observed for inter-packet delivery latency or jitter performance for each link types. On average the NLOSv model results in 40% and 60% more delay as compared with LOS and NLOSb links, respectively. Most road safety applications rely on the broadcast of awareness messages with 100ms latency constraint [51]. Packet-level simulators apply single channel model indiscriminately regardless of the link type. Essentially the performance difference regarding latency and jitter is due to the choice of different channel modeling techniques and traffic parameters. The network and MAC layer protocols can exploit this information while making routing/forwarding and scheduling transmission decisions. For example, link types experiencing with higher latency can be prioritized by the routing and scheduling algorithm accordingly.

5. Discussion

Different type of obstructions results in different propagation mechanisms that must be accounted for while calculating the propagation path loss. Especially in an urban V2V environment, buildings and other vehicles are the two dominant causes of signal obstruction between the transmitter-receiver pairs. Even most recent network simulators take a gross

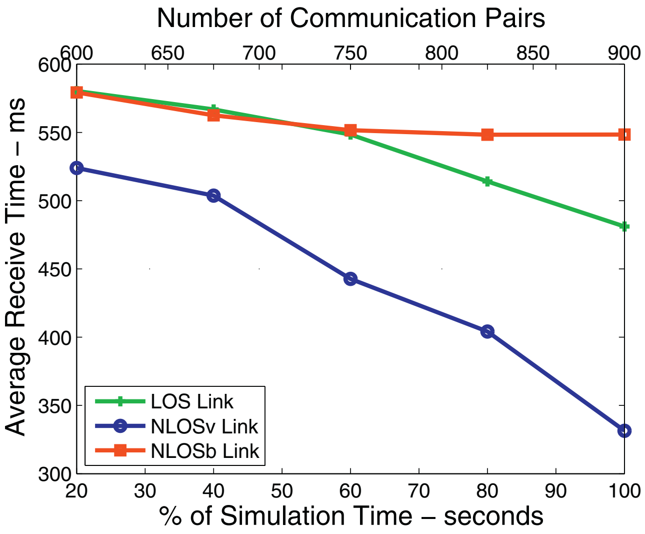

Fig. 11. Performance in terms of receive time - ms vs. % of simulation time.

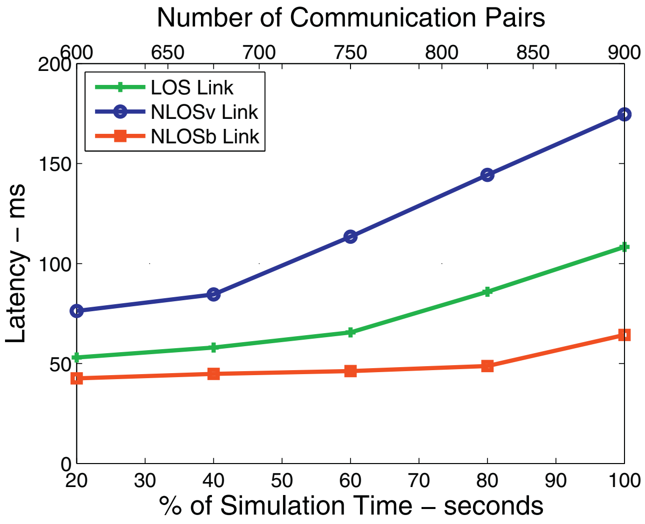

Fig. 12. Performance in terms of latency - ms vs. % of simulation time.

approach where the environments are reflected by mean of path loss exponent. Simplified versions of channel models are implemented to achieve good accuracy-performance mix, and the influencing environmental factors are applied on each link with little or no consideration for the type of obstruction. The first phase of our proposed simulation framework is built upon the work of Boban et. al. [10] wherein they design, developed and made publically available geometry-based propagation modeling technique (i.e., GEMV2). GEMV2 distinguishes precisely between different links according to the obstruction types in the V2V communication environment. For this purpose, building geometry and vehicle layout information is incorporated with realistic mobility traces. Moreover, well-established propagation modeling techniques are applied according to the link types. Incorporating, such details in a network simulator would not only increase the time as well as complexity to perform simulation by many folds. The results from the first phase are processed and applied in a network simulator where packet-level simulations are performed under realistic traffic conditions. Intensive efforts went into the framework implementation and integration. The proposed framework certainly has a practical significance on V2V network performance evaluation, where it can act as a reference scenario for test-bed implementation and evaluation of V2V communications.

