VNetIntSim: An Integrated Simulation Platform to Model Transportation and Communication Networks

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Abstract: The paper introduces a Vehicular Network Integrated Simulator (VNetIntSim) that integrates transportation modeling with Vehicular Ad Hoc Network (VANET) modeling. Specifically, VNetIntSim integrates the OPNET software, a communication network simulator, and the INTEGRATION software, a microscopic traffic simulation software. The INTEGRATION software simulates the movement of travelers and vehicles, while the OPNET software models the data exchange through the communication system. Information is exchanged between the two simulators as needed. As a proof of concept, the VNetIntSim is used to quantify the impact of mobility parameters (traffic stream speed and density) on the communication system performance, and more specifically on the data routing (packet drops and route discovery time).

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 perspective, these applications range from on-road-content-sharing Li, Yang et al. (2011), entertainment-based and location-based services (Bruner 2007). From the transportation perspective, these applications include safety applications (Hafeez, Lian et al. 2010), cooperative driving and warning applications (Van den Broek, Ploeg et al. 2011), traffic control and management (Baskar, De Schutter et al. 2007), fuel consumption and carbon emission minimization applications (Xiao, Zhao et al. 2012), speed harmonization (Talebpour, Mahmassani et al. 2013), road traffic congestion detection and management (Roy, Sen et al. 2011), and taxi/transit services (Mohammad A. Hoque 2014). 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 solution for studying 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 (V2V) 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 (Hafeez, Lian et al. 2010) as well as the data routes, and hence the communication quality (i.e. reliability, throughput and delay) (Alam, Sher et al. 2008). Another example is the attempt in (Hoque, Hong et al. 2014) to model the multi-hop V2V 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 V2V 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 (Rakha Accessed Aug. 2014) as microscopic traffic simulator and the OPNET modeler (Technology Accessed Aug. 2014) 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 V2V and V2I communication performance.

The paper is organized as follows. Section II provides a brief description of related work. Subsequently, the VNetIntSim operation and how the two simulators interact is described in section III. The architecture of the VNetIntSim and the implementation of the proposed framework is presented in section IV. A simulation case study is presented and discussed in section V, 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 Section VI.

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 inter-operability.

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.* (Choffnes and Bustamante 2005) 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 (Choffnes and Bustamante 2005; Ibrahim and Weigle 2008). Following a similar approach, the communication network simulator NCTUns extended its features to include road network construction and microscopic mobility models (Wang and Chou 2009). 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 (M. Caliskan)
SUMO	NS-2	TraNS (Piorkowski, Raya et al. 2008)
SUMO	OMNET++	VEINS (Sommer, German et al. 2011)(Sommer, German et al. 2011)(Sommer, German et al. 2011)
SUMO	NS-3	OVNIS (Pigne, x et al. 2010)
SUMO	NS-3	iTETRIS (Rondinone, Maneros et al. 2013)

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) (Piorkowski, Raya et al. 2008), which combined SUMO and NS-2. Later, VEINS (Sommer, German et al. 2011) 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) (Pigne, x et al. 2010) 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 (Rondinone, Maneros et al. 2013) 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 second which is a long interval from the communication perspective. For example if the speed is the vehicle is 60 km/h (37.28 mi/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, 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 (Rakha and Ahn 2004; Chamberlayne, Rakha et al. 2012; Van Aerde and Rakha 2013; Van Aerde and Rakha 2013; Rakha Accessed Aug. 2014). INTEGRATION is capable of simulating large scale networks up to 10000 road links and 500,000 vehicle departures with time granularity of 0.1 second. 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 (Rakha Accessed Aug. 2014).

3.2 OPNET Modeler

The OPNET modeler is a powerful simulation tool for specification, simulation and analysis of data and communication networks (Technology Accessed Aug. 2014). 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 (Jiang, Taliwal et al. 2006), nor Vehicular Routing Protocols). Consequently, for now, the IEEE 802.11g for wireless LAN simulation is used in the scenarios and AODV (Perkins, Belding-Royer et al. 2003) for routing purposes.

