Evaluation of VANET-based Advanced Intelligent Transportation Systems[*]

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ABSTRACT

This paper aims at enabling accurate and efficient evaluation of emerging vehicular network applications such as Intelligent Transportation Systems (ITS). A distributed simulation platform that integrates transportation simulation and wireless network simulation is proposed and implemented, providing a user level simulation environment to evaluate the feasibility and performance limitations of VANETs in supporting ITS. The proposed simulation platform facilitates the dynamic interaction between the two simulation domains, allowing runtime control of vehicles' behavior in the transportation simulation as they react in real time to information exchange in the simulated communication network. Case studies are conducted within the proposed simulation platform to evaluate the performance of Dynamic Route Planning when deployed in VANETs, using metrics collected at the transportation system level such as travel and delay time. The effectiveness of three representative VANET dynamic adaptation protocols in enhancing the application performance in scenarios with high vehicle density are compared in the case studies. The experiment results show that Dynamic Route Planning can be effectively supported by a VANET system with up to 118% increase on the number of vehicles reaching the destination, 36.2% reduction on travel time and 56.1% reduction on delay time.

Categories and Subject Descriptors

I.6.m [**Computing Methodologies**]: Simulation and Modeling

General Terms

Experimentation, Performance

Keywords

Intelligent Transportation Systems, Vehicular Ad Hoc Networks, Integration, Traffic Simulation, Communication Network Simulation, Performance Evaluation, Dynamic Route Planning

1. INTRODUCTION

Recent surveys show that traffic congestion costs are staggering: total amount delay of 3.7 billion hours, wasted fuel of 2.3 billion gallons and annual costs of $63 billion to the US economy [15]. Intelligent Transportation Systems (ITS) that exploit in-vehicle information technology (e.g. mobile computing and wireless communication) in surface transportation systems are an example of emerging technologies to reduce the impact of traffic congestions. Vehicle-to-vehicle communication systems are an important component of ITS and useful for a wide variety of applications that include incident detection, crash reporting, congestion warning and traveler information dissemination. In-vehicle sensors and communication devices offer the potential for detailed and accurate data collection (e.g. second-to-second position, speed, acceleration and deceleration) and information transfer and allow coverage to extend beyond areas where roadside equipment has been placed.

As emerging vehicle-to-vehicle ad hoc networks (VANETs) extend existing roadside infrastructures (e.g. sensors, access points and centralized servers), it is imperative to understand their impact on end-user ITS applications that will utilize these networks and more importantly to isolate fundamental performance limitations of VANETs in order to expand their applicability to support appropriate higher level application services. Test bed environments are an important component that may be used to evaluate new techniques, system designs and architectures. However experimentation in operational transportation systems is costly, can be dangerous, does not scale well and often does not provide sufficient means of control for comprehensive experimentation. Simulated systems are capable of overcoming these limitations. As both traffic conditions and network communication patterns are highly variable and unpredictable, simulation tools that include not only accurate communication network models but also realistic transportation models are vital to assess the benefits of ITS in a planning mode as well as to generate scenarios, optimize control and predict network behavior at the operational level for transportation professionals to develop effective traffic management systems and to compare transportation alternatives. Thus simulation environments that allow user level traffic simulations and wireless network simulations to be integrated in a common framework offer substantial benefits.

One key limitation of many existing tools that integrate vehicular traffic and network simulation is the lack of dynamic interactions between the two domains. Thus transportation simulators would use pre-computed and aggregate network level delay and packet loss computations whereas network simulators would use pre-scripted mobility data. The shortcoming of these approaches is the lack of dynamic interaction between an event (e.g. accident) as it unfolds in the transportation simulator and its dissemination

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to the vehicles using the network as embedded within the vehicles in its vicinity and the feedback to the transportation simulator the change in velocities and positions of the vehicles as they react in real-time to the information conveyed to them by the communication network. The lack of the above type of dynamic interaction between the transportation and the network simulator reduces the level of realism that can be achieved for key ITS applications like active safety and traveler information systems which in reality influence the vehicles' movements significantly. In this paper, we propose a distributed simulation platform that allows runtime control of vehicle behavior by events generated by an application as a result of information exchange in the communication network. The proposed simulation architecture uses a standard TCP connection to dynamically link a microscopic transportation simulator (VISSIM [16]) and a packet-level network simulator (QualNet [11]). Such TCP-based simulator coupling provides cross operating system communication necessary for these two simulation packages running in a distributed fashion on separate computers connected via LAN. To make TCP connection feasible, a program called VISSIM Control is developed, which interacts with the Component Object Model (COM) interface provided by VISSIM to control the transportation simulation. Meanwhile, VISSIM Control establishes TCP socket and communicates with QualNet on behalf of VISSIM. The proposed simulation platform also provides the capability of executing real applications in a simulated environment. Such capability facilitates, in additional to conventional network-centric metrics, the measurement of performance metrics at the application and transportation system level, which more closely reflect the interest of transportation system planners, providers and consumers.

Another major contribution of this paper derives from the observation that most studies of VANET systems focus on safety applications such as emergency warning and are limited to measuring network characteristics like packet delivery ratio and latency. Very few results have been published that relate these network metrics to relevant metrics at the application or transportation system level. In this paper, we present case studies to evaluate the performance of Dynamic Route Planning using metrics collected at the transportation system level (e.g., travel time, delay time, vehicle density and speed, traffic volume, traffic knowledge availability and accuracy).

A third contribution of the paper is to demonstrate how VANETs can significantly expand the deployment of Advanced Traveler Information Systems (ATIS). The application in our case studies – Dynamic Route Planning – is a specific kind of ATIS where individual vehicles react to current and changing traffic conditions to make better routing decisions so that travel time is reduced and trip reliability increased. Existing ATIS rely only on road-side sensors whose deployment costs limit their applicability to major highways. However, by linking ATIS with VANETs, vehicles can share travel time information in a peer-to-peer fashion, significantly enhancing their applicability without incurring corresponding high cost of widespread roadside sensor deployments. An issue with this approach is that since the wireless channel is shared by every vehicle in VANET, the channel can be easily saturated due to the transmission of traffic information when vehicle density is high. Hence, the load imposed by such exchange of data needs to be carefully controlled for reliable and low-latency transmission. Various schemes have been proposed to save the bandwidth consumed by traffic data transmission. We conduct case studies to compare three representative protocols, cost-based and hierarchical aggregation, adaptive broadcast, and distributed fair power adjustment (D-FPAV) that aim at reducing the traffic data load. We show the impact of these alternatives not just by comparing traditional network level metrics, but in terms of how they impact the traffic system.

The highlights of the experiment results from the case studies are summarized as follows.

