An Integrated Architecture for Simulation and Modeling of Small- and Medium-Sized Transportation and Communication Networks

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Abstract. The emergence of Vehicular Ad-hoc Networks (VANETs) in the past decade has added a level of complexity to the modelling of Intelligent Transportation System (ITS) applications. In this paper, the Vehicular Network Integrated Simulator (VNetIntSim) is introduced as a new transportation network and VANET simulation tool by integrating transportation and VANET modelling. Specifically, it integrates the OPNET software, a communication network simulator, and the INTEGRATION software, a microscopic traffic simulation software. The INTEGRATION software simulates the movement of travellers and vehicles, while the OPNET software models the data exchange through the communication system. Information is exchanged between the two simulators as needed. The paper describes the implementation and the operation details of the VNetIntSim as well as the features it supports such as multiclass support and vehicle reuse. Subsequently, VNetIntSim is used to quantify the impact of mobility parameters (vehicular traffic stream speed and density) on the communication system performance considering Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) applications. Specifically, the routing performance (packet drops and route discovery time), IP processing delay in case of a file transfer protocol (FTP) application, and jitter in case of a Voice over Internet Protocol (VoIP) application and evaluated.

Keywords: Vanet · Intelligent Transportation Systems · Transportation System Modelling · Simulation

1 Introduction

Vehicular Ad Hoc Networks (VANETs) and Intelligent Transportation Systems (ITSs) have a wide spectrum of applications, algorithms and protocols that are important for the public, commercial, environmental and scientific communities. From the communication

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perspective, these applications range from on-road-content-sharing Li, et al. [1], entertainment-based and location-based services [2]. From the transportation perspective, these applications include safety applications [3], cooperative driving and warning applications [4], traffic control and management [5], fuel consumption and carbon emission minimization applications [6], speed harmonization [7], road traffic congestion detection and management [8], and taxi/transit services [9]. This wide application spectrum demonstrates the importance of these systems.

On the other hand, evaluating these systems is challenging, not only because of the cost needed to implement these systems because of the need for a large number of vehicles equipped with communication devices, the required communication infrastructure and signal controllers, but also for the need for roads to run the required experiments. A third reason is that some applications/algorithms work in special conditions of either weather and/or traffic congestion, which are not easily provided. Fourthly, and most importantly, the failures in some of these applications may result in loss of lives of the participants.

Thus, currently, the best approach to study these systems is to use simulation tools. However, simulating ITS and VANET systems is challenging. The reason is that these systems cover two fields, namely the transportation field and the communication field. The transportation field includes the modeling of vehicle mobility applications including traffic routing, car-following, lane-changing, vehicle dynamics, driver behavior modeling, and traffic signal control modeling, in both macroscopic and microscopic modeling scales. The other main field is the data and communication network modeling that includes data packet flow, vehicle-to-vehicle (V2 V) communication as well as vehicle-to-infrastructure (V2I) communication, wireless media access, data transportation, data security and other components. These two fields are not distinct or isolated, but instead are interdependent and influence one another. For example vehicle mobility, speeds and density affect the communication links between vehicles [3] as well as the data routes, and hence the communication quality (i.e. reliability, throughput and delay) [10]. Another example is the attempt in [11] to model the multi-hop V2 V connectivity in urban vehicular networks using archived Global Positioning System (GPS) traces that revealed many interesting characteristics of network partitioning, end-to-end delay and reachability of time-critical V2 V messages. In the opposite direction, the number of packet losses between vehicles and the delivery delay will affect the accuracy of the data collected, and hence the correctness of the decisions made by the ITS's systems. Taking in consideration the complexity of each system (transportation and communication) in addition to the high and complex interdependency level between them, we can see how challenging the modeling and simulation of VANET and ITS.

Most of the previous efforts in simulating VANET and ITS platform are based on using fixed mobility trajectories that are fed to the communication network simulator. These trajectories may be generated off-line using a traffic simulator platform or extracted from empirical data sets. This simulation paradigm is useful for single directional influence (i.e. studying the effect of mobility on the network and data communication) such as data dissemination in a VANET. However, this approach cannot be used in case the opposite direction of interdependence is important (i.e. the effect of the communication system on the transportation system). Such as vehicle speed control in the vicinity of traffic signals,

where vehicles and the signal controllers exchange information to compute and optimal vehicle trajectory. These interactions have to be run in real-time to accurately model the various component interactions.

In this paper, we introduce a new framework for modeling and simulating an integrated VANET and ITS platform. This new framework has the capability of simulating the full VANET/ITS system with full interdependence between the communication and transportation systems, and hence allows for the analysis of VANET and/or ITS applications and algorithms with any level of interaction or interdependence between them. This framework integrates two simulators, namely; the INTEGRATION [12] as microscopic traffic simulator and the OPNET modeler [13] as the data and communication simulator by establishing a two-way communication channel between the models. Through this communication channel, the two simulators can interact to fully model any VANET/ITS application. Subsequently, the developed framework is used to study the effect of different traffic characteristics (traffic stream speed and density) on V2 V and V2I communication performance.

The paper is organized as follows. Section 2 provides a brief description of related work. Subsequently, the VNetIntSim operation and how the two simulators interact is described in Sect. 3. The architecture of the VNetIntSim and the implementation of the proposed framework is presented in Sect. 4. A simulation case study is presented and discussed in Sect. 5, in which the VNetIntSim is used to study the effect of various traffic mobility measures on the communication performance. Finally, conclusions of the study and future research directions are presented in Sect. 6.

2 Literature Review

The necessity of integrating a full-fledged traffic simulator with a wireless network simulator to model the cooperative ITS systems built on V2X communication platform has been perceived since the past decade. A number of attempts have been made within recent years to develop an integrated traffic simulation platform that allows the vehicles' mobility conditions dynamically adapt to the wirelessly received messages. Two different approaches have been considered by the researchers to facilitate this interoperability.