3.3 Integrating OPNET & 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.

3.3.1 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. If the map size does not satisfy this condition, OPNET will send a Synchronization Error message to INTEGRATION, and the simulation will stop.

After successful synchronization, the simulation process should start by exchanging the simulation start message sent from OPNET.

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 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

3.3.2 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 Figure 1. This cycle is repeated each update_interval, which is typically 0.1 seconds 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.

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.

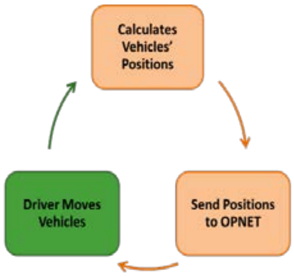


Figure 1: Location update cycle.

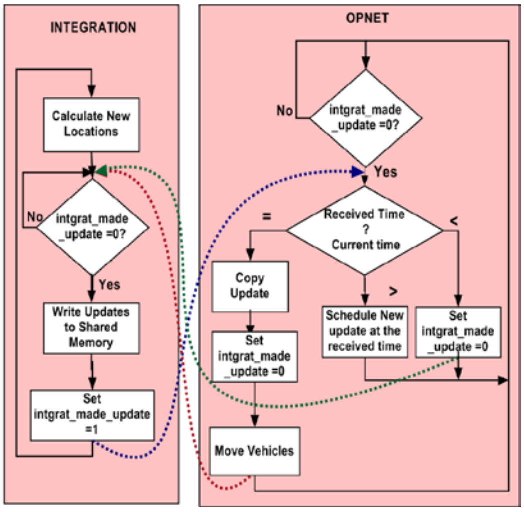


Figure 2: VNetIntSim basic operation.

3.3.3 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.

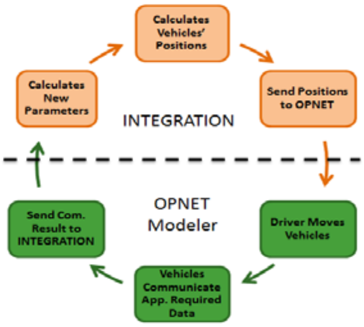


Figure 3: Complete communication cycle.

For example, in variable speed control systems, the 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 AND IMPLEMENTATION OF VNETINTSIM

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.

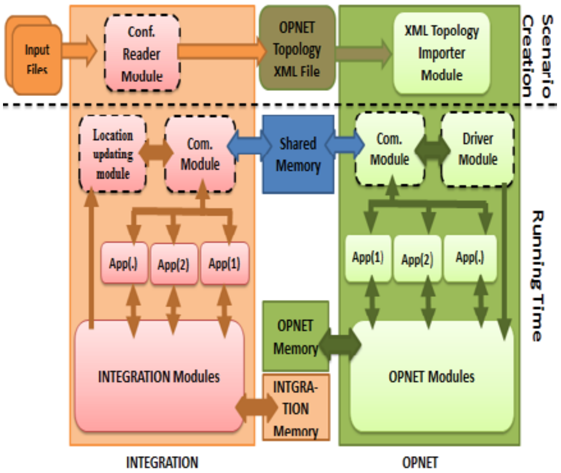


Figure 4: VNetIntSim architecture.

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 Figure 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.

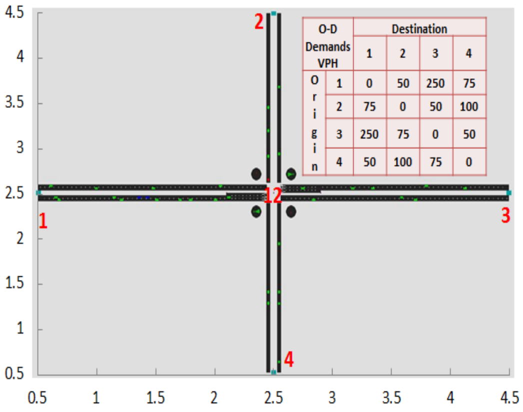
Moreover, most of the computations are made in the INTEGRATION software to take the advantage of the FORTRAN high computing speed. For example, one option was to send the vehicle speeds and directions and have OPNET compute the vehicle updated locations, however because FORTRAN is faster than C, all computations were made in the FORTRAN environment.