- Incorporating accurate network simulations into transportation simulators is proven to have significant impact on the predicted performance of applications under realistic operating conditions of the VANET network. The performance discrepancy caused by the lack of high-fidelity wireless communication models is shown to be up to 116.8% in the number of vehicles reaching the destination, 54% in travel time, 125.8% in delay time, 388.9% in vehicle density, 166.9% in vehicle speed and 71.1% in traffic volume.
- With calibrated parameter values, Adaptive Broadcast substantially enhances the performance of Dynamic Route Planning, by up to 118% on the number of vehicles reaching the destination, 36.2% on travel time and 56.1% on delay time.
- The effectiveness of D-FPAV is reduced due to incomplete knowledge about the traffic network maintained at vehicles (less than 50% for regions within one transmission range) in scenarios of high vehicle density. By setting a strict maximum load threshold, D-FPAV is able to achieve performance gain of up to 21.9% on travel time.
- The penetration ratio required for Dynamic Route Planning to achieve sufficient performance gain in scenarios of high channel bandwidth is determined by the relative roadway capacity on alternative routes. In these cases, tipping point increases as the relative capacity enlarges. With limited channel bandwidth, higher penetration ratio beyond the tipping point greatly impairs the application performance due to channel saturation.

The rest of the paper is organized as follows. Section 2 discusses the related work of vehicular traffic and network simulation integration. Section 3 presents the architecture of the proposed simulation platform and elaborates on data exchange and synchronization among various simulation components in the architecture. A comprehensive case study is described in Section 4. The experiment results of the case study are presented in Section 5. Section 6 concludes the paper.

2. RELATED WORK

The last few years have witnessed a major proliferation of tools that attempt to integrate vehicular traffic and wireless network simulation [1, 3, 4, 5, 6, 7, 9, 10, 12, 13, 17, 19]. Considering that the motion of vehicles on real street maps cannot be accurately captured by the commonly used random waypoint mobility model, one class of these proposals [1, 4, 5, 12] allow users to rapidly generate realistic VANET mobility traces or models that can be immediately used by popular network simulators such as NS-2 and QualNet. However this approach fails to support models of other important traffic components such as vehicle interaction, intersection actuators, traffic lights, etc. and prohibits runtime control of vehicle behavior by applications.

The second class of existing approaches incorporate vehicular traffic and wireless networking into a single simulation engine [3, 9, 17]. However, due to the difficulty of writing efficient transportation and wireless network simulators from scratch, such simulation tools tend to lack high-fidelity communication models, validated VANET protocol models or complex traffic models, as compared with the existing set of established traffic or network simulators.

The most promising approach is to couple and synchronize existing traffic and network simulators. The majority of the work in this area [6, 7, 10, 13, 19] has linked NS-2 or QualNet network simulators with diverse transportation simulators such as SUMO,

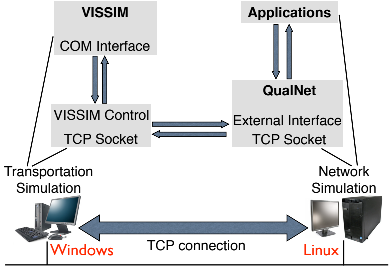

Figure 1: Simulation platform architecture

CARISMA, CORSIM and VISSIM. [19] uses the Federated Distributed Simulation Kit (FDK) runtime infrastructure (RTI) software to integrate CORSIM, QualNet and applications. In [6], VISSIM incorporates the module called VCOM that simulates inter-vehicle communication as a dynamic link library (dll) to allow direct method invocation. The rest of the proposals in this class [7, 10, 13] use a standard TCP connection to link the transportation and the network simulators. Our work extends these projects to provide a platform that can be used to evaluate and compare VANET protocols in terms of their impact in supporting not just safety applications, but also the emerging class of VANET applications like ATIS under realistic operating conditions as determined by both the transportation system and the communication network .

3. SIMULATION PLATFORM ARCHITECTURE AND INTERFACES

The simulation platform proposed in this paper is a composition of two independent simulation packages running in a distributed fashion over multiple networked computers (see Figure 1): VISSIM [16], a microscopic transportation simulator and QualNet [11], a packet-level network simulator. To maintain maximum flexibility and cross-platform interoperability in the architecture, each simulator is run on independent machines running different OS, communicating over a TCP socket to provide a fast and reliable connection. The bi-directional communication between VISSIM and QualNet enables the run-time control of vehicle behavior. As VISSIM is distributed as a licensed COTS product with limited source code, an external program called VISSIM Control was implemented to (a) perform the communication tasks to QualNet via TCP sockets and (b) interact with the VISSIM Component Object Model (COM) interface (discussed below) to control the transportation simulation as well as to access traffic data and alter vehicle behavior. The last component in the simulation architecture is the application, which provides overall control of the simulation environment. For simplicity, the VANET applications were implemented in the network simulator, although emulation frameworks such as those proposed in [21] can be utilized to directly interface real applications with the network simulator.

3.1 Simulation Components

Transportation simulator and VISSIM Control VISSIM [16] is a microscopic transportation simulator that contains detailed models of traffic network components, traffic flow and traffic control. VISSIM uses commonly accepted vehicle and driver behavior models to represent traffic networks. Extensive geometric and operational data are required to model a network in VISSIM. Data requirements include location and distance of links (i.e. freeways and local streets), number of lanes on each link segment, connectors, source and destination parking lots, signalized intersection control plans, free flow speeds, traffic composition and flows. VISSIM generates various metrics including average vehicle speed, average and total travel and delay times, average link density etc. VISSIM provides a COM interface which allows full control to most aspects of VISSIM simulation, including modification of attributes such as speed and route of a vehicle. The proposed simulation platform utilizes this COM interface to automate tasks in VISSIM by executing COM commands from the external VISSIM Control program.

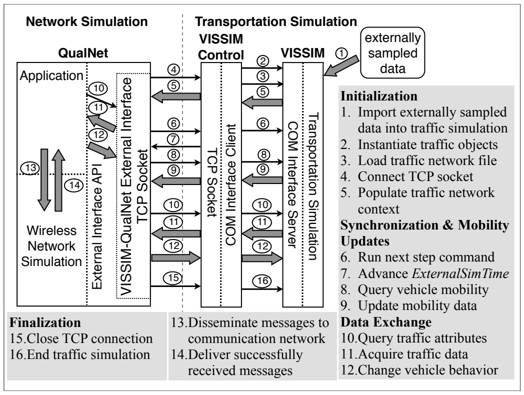

Figure 2: Communication among transportation simulator, network simulator and applications (described in Section 3.2)

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Network Simulator and External Interface The widely used network simulator QualNet [11] is used to model and simulate vehicular networks including various protocols at different layers of the protocol stack and wireless communication. QualNet provides a comprehensive set of network models for the entire protocol stack from the application to physical layer and includes a variety of ad hoc and VANET routing protocols. It also includes high-fidelity wireless models that incorporate physical environment effects (e.g. fading and shadowing). Extensive performance metrics for a complete understanding of network behavior can be collected including throughput, latency, dropped packets etc. QualNet provides the external interface API which allows the simulator to interact with external entities such as other programs or physical devices. In the simulation platform, an external interface that links QualNet to VISSIM is implemented which communicates with VISSIM via the TCP connection.