One common approach was to embed the well-known vehicular mobility models into the established network simulators. These features are sometimes combined with the original simulator as separate functional modules or APIs. For example, Choffnes et al. [14] integrated the Street Random Waypoint (STRAW) model into the Java-built scalable communication network simulator SWANS, which allowed parsing of real street map data and modeling of complex intersection management strategies. A collection of application-aware SWANS modules, named as ASH, were developed to incorporate the car-following and lane-changing models providing a platform for evaluating inter-vehicle Geo-cast protocols for ITS applications [14, 15]. Following a similar approach, the communication network simulator NCTUns extended its features to include road network construction and microscopic mobility models [16]. More recently, NS-3 has been engineered to incorporate real-time interaction between a wireless communications module and vehicular mobility models using a fast feedback loop.

Another different approach is to integrate two standalone simulators - a traffic simulator coupled with a wireless network simulator. The choice of traffic simulators considered by the community for coupling in this manner included CORSIM, VISSIM, SUMO whereas network simulators ranged from NS-2, NS-3, QUALNET, and OMNET ++. Table 1 summarizes some of these integration attempts:

Table 1. Integrated simulators summary.

Traffic sim.	Network sim.	Integrated simulator
VISSIM	NS-2	MSIE [17]
SUMO	NS-2	TraNS [18]
SUMO	OMNET ++	VEINS [19]
SUMO	NS-3	OVNIS [20]
SUMO	NS-3	iTETRIS [21]

CORSIM is a commercial traffic simulator that does not provide dynamic routing capabilities, while VISSIM does provide some dynamic routing capabilities these are limited compared to the INTEGRATION software, which provides a total of ten different routing strategies ranging from feedback to predictive dynamic routing. Consequently, both CORSIM and VISSIM do not provide sufficient routing algorithms for testing in a connected vehicle environment. The first attempt of integrating two independent open source traffic and wireless simulators was TraNS (Traffic and Network Simulation Environment) [18], which combined SUMO and NS-2. Later, VEINS [19] also adopted the open source approach of TraNS by combining the network simulator OMNET ++ with SUMO. VEINS allowed for the interaction between the two simulators by implementing an interface module inside OMNET ++ that sends traffic mobility updating commands to SUMO. For example, VEINS could impose a given driving behavior to a particular vehicle upon receiving wireless messages from another vehicle. Most recently, the Online Vehicular Network Integrated Simulation (OVNIS) [20] platform was developed, that coupled SUMO and NS-3 together and included an NS-3 module for incorporating user-defined cooperative ITS applications. OVNIS extends NS-3 as a ‘‘traffic aware network manager’’ to control the relative interactions between the connected blocks during the simulation process. Last but not the least, iTETRIS [21] moves one step beyond the state-of-the-art solutions and overcomes one limitation that is present in Trans, VEINS and OVNIS by providing a generic central control system named iCS to connect an open-source traffic simulator with a network simulator, without having to modify the internal modules of the interconnected simulation platforms.

VNetIntSim uses the concept of separation between the internal simulators modules and the new modules that were added to support the model integration. This feature is actually inherited from the two simulators we selected for the VNetIntSim. INTEGRATION is fully built in modular fashion with a master module that manages and controls of all the modules. The interaction between the modules is modeled using interfaces between the modules. Consequently, updating any modules will not affect the others as

long as this interface does not change. OPNET is built in a hierarchical modular fashion at all its levels (network, nodes, links and processes). The network consists of a set of nodes and links. Each node consists of a set of process modules. The process modules interact through interrupts and the associated Interface Control Information (ICI). The modules added to the simulators in this research effort maintain the same concept, so that updating the simulators does not affect the integration between them.

OPNET and INTEGRATION have their unique features compared to the other simulators. Compared to NS-2 and NS-3, OPNET has these features; (1) a well-engineered user interface that allows for easy building and managing of different simulation scenarios. (2) the OPNET modeler provides its powerful debugging capabilities. (3) OPNET supports a visualization tool that allows for tracking data packets within the nodes. OMNET ++ is a simulation framework that does not have modules. However, there are many open source frameworks based on OMNET ++ that implement different modules such as VEINS. In VEINS, the update interval is 1 s which is a long interval from the communication perspective. For example if the speed is the vehicle is 60 km/h (37.28 miles/h) which is a common speed in cities, this update interval corresponds to 16.6 m which is a long step that can affect the communication between vehicles.

From the traffic perspective, INTGRATION supports many features, such as dynamic vehicle routing and dynamic eco-routing [22], eco-drive systems, eco-cruise control systems, vehicle dynamics and other features that are not supported in other traffic simulation software, including SUMO. The INTEGRATION model has been developed over three decades and has been extensively tested and validated against empirical data and traffic flow theory. Furthermore, the INTEGRATION software is the only software that models vehicle dynamics, estimates mobility, energy, environmental and safety measures of effectiveness. The model also includes various connected vehicle applications including cooperative adaptive cruise control systems, dynamic vehicle routing, speed harmonization, and eco-cooperative cruise control systems.

3 VNetIntSim Operation

This section introduces the operation of the VNetIntSim platform which integrates two simulators; namely OPNET and INTEGRATION. First, a brief introduction about INTEGRATION and OPNET is presented. Then, the VNetIntSim operation is described.

3.1 Integration Software

The INTEGRATION software is agent-based microscopic traffic assignment and simulation software [12]. INTEGRATION is capable of simulating large scale networks up to 10000 road links and 500,000 vehicle departures with time granularity of 0.1 s. This granularity allows detailed analyses of acceleration, deceleration, lane-changing movements, car following behavior, and shock wave propagations. It also permits considerable flexibility in representing spatial and temporal variations in traffic conditions. These are very important characteristics needed when studying the communication between these vehicles.

The model computes a number of measures of performance including vehicle delay, stops, fuel consumption, hydrocarbon, carbon monoxide, carbon dioxide, and nitrous oxides emissions, and the crash risk for 14 crash types [12].

3.2 OPNET Modeler

The OPNET modeler is a powerful simulation tool for specification, simulation and analysis of data and communication networks [13]. OPNET combines the finite state machines and analytical model. The modeling in OPNET uses Hierarchical Modeling, which has a set of editors (Network, Node and Process editors), all of which support model level reuse. The most important OPNET characteristic is that has been tested using implementations for many standard protocols. However, it does not yet support any VANET technology protocols (i.e. IEEE 802.11p DSRC [23], nor Vehicular Routing Protocols). Consequently, for now, the IEEE 802.11 g for wireless LAN simulation is used in the scenarios and AODV [24] for routing purposes.