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 (Perkins, Belding-Royer et al. 2003) routing, in case of FTP traffic. 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 Figure 5 is used. 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 location. Each road link is 2 kilometers in length. The vehicular traffic demand that was considered in the study is presented in Figure 5. For example, the demand from zone 2 to 1 is 75 veh/h. The road speed is determined using two speed parameters, namely; the free-flow speed and the speed-at-capacity (Van Aerde and Rakha 1995). 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.



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

Figure 5: Road network and O-D demands.

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 seconds, the moving vehicles attempted to download a 100 Kbyte file from this server. The FTP clients re-established a new connection every 20 seconds. The FTP server was spatially fixed and modeled as a road side unit (RSU). The IEEE82.11g 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 Concurrent Vehicles

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 Figure 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. 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) (Fall 2003) and intermittently connected mobile networks (Lindgren, Doria et al. 2003).

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.

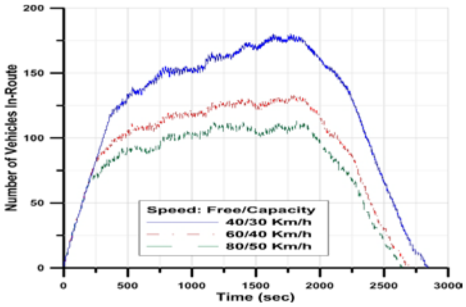


Figure 6: Number of vehicles in the network.

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.

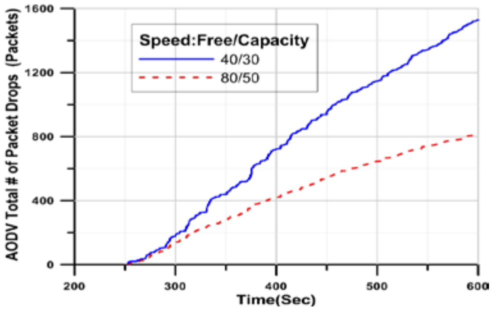


Figure 7: AODV total # of packet drops.

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, Figure 8 illustrates how the average number of drops vary across the network. It shows that around 300 seconds, 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.

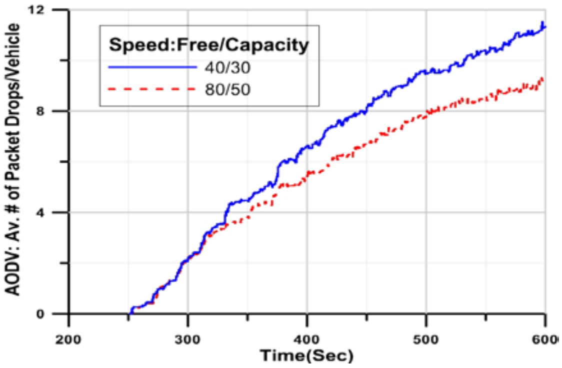


Figure 8: AODV Av. # of Packet Drops per vehicles.

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, 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 Figure 9. It shows the correlation between the route discovery time and the IP processing and queuing delay on the vehicles. After 250 seconds 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 Figure 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 seconds). 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.

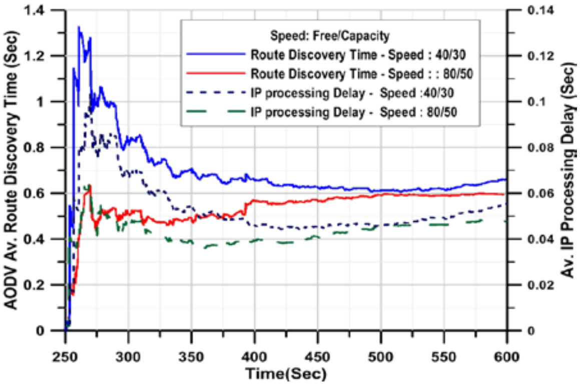


Figure 9: AODV Av. route discovery time and Av. IP processing delay.