Applications Within the framework of this paper, VANET applications have been integrated into the network simulator as additional modules at the application layer. The emulation testbed proposed in [21] can be utilized to run operational applications in a simulated vehicular network, as realized in our previous work [20]. In both implementations, the existing TCP socket can be leveraged for interaction between the application and VISSIM. In general, it would be possible to implement the application using a third environment that interacts via separate interfaces with the two simulators; however, our approach considerably simplifies the simulation architecture without compromising the fidelity of the applications that need to be interfaced with the simulation environment.

3.2 Data Exchange

The interaction among VISSIM, QualNet and applications is described in Figure 2. The distributed simulation starts with the initialization phases of both the transportation and the network simulation. Initially, VISSIM transmits the geographic size of the simulated traffic network, the number of vehicles currently in the network and their positions to QualNet (Figure 2-(5)). Once the simulation starts, mobility data i.e. vehicle position updates including the entering and exiting of vehicles to and from the traffic network are sent to QualNet and mapped to mobile nodes in the wireless network simulation.

To represent the behaviors of individual vehicles, an application queries VISSIM about various attributes of the current vehicle (Figure 2-(10)). In particular, Dynamic Route Planning requires information including a vehicle's current position, speed and the index of the next intersection it is heading towards. Receiving such queries, VISSIM feedback the related traffic data to the application (Figure 2-(11)). Events generated by an application, for example, the occurrence of an incident, and the results of computation performed in the application logic, e.g. a new route to be followed by a vehicle, change the behavior of individual vehicles by assigning new values to a vehicle's attributes. Data of such change of behavior are communicated from applications to VISSIM to be incorporated into the simulation of the traffic network (Figure 2-(12)).

Messages generated by an application to be disseminated into the vehicular network are transfered to QualNet (Figure 2-(13)), which models the handling of these messages by VANET protocols running at different layers of the network protocol stack and wireless radio propagation. Successfully received messages are delivered back to the application for further processing (Figure 2-(14)).

3.3 Synchronization

VISSIM and QualNet must be synchronized such that the shared attributes between the simulators are kept consistent for accurate modeling of the system. The common practice in existing integrations of a transportation and a network simulator [7, 10, 13] is to use periodic time synchronization, where each simulator runs autonomously for a pre-specified synchronization horizon (e.g. one second), at the expiry of which, common attributes are synchronized (e.g., a request for new mobility data is sent from the network simulator to the transportation simulator), and the process is repeated periodically every synchronization horizon. We implement an adaptation of the time-stepped synchronization mechanism that maintains consistency of shared attributes regardless of the relative execution speed of VISSIM and QualNet. The synchronization mechanism utilizes a variable, **ExternalSimTime**, maintained at the external interface connecting QualNet with VISSIM. As VISSIM is inherently a time-stepped simulator, its control logic is used to set the duration of the next time step, which is communicated to QualNet and implemented using the ExternalSimTime variable, which determines how far ahead in the future QualNet can advance before it needs to interact with VISSIM. Note that although QualNet uses a parallel discrete-event synchronization algorithm internally, this scheme allows us to separate out QualNet's ability to run the network simulator on parallel machines from its interactions with VISSIM. In addition, the duration of the next time step can be dynamically adjusted during a simulation run based on the required fidelity and the number of traffic and wireless communication events. Initially, both simulations start at virtual time 0 and run one time step. The simulation that gets to the next time step first waits for the other to finish. Once both simulations are at the same time step, QualNet issues a query to VISSIM for mobility updates and VISSIM transmits the up-to-date mobility data. At this point, VISSIM also incorporates the received change of behavior data. Afterwards, both simulations start to (independently) execute the next time step and the above process repeats for the specified simulation duration.

4. CASE STUDY

4.1 Dynamic Route Planning

In our implementation of Dynamic Route Planning, each vehicle maintains a knowledge base of vehicle and travel time information which it uses to dynamically improve its route. The knowledge base consists of two types of records: (1) vehicle record, containing fields of ID_{veh}, $Position$, $Speed$, $Direction$ and $Record\ Time$, that provides updated information for multiple vehicles and (2) travel time record, containing fields of ID_{seg}, $Travel\ Time$ and $Record\ Time$, which provides updated information on the state of multiple road segments that the vehicle is expected to traverse. Note that $Record\ Time$ is the global time when the information about a vehicle or road segment is originally recorded. With a GPS receiver and a digital map installed, a vehicle is able to keep track of its location and speed. When a vehicle reaches the end of an identified road segment, ID_{seg}, it records its travel time. Each vehicle periodically broadcasts information in its knowledge base. Whenever a vehicle receives a broadcast message, it incorporates the data contained in the message into its knowledge base. When the next broadcast period comes, the vehicle broadcasts the updated information. By sharing traffic information in such a peer-to-peer fashion, vehicles can be aware of the traffic situation of the entire road network and accordingly change their routes to avoid congested areas. Each vehicle maintains an estimated travel time for every road segment in the network to dynamically compute the optimal route. Initially, when a vehicle enters into the network, the estimated travel time is set to be the free flow travel time, i.e. the time to travel through a road segment at its speed limit. The estimated travel time is subsequently updated either when a vehicle records its own experienced travel time or whenever a more recent travel time record of the corresponding road segment is received.

4.1.1 Route Computation

From the experiment results, it is seen that the response time to congestion, i.e. delay from the time instance the congestion happens till the time instance vehicles start to travel on alternative routes to avoid the congested area, is relatively long (explanation given in Section 5.2). To improve performance, a supplement method to compute the estimated travel time is implemented, where each vehicle maintains a second attribute for every road segment – estimated travel speed. This estimated travel speed is calculated as the weighted average of the current estimated value and a newly reported one. Equation 1 shows the computation of weight coefficients, where T is the current simulation time, (v_e, t_e) the current estimated travel speed and record time, and (v, t) the speed and record time of the received record. The new estimated travel speed and record time $(v_e^{'}, t_e^{'})$ are computed as in Equation 2 and 3 respectively. Subsequently, the estimated travel time is calculated by dividing the distance of the road segment by its estimated travel speed.

$$\alpha_e = \frac{T - t}{(T - t_e) + (T - t)} \qquad \alpha = \frac{T - t_e}{(T - t_e) + (T - t)} \tag{1}$$

$$v_e^{'} = v_e \times \alpha_e + v \times \alpha \tag{2}$$

$$t_e^{'} = T - ((T - t_e) \times \alpha_e + (T - t) \times \alpha) \tag{3}$$

These two types of information (i.e. vehicle speed and travel time) are chosen to be handled in different manners in the computation of the estimated travel time because a reported vehicle speed is considered to be relatively random while a reported travel time more stable. Comparing the record time of the estimated travel time computed using the two methods, a vehicle sets the final estimated travel time to the one with more recent record time.