3.3 Integrating OPNET and INTEGRATION

The main idea behind VNetIntSim is to use the advantages of both the INTEGRATION and OPNET platforms by establishing a two-way communication channel between them. Through this channel the required information is exchanged between the two simulators. The basic and necessary information that should be exchanged periodically is the vehicle locations. The locations of vehicles are calculated in INTEGRATION every deci-second and transmitted to the OPNET modeler, which updates the vehicle locations while they are communicating.

For this version of VNetIntSim, the communication channel between OPNET and INTEGRATION is established by using shared memory as we will explain in the next section. The shared memory supports the required speed and communication reliability between the two simulators.

Initialization and Synchronization. When starting the simulators, and before starting the simulation process, the two simulators should initialize the communication channel using two-way Hello Messages. After establishing the connection, the two simulators synchronize the simulation parameters; simulation duration, network map size, location update interval, maximum number of concurrent running vehicles and number of signals. In this synchronization phase the INTEGRATION serves as a master and OPNET serves as a slave, i.e. values of these parameters in OPNET should match those calculated in INTEGRATION. Mismatching in some of these parameters (such as simulation duration, number of fixed signal controllers and the maximum number of concurrent running vehicles) will result in stopping the simulators. In this case the OPNET software sends a Synchronization Error message to the INTEGRATION software. This behavior guarantees the consistency of the operation and the results collected in both system. Additional parameters allow some tolerances. For example, the map size in OPNET should be greater than or equal to that in INTEGRATION.

After successful synchronization, the simulation process should start by exchanging the simulation start message sent from OPNET. OPNET starts the simulation by initializing its scenario components and initializing the vehicles locations and status. The component initialization take place by sending start simulation interrupt to each module in each component in the scenario (i.e. routers, hosts, vehicles…etc.). The purpose of this interrupt is to read the configuration parameters, initialize the modules state variable and invoke the appropriate processes based on the configuration. After this initialization, OPNET finds all the vehicles nodes in the scenario and map each one to a vehicle ID in the INTEGRATION software. Using this mapping, each vehicle in OPNET corresponds to only one vehicle in the INTEGRATION. However, this behavior can be overridden as described in the next section. Then, OPNET disable all the vehicles, which means that all the vehicles will be inactive. After that, OPNET enables vehicles based on the information it receives from INTEGRATION. The vehicle in OPNET is a mobile node that we customized by adding new attributes such as speed, acceleration and movement direction. Also we added some modules to this this vehicle node to represent some vehicular applications such as eco-routing module that implement the eco-routing [22] algorithm for minimizing fuel consumption. However this is out of the scope of this article.

During the simulation phases, there are many types of messages that can be exchanged between the two simulators. Each message type has its unique Code. Based on the code, the message fields are determined. Table 2 shows the different message codes. The gaps between the code values allow for the addition of new functionalities in the future.

Table 2. Message codes.

Code	Function
01	Initialization; Hello Message
02	Initialization: Connection Refused
10	Parameter Synchronization
11	Synchronization Error
30	Signal Locations Request
31	Signal Locations Updates
40	Start Simulation
50	Locations Information Request
51	Locations Information Updates
60	Speed Information Request
61	Speed Information Updates
99	Termination Notification

Location Updating. During the simulation, the INTEGRATION software computes the new vehicle coordinates and sends them to the OPNET software, which in turn updates the location of each vehicle, as shown in Fig. 1. This cycle is repeated each update_interval, which is typically 0.1 s in duration. The time synchronization during the location updating is achieved in two ways, (1) using two semaphores (intgrat_made_update and opnet_made_update) one for each simulator, (2) at each update time step the INTEGRATION software sends the current simulation time to OPNET. If it does not match the OPNET time, OPNET will take the proper action to resolve this inconsistency. Figure 2 shows the flow chart for the basic location update process. In each location update cycle, the INTEGRATION software computes the updated vehicle locations. Subsequently, it checks whether the last update has been copied (intgrat_made_update = 0). If so, it writes the new update to the shared memory and sets the intgrat_made_update flag to 1.

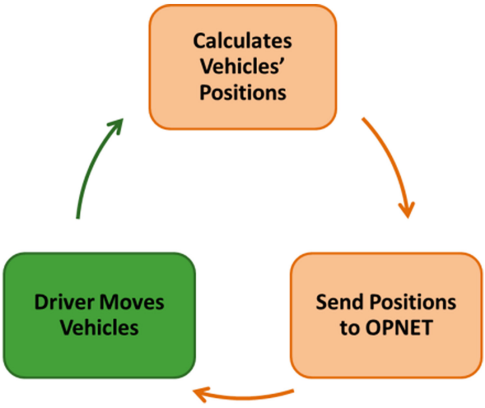


Fig. 1. Location update cycle.

OPNET waits for new updates. When it receives a new update, if the received time equals its current time, the driver process in OPNET will copy the locations, set the intgrat_made_update flag to 0, and then moves the vehicles to the new locations. If the received time is greater than the OPNET current time, it schedules the process to be executed again in the received time. If the received time is less than the current time, OPNET discards this update.

Application Communication. The basic operation described above is only for updating locations, which is the core of the VNetIntSim platform. However, ITS applications need the exchange of other types of information that reflect the communication results to INTEGRATION. This information and how/when it should be exchanged depend mainly on the application itself. Thus, the application specifications should define what other information as well as how and when it should be exchanged.

The applications will use the established communication channel to exchange the required information. VNetIntSim supports simultaneous multi-applications, where each application can use one or more codes to support its functionalities. Figure 3 shows the complete communication cycle when running an application.