The achieved trends emphasize the importance of separate channel models that cater for both on line-of-sight and non-line-of-sight signal propagation mechanisms based on different obstruction types. The difference in received signal strength indicates that the choice of propagation modeling method is critical. The impact is further analyzed by performing packet-level simulations regarding several network-level performance metrics. In the presence of protocol stack compliant with vehicular communication standard and realistic traffic conditions, the simulation results reveal that significant difference

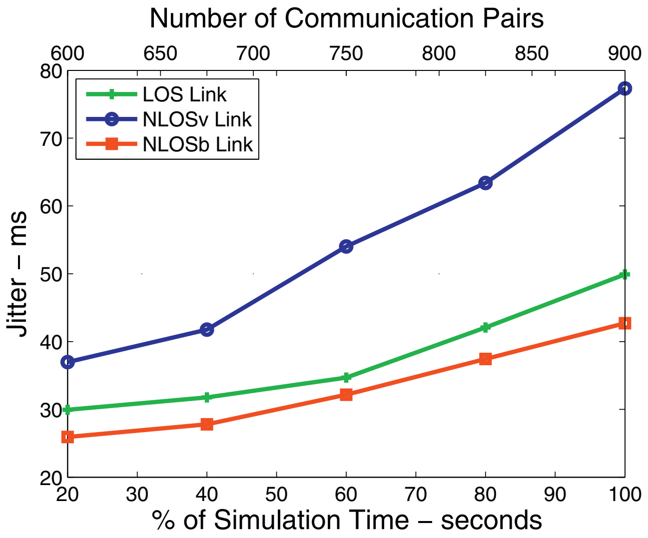

Fig. 13. Performance in terms of jitter - ms vs. % of simulation time.

arises which mainly originated from due to the fact that three different channel models are used. It is, therefore, clear that the realism of emulating realistic environment, implementation details of propagation modeling technique and the choice of simulation parameters are important as they considerably change the perceived V2V network performance in terms of PLR, throughput, latency, and jitter.

This paper aims to provide a new simulation framework and conducts comparison among different propagation models and their impact on packet-level V2V network performance. However, to improve the reliability of the obtained results more attention is required to validate accuracy through the empirical dataset. Moreover, for highlighting the simulation speed and other statistics, an online interface must be implemented to collect the real calculation time and complexity cost of the proposed and other simulators. It is also worth noting that the moving decision of V2V-enabled vehicles heavily depends on the received vehicular information, e.g. periodical CAM and event-driven DENM, resulting in the real-timely varying mobility trace. This unique characteristic requires network simulator (e.g. ns3 and OMNET++) and mobility generator (e.g. SUMO) bidirectional linked, for example, Veins. The proposed framework cannot support the simulation of V2V-enabled applications, e.g. cooperative trajectory planning, V2V-based driving control, etc.

6. Conclusion and future work

In this paper, a two-stage simulation framework is proposed for large-scale simulations and performance evaluation of V2V ad hoc networks. The framework utilized two layers of simulators and associated toolchain to construct realistic environment surrounding the vehicles. For this purpose, metropolitan-wide building geometry data was procured, and vehicle mobility traces were generated to create realistic simulation scenarios over which geometry-based vehicular channel model (GEMV2) was applied. The GEMV2 output regarding propagation path loss among all potential communicating TX-RX pairs is then fed into ns-3 discrete-event network simulator to assess its impact on network-level performance evaluations. A comparative study of standard propagation models implemented in ns-3 shows −2 to −6 dBm difference in received signal power between the LOS and NLOS type links which signifies the need of incorporating the impact building and vehicles obstructions into the packet-level simulations. Furthermore, the impact of realistic propagation model on network-level performance evaluation was also studied regarding packet loss rate (PLR), throughput, latency, and jitter. There are two ways to extend further on the proposed framework. Firstly is to develop an online interface between the external propagation model, mobility generator, and network simulator. The online approach would be fast and capable of providing real-time performance evaluations to support simulation of V2V-enabled applications, e.g., cooperative trajectory planning, driving control, etc. However, the main challenge would remain to achieve a good accuracy-performance mix. Secondly, to study the impact of joint propagation model and network simulation on the performance of control protocols such as routing, scheduling, MAC and topology control in vehicular ad hoc networks.

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