4.1.2 Information Aging

Information aging is implemented to eliminate obsolete or inaccurate records. Whenever a record is received, a module called *Receive Aging* [2] calculates the expected latency for receiving the record and compares that to the actual latency. If the difference between these two is lower than a threshold, the record is merged into the knowledge base; otherwise, it is considered out-of-date and ignored. In addition, a timer is associated with each record in the knowledge base. This timer is reset each time the record is updated by a more recent one. If the timer expires, the record is dropped. When there are multiple records containing information about the same vehicle or road segment (in the broadcast message and the knowledge base), only the most recent record is kept and older versions removed.

4.2 VANET Protocols

As discussed in Section 1, an issue with deploying Dynamic Route Planning on VANET is that the wireless channel shared by vehicles can be easily saturated due to the transmission of traffic data. The load imposed by traffic data can be controlled by adjusting three primary parameters: (1) broadcast message size (2) broadcast interval and (3) transmission power (correspondingly, transmission range). In this case study, we present performance comparisons on the effectiveness of a representative protocol that implements each of these approaches.

4.2.1 Aggregation

If the spatial density of vehicles is assumed to be approximately constant, the amount of traffic data increases quadratically with the covered radius, increasing size of data to be broadcast by each vehicle thus limiting system scalability. To overcome this problem, the use of data aggregation has been proposed: with increasing distance, observations concerning larger and larger areas are combined into one single value. Coarse aggregates are made available at greater distances; more detailed data are kept only in the near vicinity. In this case study, *Cost-Based Aggregation* [2] is implemented to aggregate vehicle records and *Hierarchical Aggregation* [8] to aggregate travel time records.

4.2.2 Adaptive Broadcast

Traffic data load on the wireless channel can also be controlled by adjusting the inter-transmission interval of broadcast messages. In this case study, *Adaptive Broadcast* proposed in [18] is implemented. The basic idea of Adaptive Broadcast is as follows. Upon the reception of a broadcast message P, a weight w_P is computed based on the comparison of the vehicle and travel time records contained in P with the local knowledge base. For each record r_i in P, $i = 1, ..., n$, let r_i^o be the corresponding record of the same vehicle or road segment in the knowledge base. If the difference between the record time of r_i and r_i^o exceeds the time threshold ΔT, w_P is increased by a constant q_{time} (so-called time quantum). Similarly, if the difference of information values (e.g. speed or travel time) of the two records exceeds the information threshold ΔI, w_P is increased by q_{info} (so-called info quantum). Therefore, a message is assigned a high weight if it contains significantly different information (including both info and time difference). In contrast, a low weight means this vehicle has a very similar view of the traffic network as the vehicle that has sent the message. w_P is then compared to the thresholds w_{inc} and w_{dec} to determine how the remaining time until the next broadcast transmission should be adjusted. w_P being less than w_{inc} causes an increase of the remaining time; and w_P larger than w_{dec} decreases this time.

4.2.3 Distributed Fair Power Adjustment

Transmission power used by a vehicle to send out broadcast messages can be adjusted dynamically in response to vehicle density observed in the network so as to save bandwidth consumed by traffic data. Each vehicle sends a broadcast message with a certain transmission power $p \in [P_{min}, P_{max}]$. The function of a transmission power control scheme is to compute a power assignment A that assigns to every vehicle v_i, with $i = 1, ..., n$, a ratio $A_i \in [0, 1]$. The power used by vehicle v_i is $P_{min} + A_i \times (P_{max} - P_{min})$. The objective to be achieved is that using A, the minimum of the transmission powers used by vehicles for broadcast is maximized, and the network load experienced at the vehicles remains below the predefined threshold *Maximum Load* (ML). This case study implements *Distributed Fair Power Adjustment for Vehicular Networks (D-FPAV)* proposed in [14]. In D-FPAV, a vehicle continuously collects information about the status of all the vehicles within its maximum carrier sensing range CS_{max}. Based on this information, the vehicle locally computes the maximum common value P_i of the transmission powers for all the vehicles in CS_{max} such that the condition on the ML is not violated.

4.3 Scenario and Parameters

The traffic network scenario analyzed in this case study is an area of size $3.5 \times 1.6\ km^2$, consisting of a freeway and the local streets in the surrounding area. The freeway serves as the main route vehicles take to travel from a designated source location to a designated destination one. The local streets either intersect with the freeway (i.e. having entrances or exits for getting on and off the freeway) or run in parallel. These local streets can serve as alternative routes for vehicles when the freeway is congested. When the simulation first starts, every vehicle travels on the freeway as this is the fastest route to reach the destination. About three minutes into the simulation, an accident happens on the freeway at a location half way to the destination. The immediate vicinity of the accident starts to become congested causing nearby vehicles to slow down. These vehicles disseminate such change to other vehicles in the network via broadcast messages, which accordingly update the estimated travel time. As a result, the freeway is no longer the fasted route to the destination and vehicles start to use the local streets to bypass the congested area. Six minutes or so, the congested area starts to clear and finally opens up at the twelfth minute. The entire simulation is 900 seconds. Besides the vehicles in question which travel from the source to the destination, there are other vehicles distributed on the local streets moving with a random source and destination and disseminating traffic information about the local streets. The vehicles in question however constitute the major fraction of traffic.

IEEE 802.11b is used as the underlying wireless communication technology for vehicle broadcast with transmission rate 2Mbps. Two-Ray pathloss model and Rayleigh fading model are used in the simulation. The default transmission power is set to be $15dBm$. For transmission power control, the range of transmission powers is $[0.0, 20.0]$dBm, with each level being 0.5dBm apart. The maximum size of broadcast messages is 1500bytes. The broadcast rate is chosen from 1, 5 and 10 packets/sec.

4.4 Performance Measures

Table 1 summarizes the set of metrics used in the case study. Both application/system and network level metrics are studied. The definition of most metrics in the table are straightforward. For the couple of less used metrics, they are defined below.