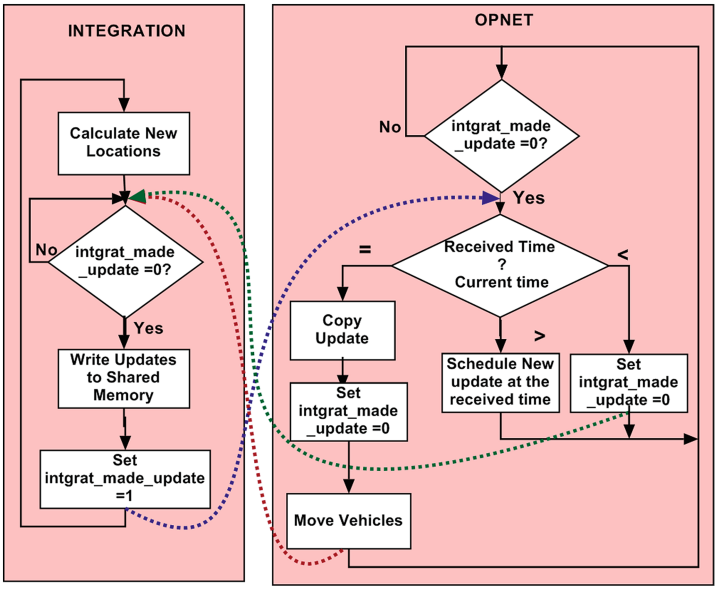


Fig. 2. VNetIntSim basic operation.

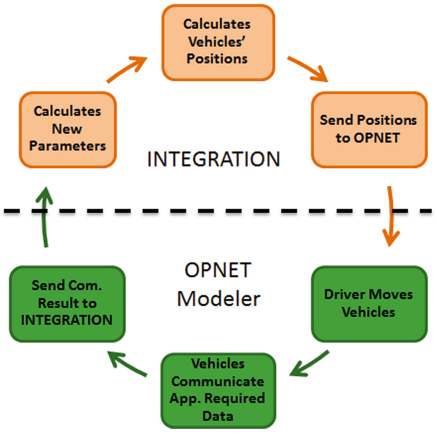


Fig. 3. Complete communication cycle.

For example, in variable speed control systems, INTEGRATION will move the vehicles. Then, in OPNET, the vehicles and signals communicate the speed information. Based on the exchanged information, each vehicle finds its new speed. These new speeds should be sent to the INTEGRATION software, which computes the updated parameters (i.e. acceleration or deceleration) and then computes the updated vehicle locations.

4 Architecture, Implementation and Features of VNetIntSim

This section describes the architecture and the detailed implementation of the modeler and then the supported features in the current version.

4.1 Architecture and Implementation

Figure 4 shows the VNetIntSim architecture and the modules that were added to each simulator (dashed boxes). Within INTEGRATION, the Configuration Reader Module reads the input files and based on the configuration generates an XML topology file for OPNET. This topology file contains the vehicle specifications, signal controller locations as well as the application and profile specifications. This file is used by OPNET to generate its scenarios.

The first issue that arises during implementation entails identifying the inter-process communication mechanism that should be used to connect the simulators. In VNetIntSim two methods were selected, namely; TCP sockets and shared memory. Each of these methods has its advantages over all the other methods. The shared memory approach supports very high speed communication, which is needed when modeling large simulation networks. In addition, the operating system manages the mutual execution of this shared memory so this does not need to be considered.

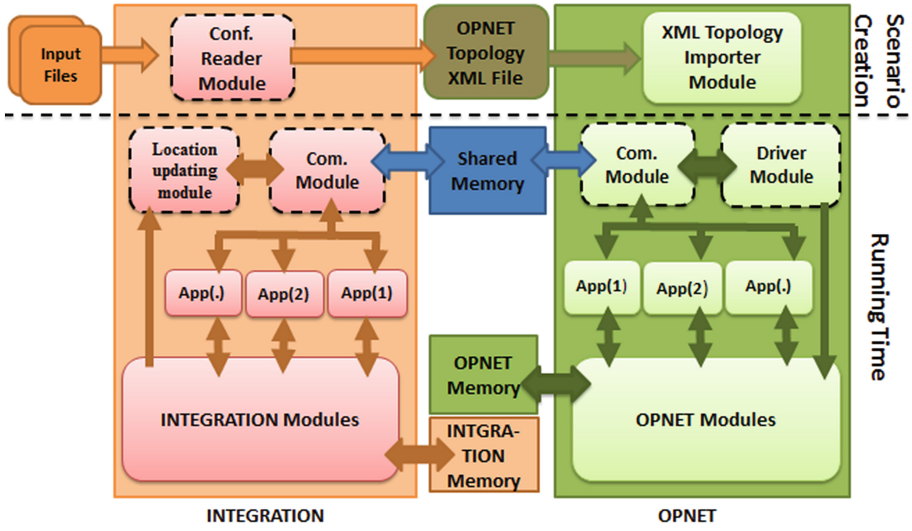


Fig. 4. VNetIntSim architecture.

However, it is limited by the machine capabilities in terms of processing speed and memory size. On the other hand, TCP sockets provide more flexibility so that the INTEGRATION software can be connected to any other simulator on a different OS/machine, in addition to the processing capabilities that will be gained from the other machine. However, TCP sockets introduce the network dynamics, reliability and delay problems

to the simulation process which may result in some communication delay. Consequently, the approach used in this paper is the shared memory approach. In future we plan to implement the TCP socket communication.

In each of the two simulators, a communication module was created. These two modules are responsible for (1) establishing the communication channel by creating a shared memory, (2) exchanging the information between the two simulators through the shared memory, (3) addressing the applications using the message codes shown in Table 2, based on the received code the communication module forwards the data to the appropriate application, and (4) synchronizing the communication against the data damages or losses by using intgrat_made_update and opnet_made_update semaphores, one for each direction.

The location updating module in INTEGRATION is responsible for calculating the location of each vehicle (because INTEGRATION works based on the distance on the link) and sending them along with the other parameters to the driver module in OPNET. The other parameters basically include the number of moving vehicles, the vehicle IDs, and the current time. Moreover, in the location updating message, the location updating module notifies OPNET about the vehicles that completed their trips.