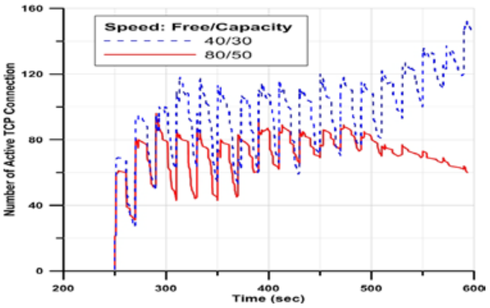


Figure 10: Number of TCP connections of the FTP server.

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

5.4 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 preliminary study results show that the number of nodes and the data traffic rate 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 Figure 11. The result shows also that the execution time is mainly dependent on the traffic on the network

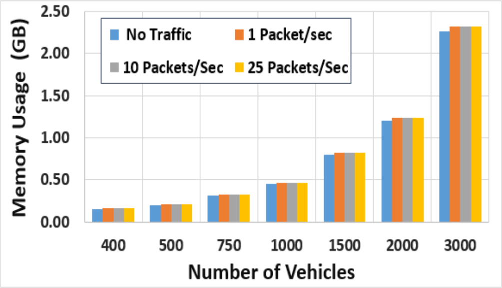


Figure 11: The memory usage (GB) vs. the number of nodes for different traffic rates.

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 vehicles. In case of focusing on global analysis, where the individual vehicle's behavior is not important, we can reduce the number of vehicles in the network by reuse the same vehicle. Thus the maximum number of vehicles we need in the simulation network become the maximum concurrent number of vehicles. To achieve both advantages we enabled the vehicle reuse option in the VNetIntSim.

6. CONCLUSIONS AND FUTER WORK

In this paper we presented the VNetIntSim, an integrated platform for simulating transportation and VANET networks. VNetIntSim integrates a transportation simulator (INTEGRATION) with a data communication network simulator (OPNET modeler). Results obtained from the simple scenarios are realistic and consistent with protocol behavior. The most important advantage of VNetIntSim is its 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 in each system at a microscopic level considering a 0.1 second granularity. The most important challenge is the simulation speed which is slow due to the number of vehicles in the network.

In the future we will try to enhance the simulation speed by creating a vehicle module with the necessary sub-modules. Also we plan to implement the DSRC module in the OPNET modeler. The most important future work is to implement some applications for ITS such as speed harmonization, eco-driving, congestion avoidance and vehicles re-routing. We can also study 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.

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REFERENCES

Alam, M., M. Sher and S. A. Husain (2008). VANETs Mobility Model entities and its impact. 4th International Conference on Emerging Technologies, ICET. .

Baskar, L. D., B. De Schutter and H. Hellendoorn (2007). Hierarchical Traffic Control and Management with Intelligent Vehicles. Intelligent Vehicles Symposium.

Bruner, G. C., and A. Kumark (2007). "Attitude toward location-based advertising." Journal of Interactive Advertising **7**(2): 3-15.

Chamberlayne, E. P., H. A. Rakha and D. R. Bish (2012). "Modeling the capacity drop phenomenon at freeway bottlenecks using the INTEGRATION software." Transportation Letters: The International Journal of Transportation Research **4**(4): 227-242.

Choffnes, D. R. and F. E. Bustamante (2005). An integrated mobility and traffic model for vehicular wireless networks. Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks, ACM.

Fall, K. (2003). A delay-tolerant network architecture for challenged internets. Proceedings of the conference on Applications, technologies, architectures, and protocols for computer communications, Karlsruhe, Germany, ACM.

Hafeez, K. A., Z. Lian, L. Zaiyi and B. N. Ma (2010). Impact of Mobility on VANETs' Safety Applications. Global Telecommunications Conference (GLOBECOM 2010).

Hoque, M. A., X. Hong and B. Dixon (2014). "Efficient multi-hop connectivity analysis in urban vehicular networks." Vehicular Communications **1**(2): 78-90.

Ibrahim, K. and M. C. Weigle (2008). ASH: Application-aware SWANS with highway mobility. INFOCOM Workshops

Jiang, D., V. Taliwal, A. Meier, W. Holfelder and R. Herrtwich (2006). "Design of 5.9 GHz DSRC-based vehicular safety communication." Wireless Communications, IEEE **13**(5): 36-43.