Delay Time determines, compared to the ideal travel time (no other vehicles, no signal control), the time delay resulted from the actual travel time of a vehicle.

Estimation Error determines the accuracy of information available at a vehicle. The road around each vehicle is divided into regions of 200 meters long and the average error in estimating the positions of vehicles in each region is calculated. In the accuracy graph, the average error for each region is shown, averaged over all the vehicles during the simulation run.

Knowledge Percentage is a metric used to measure the availability of information about other vehicles at a vehicle. The road around each vehicle is divided into regions of 200 meters long. For

Application and System Level Metrics

Route Quality	Number of Vehicles Arrived
	Travel Time (s)
	Delay Time (s)
Traffic Knowledge Availability & Accuracy	Estimation Error (m)
	Knowledge Percentage (%)
Congestion	Density (veh/km)
	Speed (m/s)
	Volume (veh/h)

Network Level Metrics

Packet Transmission	Throughput ($Mbps$)
	End-to-End Delay (s)

Table 1: Performance measures

each region, the percentage of vehicles in that region about which the current vehicle knows is defined as the knowledge percentage of that vehicle for that region. The knowledge percentage graph presents the knowledge percentage for each region, averaged over all the vehicles during a simulation run.

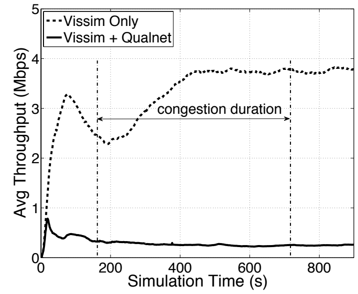
5. EXPERIMENT RESULTS

5.1 Integration of Network Simulation

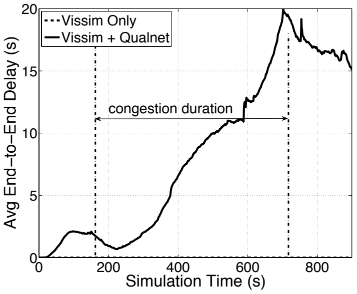
The first set of experiments demonstrate the impact of incorporating accurate network simulation into transportation simulators like VISSIM. We run two experiments with the same scenario setting and parameters (max broadcast message size 1500bytes, broadcast rate 10pkt/s, transmission power 15dBm and transmission rate 2Mbps). The first experiment is run without QualNet, with the application integrated directly with VISSIM. Due to the lack of any radio propagation and channel access model, ideal transmission conditions are assumed in this experiment, i.e. unlimited bandwidth, no transmission delay and no packet loss. The second experiment is run using an identical scenario, with the QualNet network simulator used to model realistic VANET operations. Our expectation is that due to high vehicle density and broadcast rate, the wireless channel will be saturated, which causes a large fraction of broadcast messages to collide. As a consequence, vehicles have no means of receiving accurate traffic information and therefore fail to change their routes to avoid the congested area, which impacts the transportation system metrics.

The results shown in Figure 3 and 4 confirm our hypothesis. Figure 3(a) demonstrates that VISSIM Only predicts that on most part of the freeway, vehicle density remains constantly low over the entire simulation. This means that most vehicles are able to make better routing decisions and take the local streets before reaching the accident area. While in reality most vehicles get stuck on the freeway. Compared to VISSIM Only, for the part of the freeway leading to the accident area, VISSIM + QualNet produces vehicle density up to 388.9% higher. The same disparity in application performance is shown in Figure 3(b) and 3(c) concerning the average vehicle speed and volume at various locations on the freeway. Compared to VISSIM Only, VISSIM + QualNet generates vehicle speed up to 58.3% lower and volume up to 40.5% lower.

The average travel quality experienced by vehicles that have successfully reached the destination over the course of the simulation is presented in Figure 4. As was the case with other metrics already discussed, the travel quality exhibited with VISSIM Only and VISSIM + QualNet diverges largely. Twice as many vehicles appear to have completed their trip with VISSIM Only as compared with VISSIM + QualNet (see Figure 4(a)). In addition, for much of the duration of the accident, VISSIM + QualNet shows that the number of vehicles reaching the destination remains constant. In contrast, with VISSIM Only, the corresponding number of vehicles increases steadily, up to 116.8% higher than with VISSIM + QualNet. The same effect is seen with the average travel time metric (Figure 4(b)), where VISSIM Only predicts a gradual increase as vehicles are successfully diverted onto local streets. However, as seen with the results from VISSIM + QualNet, this metric increases sharply over the duration of the accident (up to 54% longer) because relatively few vehicles have learned about the congestion under realistic operating conditions of the VANET network. As a result, the average travel time keeps increasing sharply till the end of the simulation. The average delay time anticipated by VISSIM Only and VISSIM + QualNet also differs largely, with the performance difference up to 125.8% (Figure 4(c)).



(a) Average throughput



(b) Average end-to-end delay

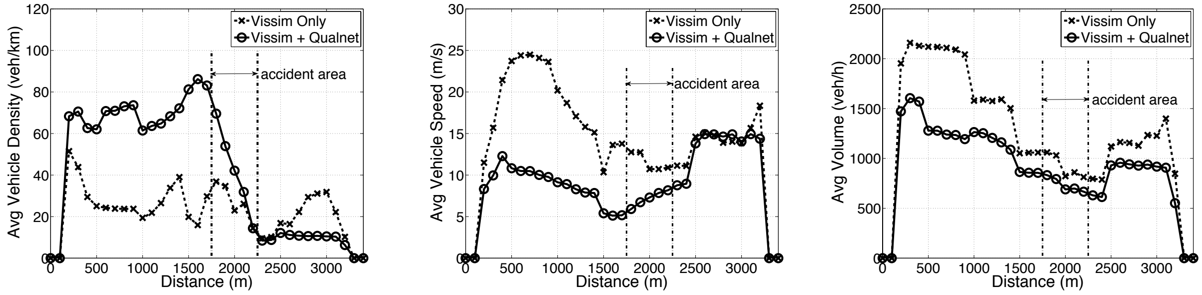
Figure 5: End-to-end performance of broadcast transmission, Vissim Only vs Vissim + Qualnet

To fully grasp the performance discrepancy caused by the lack of high-fidelity wireless communication simulation, throughput and end-to-end delay of broadcast transmission with VISSIM Only and VISSIM + QualNet are compared in Figure 5. It is seen that under the ideal transmission conditions, the throughput achieved with VISSIM Only is close to 4Mbps, which indicates that the traffic data load requires a channel capacity of 4Mbps or higher. With the actual capacity being only 2Mbps (achievable goodput at the application layer even less), the throughput is barely 0.2Mbps (Figure 5(a)). Similarly, as expected with VISSIM Only, broadcast transmission experiences zero delay while the realistic end-to-end delay increases almost linearly the entire duration of congestion with a maximum delay of 20 seconds (Figure 5(b)).