The driver module in OPNET receives the location updating messages (code 51) from the communication module and then (1) checks the received simulation time from the other side, and in case of time mismatch it takes the appropriate decision to overcome this mismatch as shown in Fig. 2, (2) updates the location for the moving vehicles, (3) activates any required new vehicles, and (4) deactivates the vehicles which finished their trips. Using the number of moving vehicles and the activation/deactivation mechanism drastically reduces the processing time in OPNET, especially for large scenarios. That is because OPNET cannot dynamically create or delete communication nodes (vehicles) during the run time, and all the vehicles must be created before running the scenario.

We faced many challenges in the implementation. This section describes the main challenges. The first one is that INTEGRATION is built using FORTRAN which does not support any of the inter-process communication mechanisms. To overcome this problem, we used Mixed-Language Programming by building the communication module using the C language and then compiling its object file into FORTRAN.

The second problem is that OPNET cannot dynamically create or delete communication nodes (vehicles) during the run time. This means that all thevehicles must be created and configured before running the scenario i.e. if we have 50,000 vehicle scenarios, then we have to create 50,000 communication nodes in OPNET at the design time. The problem is this number of communication nodes in OPNET will result in a very slow simulation process. Here we used the Activation/Deactivation mechanism for communication nodes. This mechanism starts by deactivating all the communication nodes and when receiving location updates activating the required nodes. When INTEGRATION sends a notification about a vehicle that completes its trip, the mechanism deactivates that vehicle. This mechanism drastically reduces the number of active vehicles in OPNET and thus enhances the simulation speed.

Moreover, most of the computations are made in the INTEGRATION software to take the advantage of the FORTRAN high computing speed. For example, one option was to send the vehicle speeds and directions and have OPNET compute the vehicle

updated locations, however because FORTRAN is faster than C, all computations were made in the FORTRAN environment.

4.2 Modeler Features

VNetIntSim has some features that were added to achieve different objectives, as described in this section.

Vehicle Reuse. One of the main issues when simulating the vehicular network is scalability, which is mainly affected by the number of vehicles traveling along the network. As mentioned in the previous subsection, OPNET cannot create vehicles in run time. Consequently we have to create all the required vehicles in the design phase. In case of large network scenarios, the large number of vehicles will result in a very long initialization time when starting the simulation and also results in large memory usage. Subsequently, this limits the model scalability. To overcome this limitation VNetIntSim can make reuse of the same vehicle as a communication node to represent multiple moving vehicles, obviously in different time slots. In this way, the required number of vehicles in OPNET can be reduced from the total number of vehicles or trips (which may be thousands of vehicles) to the maximum number of concurrent vehicles which is much smaller than the total number of vehicles or trips. The vehicle reuse feature can significantly increase the scalability by reducing the number of vehicles simulated in OPNET, consequently, decreases the memory requirements and the execution time. This feature can be safely used when we are interested in studying the global system behavior. However, it is not suitable when studying the individual communication behavior of a vehicle or a connection.

Vehicles Multi-class Support. This capability is inherited from INTEGRATION which supports up to five classes of vehicles. Each class can be configured to run in different way and use different algorithms. We extend this feature to OPNET, where the class information is associated with the vehicle and transferred from INTEGRATION to OPNET. So, the user can implement communication protocols or configure them to work differently for different classes of vehicles. For example, in data dissemination in VANET, the user can chose to send the data only to specific vehicle class (i.e. Trucks). Using this feature also, routing protocol can prioritize next hop based on its class (i.e. vehicles of the same class move in similar speeds, thus their relative speeds are very low). Another application of this feature is the penetration ratio of a specified technology where we want to check the effect of the penetration ratio of some new technologies (i.e. cooperative driving).

Customizable Updating Interval. The location updating interval determines how frequently the location information are sent from INTEGRATION to OPNET. The shorter the updating interval, the higher the accuracy of the mobility. However, the shorter the updating interval the more the processing, and thus, the longer the execution time. VNetIntSim, enable the user to change this interval based on the network requirements. Its default is 0.1 s which is also the minimum updating interval. It can be changed

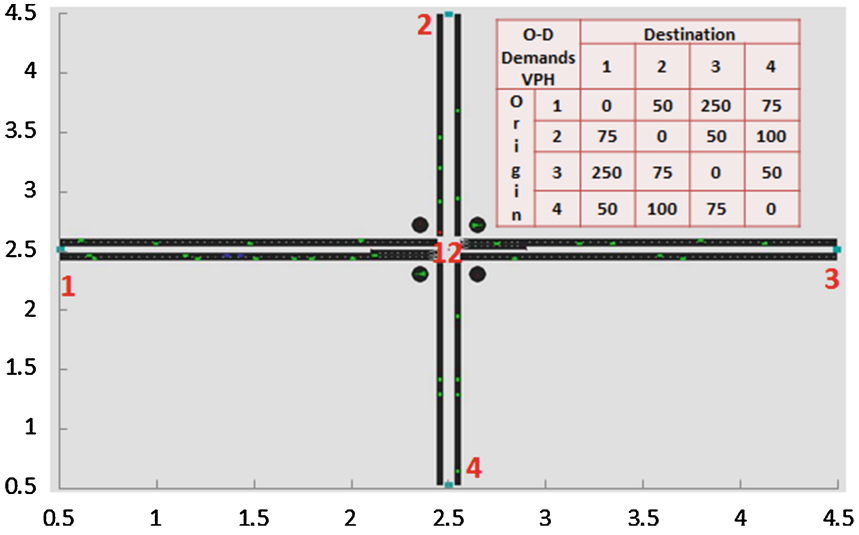
to any value that is multiple of 0.1 s. Also, it is not necessary to be matched in the two sides of the VNetIntSim because the INTEGRATION can overwrite the updating interval setting n OPNET.

5 Case Study

Routing is one of the important protocols that are sensitive to vehicle mobility and density parameters. In this section, the VNetIntSim is used to study the effect of mobility measures on the AODV [24] routing, in case of FTP traffic. In addition, the effect of vehicle density on VIOP jitter is studied. Subsequently the scalability of the VNetIntSim modeling tool is tested because scalability is a critical drawback in existing simulators, including: VEINS and iTETRIS.

5.1 Simulation Setup

In this case study, the road network shown in Fig. 5 is used.