Li, M., Z. Yang and W. Lou (2011). "CodeOn: Cooperative Popular Content Distribution for Vehicular Networks using Symbol Level Network Coding." IEEE J.Sel. A. Commun. **29**(1): 223-235.

Lindgren, A., A. Doria and O. Schel (2003). "Probabilistic routing in intermittently connected networks." SIGMOBILE Mob. Comput. Commun. Rev. **7**(3): 19-20.

M. Caliskan, C. L., B. Scheuermann, M.Singhof "Multiple Simulator Interlinking Environment for C2CC in VANETs." http://www.cn.hhu.de/en/our-research/msiecv.html **Accessed Aug. 2014**.

Mohammad A. Hoque, X. H., Brandon Dixon (2014). "Innovative Taxi Hailing System using DSRC Infrastructure." ITS World Congress, Detroit.

Perkins, C., E. Belding-Royer and S. Das (2003). "RFC 3561-ad hoc on-demand distance vector (AODV) routing." Internet RFCs: 1-38.

Pigne, x, Y., G. Danoy and P. Bouvry (2010). A platform for realistic online vehicular network management. IEEE GLOBECOM Workshops (GC Wkshps).

Piorkowski, M., M. Raya, A. L. Lugo, P. Papadimitratos, M. Grossglauser and J.-P. Hubaux (2008). "TraNS: realistic joint traffic and network simulator for VANETs." ACM SIGMOBILE Mobile Computing and Communications Review **12**(1): 31-33.

Rakha, H. (Accessed Aug. 2014). "INTEGRATION Rel. 2.40 for Windows - User's Guide, Volume I: Fundamental Model Features." http://filebox.vt.edu/users/hrakha/Software.htm#Integration **1**.

Rakha, H. and K. Ahn (2004). "Integration modeling framework for estimating mobile source emissions." Journal of Transportation Engineering **130**(2): 183-193.

Rondinone, M., J. Maneros, D. Krajzewicz, R. Bauza, P. Cataldi, F. Hrizi, J. Gozalvez, V. Kumar, M. Röckl and L. Lin (2013). "iTETRIS: a modular simulation platform for the large scale evaluation of cooperative ITS applications." Simulation Modelling Practice and Theory **34**: 99-125.

Roy, S., R. Sen, S. Kulkarni, P. Kulkarni, B. Raman and L. K. Singh (2011). Wireless across road: RF based road traffic congestion detection. Third International Conference on Communication Systems and Networks (COMSNETS).

Sommer, C., R. German and F. Dressler (2011). "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis." Mobile Computing, IEEE Transactions on **10**(1): 3-15.

Talebpour, A., H. Mahmassani and S. Hamdar (2013). "Speed Harmonization." Transportation Research Record: Journal of the Transportation Research Board **2391**(-1): 69-79.

Technology, R. (Accessed Aug. 2014). "http://www.riverbed.com/products/performance-management-control/opnet.html."

Van Aerde, M. and H. Rakha (1995). Multivariate calibration of single regime speed-flow-density relationships. Proceedings of the 6th Vehicle Navigation and Information Systems Conference.

Van Aerde, M. and H. Rakha (2013). INTEGRATION © Release 2.40 for Windows: User's Guide – Volume I: Fundamental Model Features. Blacksburg, M. Van Aerde & Assoc., Ltd.

Van Aerde, M. and H. Rakha (2013). INTEGRATION © Release 2.40 for Windows: User's Guide – Volume II: Advanced Model Features. Blacksburg, M. Van Aerde & Assoc., Ltd.

Van den Broek, T. H. A., J. Ploeg and B. D. Netten (2011). Advisory and autonomous cooperative driving systems. Consumer Electronics (ICCE), 2011 IEEE International Conference on.

Wang, S. Y. and C. L. Chou (2009). "NCTUns tool for wireless vehicular communication network researches." Simulation Modelling Practice and Theory **17**(7): 1211-1226.

Xiao, Y., Q. Zhao, I. Kaku and Y. Xu (2012). "Development of a fuel consumption optimization model for the capacitated vehicle routing problem." Computers & Operations Research **39**(7): 1419-1431.