In summary, in order to produce performance results that accurately reflect the behavior of applications and the VANET network, it is vital to incorporate high-fidelity communication simulations.

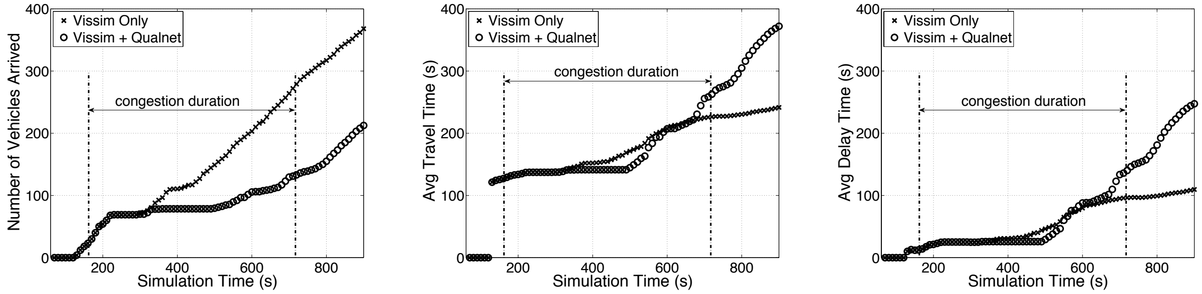
5.2 Vehicle Information Benefits Route Planning

Various proposals on dynamic route planning (e.g. [8]) use travel time collected by vehicles as the only source of traffic information for computing routes. After examining this approach, we observe that the achieved response time to congestion i.e. delay from the



(a) Average vehicle density (b) Average vehicle speed (c) Average traffic volume

Figure 3: Traffic condition on the freeway, Vissim Only vs Vissim + Qualnet



(a) Number of vehicles arrived (b) Average travel time (c) Average delay time

Figure 4: Travel quality experienced by vehicles over time, Vissim Only vs Vissim + Qualnet

time instance the congestion happens till the time instance vehicles start to travel on alternative routes to avoid the congested area, is relatively long. This observation is shown in Figure 6(a). It is seen that nearly 6 minutes after the accident happens, vehicles start to arrive at the destination again. The response time to congestion is around three and a half minutes. The reason of such performance is that as change in traffic condition is solely contained in travel time information, such dynamic can only be observed and disseminated when a vehicle reaches the end of the congested road segment and records its travel time. As this duration directly increases in the presence of congestion, the lack of timely updates to other vehicles that may be at some distance from the congested area can worsen congestion. As presented in Section 4.1.1, vehicle information can also be utilized to aid route computation. Figure 6 shows that the use of vehicle information instead of travel time information improves the performance in terms of the number of vehicles reaching the destination, the average travel time and the average delay time. The response time to congestion is only a few seconds, which can be explained by the fact that variation in vehicle speed can be recorded and disseminated to other vehicles rapidly and efficiently. The hybrid approach of combing both types of information obviously has the best performance, with up to 121.9% increase on the number of vehicles reaching the destination, 27% reduction on travel time and 46.9% reduction on delay time.

In summary, the inclusion of vehicle information in dynamic route computation improves the application performance by a fair amount, especially during a traffic jam. Travel time information contributes to the performance gain effectively in uncongested conditions.

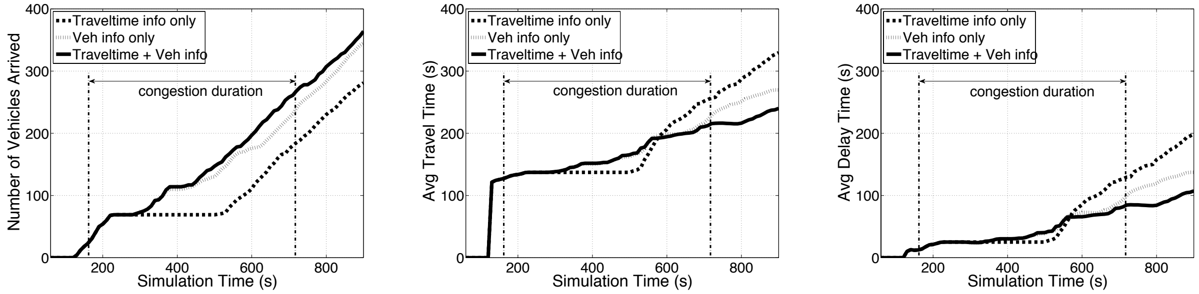
5.3 Effectiveness of Aggregation

The impact on the performance of Dynamic Route Planning by aggregating traffic data to be disseminated is shown in Figure 7, with broadcast message size of 500 and 1500 bytes. In the case of heavy data load imposed on the channel due to large packet size, e.g. 1500 bytes, travel quality experienced by vehicles such as travel time is slightly improved by the use of aggregation, which provides relatively broader knowledge of the traffic network for a vehicle to compute routes (Figure 7(a)). However, as a large fraction of data exchange is collided, the knowledge percentage achieved is nevertheless fairly low although aggregation is applied (Figure 7(b)). This results in insufficient improvement on travel quality by aggregation. When the message size is reduced to 500 bytes, the benefit of conveying more information by aggregation becomes prominent, achieving up to 20% increase on knowledge percentage, in particular about regions further away. Travel time in this case, however, is longer with aggregation (Figure 7(a)). This is related to the fact that Dynamic Route Planning favors accurate information about its immediate vicinity in order to make the optimal decision as to which road segment to take the next time instance; for larger areas, it requires only coarse information to determine the general direction. Aggregation although improves knowledge availability, sacrifices information accuracy, therefore impaires the application performance in this case (Figure 7(c)).

In summary, the use of aggregation improves the performance of Dynamic Route Planning when channel is congested. Reducing message size while applying aggregation however does not help with the application performance due to insufficient data accuracy. For applications that have less stringent requirements of accuracy but prefer wider knowledge of the traffic network, aggregation may be a more effective approach.