O-D Demands VPH		Destination			
		1	2	3	4
Origin	1	0	50	250	75
	2	75	0	50	100
	3	250	75	0	50
	4	50	100	75	0

Fig. 5. Road network and O-D demands.

The road network consists of an intersection numbered 12, and four zones numbered 1, 2, 3 and 4. Each zone serves as a vehicle origin and destination. Each road link is 2 km in length. The vehicular traffic demand that was considered in the study is presented in Fig. 5. For example, the traffic rate from zone 2 to 1 is 75 Veh/h. The vehicles speeds are determined using two speed parameters, namely; the free-flow speed and the speed-at-capacity [25]. Throughout the paper, the notation Free/Capacity will be used to represent the ratio of free-flow speed to the speed-at-capacity. Two speed scenarios are considered, namely: 40/30 km/h and 80/50 km/h.

For the application we used File Transfer Protocol (FTP), in which we can control the connection time by deciding the file size. Also, in OPNET we can control the traffic rate of the FTP connections. The FTP server is located at the intersection. Starting from 250 s, the moving vehicles attempted to download a 100 Kbyte file from this server. The FTP clients re-established a new connection every 20 s. The FTP server is spatially fixed and modeled as a road side unit (RSU). The IEEE82.11 g was employed at the wireless communication medium with a data rate of 24 Mbps. For routing the AODV was used as the routing protocol for both scenarios.

5.2 Number of Moving Vehicles in the Network

The traffic simulation included three phases; two transient and one steady-state phase. The loading and unloading phases are transient phases, which represent the two shoulders of the peak period, as illustrated in the graphs in Fig. 6. In the loading phase, vehicles enter the road network, while in the unloading phase vehicles exit. Between them there is a steady-state phase in which some vehicles are entering the network, while others are exiting. In the steady-state phase, the change in the number of the vehicles in the network is not significant. While in the loading phase the network loading changes significantly. The length of these phases depends mainly on the speed distribution, vehicle departure rates, and the road map.

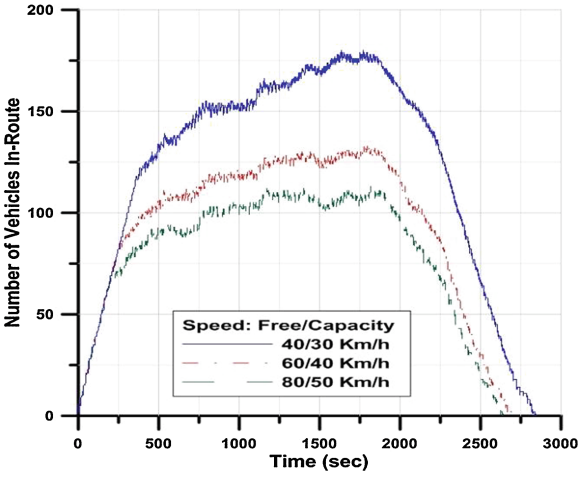


Fig. 6. Number of vehicles in the network.

Figure 6 shows the number of vehicles in the network for different speed parameters (Free/Capacity). The importance of determining these phases is that during the transient phases the communication network may be spatially partitioned without data routes that link these partitions together. While in the steady-state phase vehicles almost cover the entire road network, and most probably there is full connectivity between vehicles. Consequently, the network communication behavior during the transient phases is different from that during the steady-state phase.

By controlling the speed parameters and the departure rate distribution, we can control the network partitions during the simulation time. Using this methodology, we can model the delay tolerant communication networks (DTN) [26] and intermittently connected mobile networks [27].

Thirdly defining these phases gives us estimation for the vehicle density in the network at any instant in time. This density significantly influences the communication performance as will be shown later.

5.3 FTP Connections and AODV

In this section some results obtained from the FTP communication will be presented. As we described in the previous subsection the vehicle density significantly affects the communication performance. Figure 7 shows the cumulative number of packets dropped by AODV across the entire network due to the loss of a route to the destination.

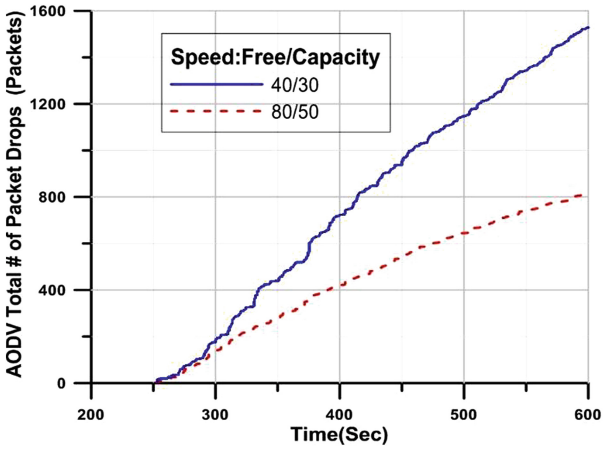


Fig. 7. AODV total # of packet drops.

The AODV packet drop can be caused by two main reasons: (1) the number of vehicles in the network; the larger the number of vehicles the larger the traffic. So any route missing will result in a larger number of drops. (2) The vehicle speeds; the higher the speed the faster the route changes, and so the larger the number of packet drops.

In an attempt to identify which of the two factors is more influential on the routing, Fig. 8 illustrates how the average number of drops vary across the network. It shows that around 300 s, both speeds have a similar average packet drop rate. During this interval the number of vehicles for both scenarios is very similar. While as the difference in vehicle density increases with time, the average number of drops also reflects the changes in traffic density.

The two figures demonstrate that for the two scenarios, despite the fact that the vehicle density is related to the traffic stream speed, the vehicle density has a more significant impact on the performance of the communication system. Consequently,

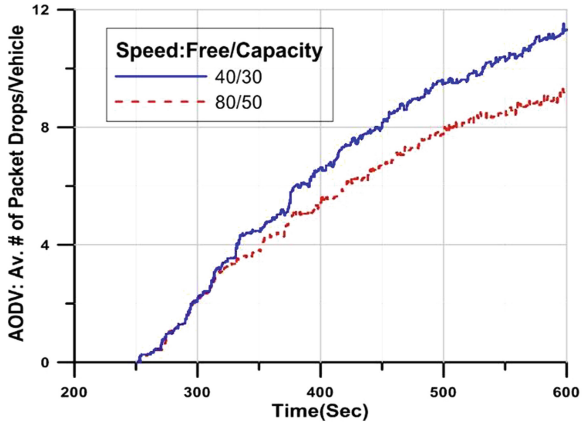


Fig. 8. AODV Av. # of Packet Drops per vehicles.