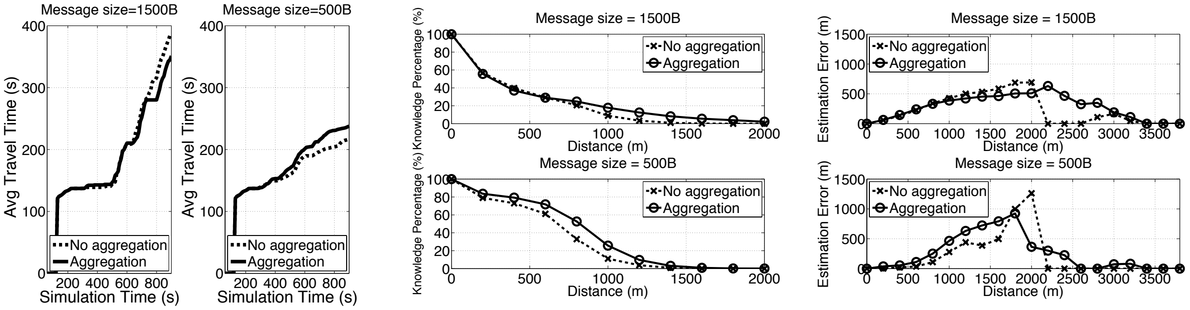
5.4 Effectiveness of Adaptive Broadcast

This set of experiments evaluate the effectiveness of Adaptive Broadcast in supporting Dynamic Route Planning. Table 2 describes the different parameter sets used for the parameters introduced in Section 4.2.2. The main parameters varied over the four sets are the info quantum q_{info}, the time quantum q_{time} and the info threshold ΔI. From the discussion in Section 4.2.2, these parameters, in combination with ΔT, w_{inc} and w_{dec}, determine how fast the adaptation of inter-transmission interval is performed. Fig-



(a) Number of vehicles arrived (b) Average travel time (c) Average delay time

Figure 6: Travel quality over time, travel time information only, vehicle information only vs combination of both



(a) Average travel time (b) Knowledge percentage (c) Average estimation error

Figure 7: Travel quality and availability and accuracy of traffic knowledge, aggregation vs no aggregation

Parameter	Set 1	Set 2	Set 3	Set 4
q_{info}	0.001	0.005	0.005	0.005
q_{time}	0.001	0.005	0.000	0.000
ΔI (m/s)	4.5			1
ΔT (s)	60			
w_{inc}	0.01			
w_{dec}	0.04			

Table 2: Parameters for Adaptive Broadcast

ure 8 shows the travel quality achieved by Adaptive Broadcast with these different parameter sets, compared to the scheme of using a fixed transmission rate of 10pkt/s. The corresponding average inter-transmission interval at each vehicle as a result of adaptation is plotted in Figure 9. Adaptive Broadcast is seen to have the best performance with set 2 in which case the inter-transmission time is adjusted aggressively by adding a large quantum to the weight whenever a record is received containing sufficiently different information (performance gain of up to 118% on the number of vehicles reaching the destination, 36.2% on travel time and 56.1% on delay time). This, in contrast to the deficient performance of Adaptive Broadcast with set 1 infers that Dynamic Route Planning requires accurate traffic information, therefore frequent data exchange among vehicles. Another observation made from the poor performance of Adaptive Broadcast with set 3 is that info difference alone is not a reliable enough source for inter-transmission interval adaptation decisions. The performance, however, can be largely improved by having a small info threshold as in set 4, which increases the sensitivity of the inter-transmission interval adaptation to info difference.

In summary, Adaptive Broadcast has the potential to significantly enhance the performance of Dynamic Route Planning. This however is achieved given that the parameters are carefully set to tailor the requirements of the application. The final parameter values relate to the type of traffic information used by the application and the degree of sensitivity the application's performance to the variation in such information.

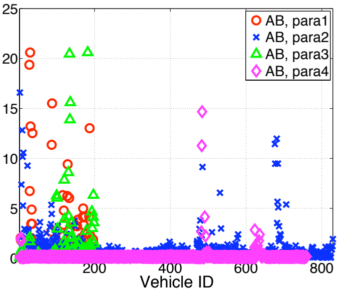
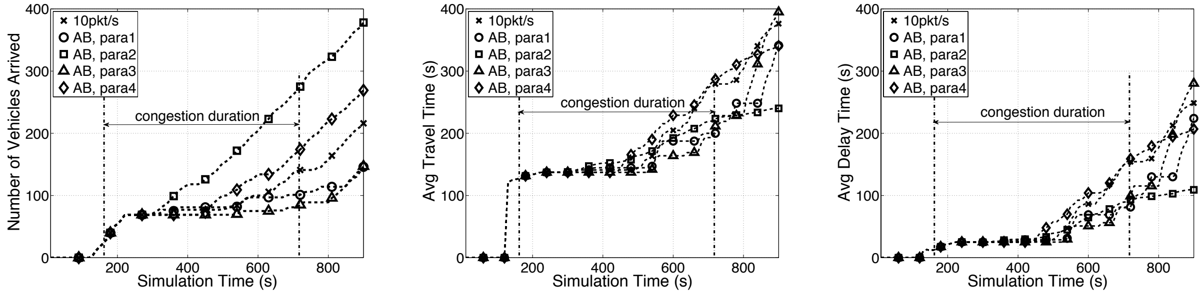


Figure 9: Average inter-transmission interval at each vehicle

5.5 Effectiveness of D-FPAV

The effectiveness of the power control protocol D-FPAV in supporting Dynamic Route Planning is studied by the set of experiments presented in this section. Figure 10 shows the travel time achieved by D-FPAV with Maximum Load threshold (ML) set at three different values (i.e. 1, 1.5 and 2 Mbps), in comparison to the scheme of fixed transmission power of 15dBm. The transmission rate used in all the cases is 2Mbps. It is noted that the value set for ML threshold affects the performance of D-FPAV. In this scenario, D-FPAV performs the best with a more strict threshold of 1Mbps (up to 21.9% reduction on travel time). Overestimating the capacity of the channel by having a large ML indeed impairs the performance. However, as D-FPAV performs nearly as poorly with ML being 1.5Mbps, overestimation is unlikely the main cause of such performance. The knowledge percentage about the traffic net-



(a) Number of vehicles arrived (b) Average travel time (c) Average delay time

Figure 8: Travel quality experienced by vehicles over time, fixed broadcast rate vs Adaptive Broadcast

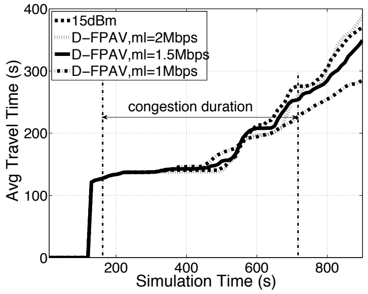


Figure 10: Travel time, fixed transmission power vs D-FPAV

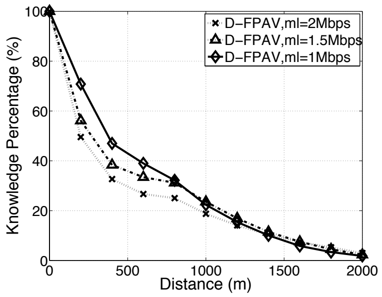


Figure 11: Knowledge percentage of traffic network, D-FPAV

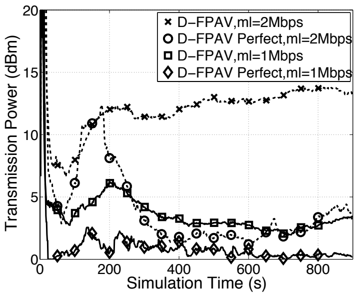


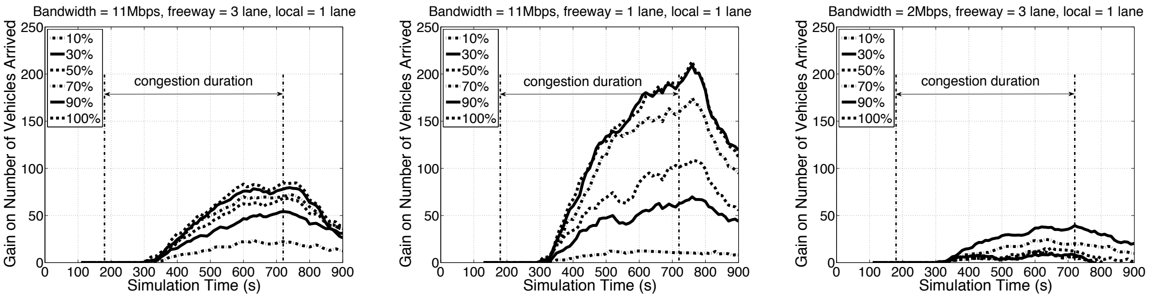
Figure 12: Distribution of computed transmission power, D-FPAV vs perfect knowledge

work maintained at each vehicle is plotted in Figure 11. It is shown that due to high collisions of data transmission, vehicles have fairly incomplete view of the traffic network. For regions within the maximum transmission range (452.492m), the knowledge percentage drops below 50%. The accuracy of D-FPAV heavily depends on the knowledge a vehicle has about other vehicles in at least one maximum carrier sensing range. With insufficient knowledge, D-FPAV underestimates the contention for the channel from other vehicles in the network when it computes the estimated network load and thus assigns overly high transmission power to vehicles. Figure 12 confirms this by comparing the transmission power that would be assigned to a vehicle with perfect knowledge (D-FPAV Perfect) and the actual transmission power used. With a tight ML, the difference to the ideal transmission power is reduced, resulting in better performance of D-FPAV.

In summary, although D-FPAV is designed to control transmission load imposed on the channel in scenarios where the channel is congested as a result of high vehicle density, the performance of D-FPAV depends on vehicles having fairly accurate knowledge about the traffic network, which is difficult to achieve with an overloaded channel. With a strict ML condition, D-FPAV is able to improve the application performance. However, if ML is set offline and cannot be dynamically adjusted, when the network becomes less congested, this may result in unnecessarily low transmission power assigned to vehicles and in turn the waste of channel bandwith.

5.6 Impact of Penetration Ratio

This set of experiments study the impact of penetration ratio on the improvement of travel quality achieved by Dynamic Route Planning. Penetration ratio is defined to be the fraction of vehicles in the traffic network that are equipped with wireless communication devices and participate in information exchange. In all of the previous experiments, penetration ratio is assumed to be 100%, i.e. every single vehicle in the network collects and transmits traffic information. In this context, tipping point denotes the penetration ratio beyond which the performance gain of Dynamic Route Planning becomes marginal. We first run experiments with realistic traffic network setting where the freeway has three lanes while the local street only one (i.e. freeway has larger capacity than local streets). Figure 13(a) plots the gain on the number of vehicles reaching the destination with penetration ratio ranging from 10% to 100%, compared to the case of penetration ratio being zero. It is seen that in this scenario, tipping point is 50%, meaning 50% penetration ratio is sufficient for Dynamic Route Planning to achieve significant performance gain e.g. 65% more vehicles are able to arrive at the destination. Beyond this point, the additional gain obtained is negligible, possibly becoming unworthy of the cost of equipping a larger fraction of vehicles with computing and communication capabilites. Next we run the same experiment with the freeway having one lane as well, representing the case where alternative routes have comparable capacity as the main route. The gain achieved by Dynamic Route Planning at various penetration ratio in this scenario is plotted in Figure 13(b). It is seen that the same amount of gain achieved at the tipping point in the three-lane freeway case can be achieved at a smaller penetration ratio of 30% in this scenario. As long as there is sufficient capacity on alternative routes, the performance gain keeps increasing. The tipping point in this scenario becomes 80%.



(a) 3 lane freeway, Bandwidth = 11Mbps (b) 1 lane freeway, Bandwidth = 11Mbps (c) 3 lane freeway, Bandwidth = 2Mbps

Figure 13: Gain on vehicles reaching the destination, compared to penetration ratio = 0%

In addition to relative capacity between alternative routes, another factor that affects the value of tipping point is channel bandwidth. Figure 13(c) shows the gain on the number of vehicles reaching the destination in the three-lane freeway scenario but with limited channel bandwidth of 2Mbps. First it is noted that the tipping point decreases to 30% due to channel saturation. Beyond tipping point, the performance gain decreases greatly. This is different from the case of sufficient channel bandwidth where the performance gain at higher penetration ratio only becomes insignificant but never decreases. This means that channel saturation greatly impairs the effectiveness of Dynamic Route Planning. Therefore, penetration ratio needs to be carefully controlled in the case of limited channel bandwidth.

6. CONCLUSIONS

This paper proposed a distributed simulation platform that allows runtime control of vehicle behavior in the transportation simulation by events generated by an application as a result of information exchange in the communication network. The proposed platform is composed of a microscopic transportation simulator VISSIM and a packet-level network simulator QualNet, running independently on different machines, linked dynamically via a standard TCP connection for fast and reliable communication. The proposed platform facilitates the measurement of metrics at the application and transportation system level. Case studies are performed to investigate the feasibility and performance limitations of VANETs in support of Dynamic Route Planning. The performance results show that the incorporation of accurate network simulation into transportation simulators like VISSIM is crucial in producing reliable performance results of applications operating under realistic conditions of VANETs. The performance discrepancy caused by the lack of high-fidelity wireless communication simulation can be up to 116.8% in the number of vehicles reaching the destination, 54% in travel time and 125.8% in delay time. The case study shows that Dynamic Route Planning can be effectively supported by VANETs. Among all the adaptation protocols, Adaptive Broadcast is the most effective in enhancing the performance of Dynamic Route Planning.

7. ACKNOWLEDGMENTS

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