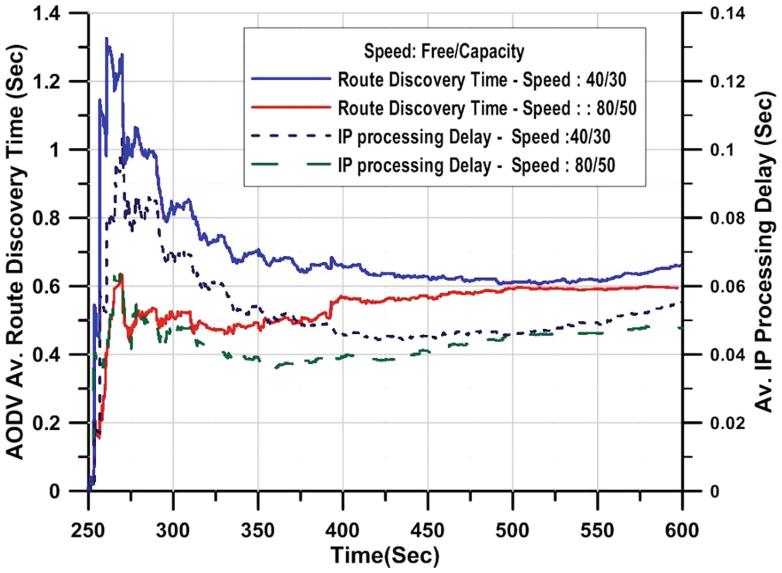


Fig. 9. AODV Av. route discovery time and Av. IP processing delay.

a change in the traffic stream density caused by other factors, such as traffic demand has a more significant impact on the routing than does changes in the traffic stream speed. Another important parameter in routing efficiency is the route discovery time which is shown in Fig. 9. It shows the correlation between the route discovery time and the IP processing and queuing delay on the vehicles. After 250 s each vehicle attempts to establish an FTP session with the server resulting in a flood of AODV route request packets. This flood increases the amount of IP packets being sent and processed at the IP layer in each vehicle, and thus increases the IP processing (queuing + processing) delay, which is reflected on the route discovery time.

From Fig. 9, it is clear that the long route discovery time when initiating the communication is mainly due to the IP queuing and processing delay in the higher density scenario. Subsequently, the TCP congestion control logic paces the packets based on the acknowledgements it receives. This pacing results in lower queuing and processing delay. Consequently, both the processing delay and route discovery time gradually decrease.

Figure 10 illustrates the effect of the speed and density on the number of active TCP connections on the FTP server. The figure demonstrates that when initiating the FTP connections there are 69 and 61 TCP connections for the 40/30 and 80/50 speeds, respectively. These numbers are proportional to the number of concurrent vehicles in the network for each scenario. The results also demonstrate that some of these connections were completed before the start of the second cycle (at 270 s). Similarly, the second cycle increases the number of connections. The results demonstrate that later the number of connections for the 80/50 scenario decreases significantly because some vehicles exit the network and so their connections are timed-out and dropped, while in the 40/30 scenario vehicles are still traveling on the network.

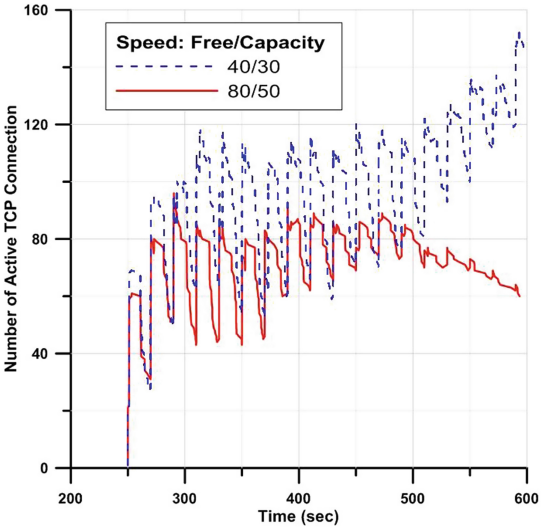


Fig. 10. Number of TCP connections of the FTP server.

The above results and analysis for the simple scenarios we used are realistic and consistent with the protocol behavior.

5.4 VOIP Jitter

This subsection focuses on the VOIP traffic and how the mobility parameters affect the performance of the voice application. The start time of the voice sessions is normally distributed with a mean and variance of 350 and 50 s, respectively. The session duration is 250 s. Figure 11 shows the average jitter across the entire network. Figure 11 shows that the jitter for the low speed is very high compared to the high speed.

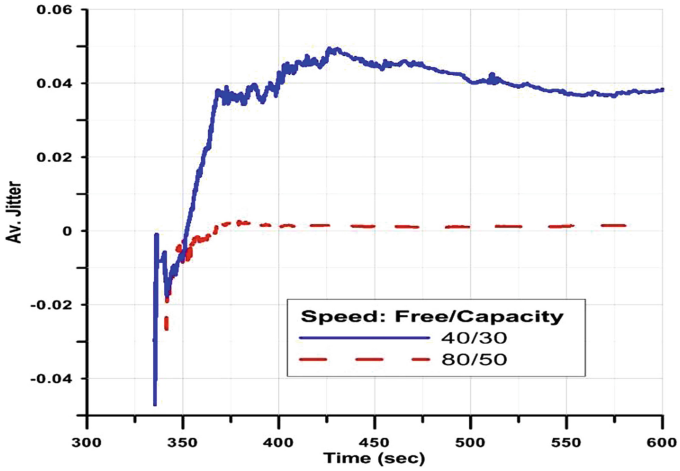


Fig. 11. Average VOIP jitter.

The results show that when the voice session starts around 350 s, the jitter in both scenarios is similar. Furthermore, as the number of sessions increases, the jitter increases gradually. For the 80/50 speeds the jitter increase seizes because the network enters a steady-state (the change in number of vehicles is not significant). While for the 40/30 scenario, the jitter continues to increase to unacceptable values because of the increase in the number of vehicles.

Figure 11 shows the importance of the vehicle density in the network and how influential it is on the VOIP connections. It shows that as the number of vehicles in the network reaches a specific value, the overall jitter across the network becomes unacceptable. Although the routes in lower speed are relatively more stable, the jitter is higher due to the vehicle density.

5.5 System Scalability

The scalability is the most critical drawback of existing platforms including the proposed platform. The two main scalability parameters are the memory usage and the execution time. The results show that the number of nodes and the data traffic rate per vehicle are key factors behind the scalability issue. Specifically, results show that, the memory usage grows exponentially with the number of vehicles in the network, as shown in Fig. 12. The result shows also that the execution time is mainly dependent on the average traffic rate per vehicle. As shown in Fig. 13.

Figure 12, shows that the memory utilization increases exponentially with the number of vehicles in the network. This possesses a scalability limitation to the modeler. This scalability problem is reasoned to the detailed implementation of the network simulation models. However, this detailed implementation is necessary when studying the behavior of individual vehicle, individual connection between two vehicles or the detailed behavior of a specific protocol.

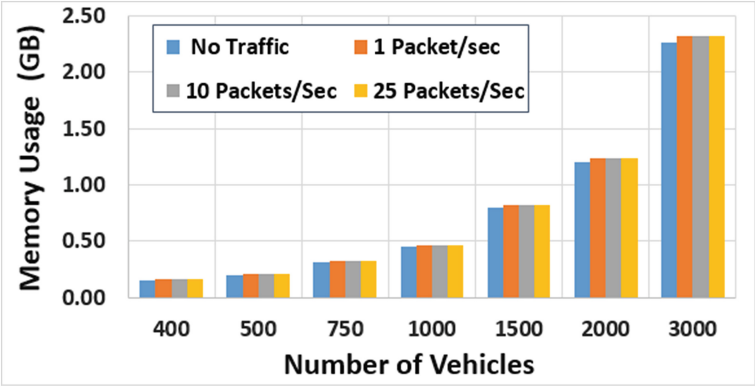


Fig. 12. The memory usage (GB) vs. the number of nodes for different traffic rates.

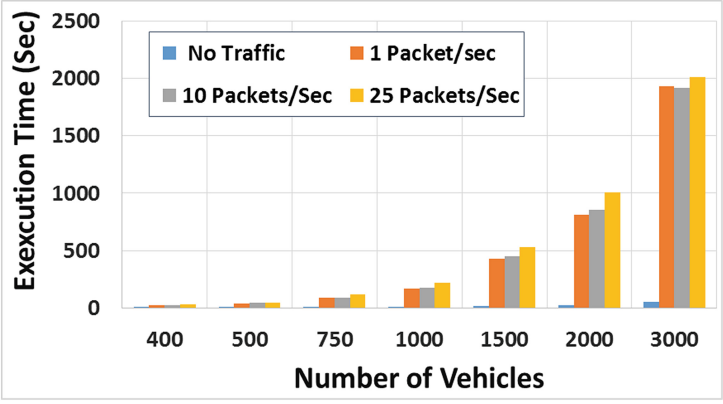


Fig. 13. The execution time (Sec) vs. the number of nodes and the traffic rate per vehicle.

On the other hand, in case of focusing on global analysis, where the individual detailed behavior is not important, we can reduce the number of vehicles in the network by reuse the vehicles as described earlier. In this case, the total number of vehicles we need in the simulation network become the maximum concurrent number of vehicles.

Figure 12 also shows that for a specific number of nodes, increasing the traffic rate has no significant effects on the memory usage. We argue that behavior to the ability of OPNET to destroy the packets after they arrived it destination application and so free its memory.

Figure 13 shows that the execution time is exponentially increasing with number of vehicles, and increases also with the average traffic rate per vehicle. We can notice the abrupt increase in the execution time when increasing the traffic rate to only one packet. This large increment is reasoned to the broadcast nature of the AODV protocol that used in this scenario. Where any application packet to a new source triggers the AODV to broadcast a route request message to all its neighbors. Each of these neighbors receives

and processes this message and might rebroadcast it. Which results in a wave of broadcast that spans overall the network. Consequently, increasing the execution time.

We also notice that increasing the traffic rate per vehicle from 1 packet to 10 packets per vehicle does not result in such increase in the execution time. That is because the first packet only initiates the broadcast waves in the network. And any other packets to the same destination needs only the route maintenance.

These results are obtained on a machine of Intel Core-i7 Quad-core processor, 4 GB of memory, and running windows 7 Ultimate.

6 Conclusions and Future Work

VNetIntSim, is presented as an integrated platform for simulating and modeling vehicular networks. VNetIntSim integrates a transportation simulator (INTEGRATION) with a data communication network simulator (OPNET modeler). Results obtained from the simulation scenarios are realistic and consistent with protocol behavior. VNetIntSim has the capability to fully simulate the two-way interdependency between the transportation and communication systems, which is necessary for many applications. In addition it provides the power of both simulators to study global network parameters as well as very detailed parameters for each system at a microscopic level considering a 0.1 s granularity.

Subsequently, the VNetIntSim modeler is used to quantify the effect of mobility parameters on the communication performance. The results show that the effect of vehicle density is of higher significance than that of the speed. More specifically, the higher speed results in a lower drop ratio and lower jitter due to the lower traffic stream density.

Proposed future work entails enhancing the model scalability by creating a vehicle module with the necessary sub-modules. Further work entails implementing the DSRC module in the OPNET modeler. The most important future work is to implement some ITS applications such as speed harmonization, eco-driving, congestion avoidance and vehicle routing. A study of the effect of quality of services and different routing mechanisms on the performance of the transportation system and services offered for both users and vehicles is also warranted.

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