32nd IEEE Conference on Local Computer Networks

Node Connectivity in Vehicular Ad Hoc Networks with Structured Mobility

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Abstract[1] – Vehicular Ad hoc NETworks (VANETs) is a subclass of Mobile Ad hoc NETworks (MANETs). However, automotive ad hoc networks will behave in fundamentally different ways than the predominated models in MANET research. Driver behaviour, mobility constraints and high speeds create unique characteristics in the network. All of these constraints have implications on the VANET architecture at the physical, link, network, and application layers. To facilitate the cross-layer designs for VANETs, understanding of the relationship between mobility and network connectivity is of paramount importance. In this paper, we focus on studying transport systems with structured mobility (e.g., bus systems), which have unique characteristics on the road such as fixed routes that have never been explored in previous work. The main contributions of this paper are three-fold: 1) we provide an analytical framework including the design requirements of the mobility model for realistic vehicular network studies, and metrics for evaluating node connectivity in vehicular networks; 2) we demonstrate, through simulation, the impacts of marco- and micro-mobility models, and various transport elements on network connectivity; and 3) we show that multi-hop paths perform dramatically poorer than single-hop links in vehicular networks. Specifically, two-hop and three-hop (communication) paths can only respectively achieve less than 27% and 13% of the average duration of single-hop links. Such kind of knowledge of the performance of multi-hop transmission will be significant for the studies of routing algorithm and other networking functions in vehicular networks.

Keywords – Vehicular Ad Hoc Networks, Mobility, Node Connectivity.

I. INTRODUCTION

Mobile Ad hoc NETworks (MANETs) is a collection of wireless nodes communicating with each other in the absence of any infrastructure. Classrooms, battlefields and vehicle-to-vehicle communications are a few scenarios where MANETs can be applied. Due to its readily deployable nature, it is attracting a lot of attention from the research community.

Inter-vehicle communication network or Vehicular Ad hoc NETworks (VANETs) is a subclass of MANETs, which would perform crucial functions in road safety, detection of traffic accidents and reduction of traffic congestions. However, VANETs exhibit very different characteristics from MANETs. Specifically, the constraints on vehicle movements, varying driver behaviour, and high mobility cause rapid topology changes, frequent fragmentation of the network, and limited utility from network redundancy. These changes have implication for the VANETs architecture from the physical to the application layers.

In VANETs, the impact of mobility on the performance of communication protocols can be realized as the block diagram shown in Figure 1. First, different mobility models have different degrees of spatial dependence, temporal dependence, relative speeds and geographic restrictions, which give rise to different link durations between nodes and thus distinct path availabilities for multi-hop transmissions. Network connectivity in turn influences the performance of the communication protocol. It was shown in [1] that higher link duration will result in higher throughput and vice versa.

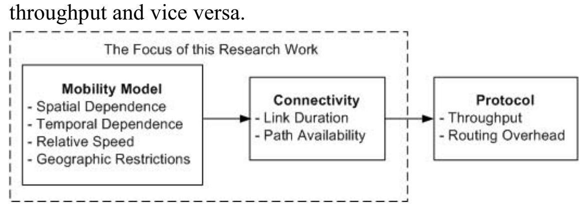

Figure 1. Block diagram illustrating the impact of mobility on the performance of communication protocols.

Therefore, to ensure the design feasibility of VANETs, we require a fundamental understanding of the impact of mobility on network connectivity (the first two blocks in Figure 1), which is the focus of this paper. In this paper, we show through simulations that commonly used mobility models in MANET research are insufficient to capture real-world vehicle movements, and suggest relevant mobility/traffic models, transport-related elements and connectivity metrics that should be included in the framework for VANET studies. Specifically, we focus on studying transport network with structured mobility, such as bus network, which have unique traffic patterns on the road with fixed routes and timetables that have never been investigated in prior work. We simulate a bus network on a road-based map and demonstrate the impact of advanced traffic models on node connectivity and, in essence, show that multi-hop paths perform dramatically poorer than single-hop links in the vehicular environment. Even if we increase the transmission range of vehicles, it is found that multi-hop connectivity cannot be improved.

This paper is organized as follows. Section II delivers related work on VANETs in terms of the mobility models and traffic simulators. Section III presents the list of parameters that should be considered in a realistic VANET simulation, especially for buses. Section IV introduces the

[1] The work reported in this paper forms part of the MESSAGE project. MESSAGE is a three-year research project which started in October 2006 and is funded jointly by the UK Engineering and Physical Sciences Research Council and the UK Department for Transport. The project also has the support of nineteen non-academic organisations from public sector transport operations, commercial equipment providers, systems integrators and technology suppliers. More information is available from the web site www.message-project.org. The views expressed in this paper are those of the authors and do not represent the view of the Department for Transport or any of the non-academic partners of the MESSAGE project.

0742-1303/07 $25.00 © 2007 IEEE
DOI 10.1109/LCN.2007.22

set of metrics for evaluating node connectivity in vehicular networks. Section V presents and analyzes the results of a bus network simulation, and explores the influences of other transport elements on network connectivity. Finally, Section VI concludes the paper.

II. RELATED WORKS

In this section, we first present the commonly used mobility models in MANET research and the macro-mobility and micro-mobility models in transport studies in Subsection A, followed by the review of existing traffic simulators in Subsection B.

A. Mobility Models

Several mobility models are widely used in the research community of MANETs. However, classic and purely random models, such as the Random Walk, Random Waypoint, and Reference Point Group Mobility models [2] are insufficient to capture the major characteristics of the real-world vehicle movement, these models can generate unreliable results as they do not even pose fixed road constraints to nodes' motions. The reader can refer to our simulation results in Section V for the comparison of node connectivity of unconstrained random waypoint and road-constrained car-following models. The more advanced Freeway and Manhattan models [2] try to restrict nodes' macro-mobility on a highway and grid topologies respectively, however, the road topology used is rather simple and regular, multiple lanes and traffic controls such as traffic lights and stop signs are neglected. Moreover, they hardly modelled micro-mobility such as vehicle-to-vehicle interaction due to individual driver behaviour (e.g., general acceleration, car following, lane changing and overtaking), and none of them treats mobile nodes as different types of vehicles (e.g., private vehicles, buses, trains, etc.), which have different traffic patterns, rules and priorities.

Vehicles in real life do not move randomly as conventional mobility models, they are restricted by the geometry of roads, traffic controls in the transport network, and movement of neighbouring vehicles. When dealing with vehicular mobility modelling, we distinguish between *macro-mobility* and *micro-mobility* descriptions [3].

For *macro-mobility*, it includes all the macroscopic aspects which affect vehicular traffic. Such as the road topology, per-road characterization, speed limits, number of lanes, overtaking and safety rules over each street of the aforementioned topology; the traffic controls mechanism, the vehicle class dependent constraints, provide different rulings and priorities to different types of vehicles.

For *micro-mobility*, it refers to the individual drivers' behaviour [4] when interacting with neighbouring vehicles or with the road infrastructure. For example, travelling speed in different traffic conditions, general acceleration, car following, lane changing, gap-acceptance and overtaking criteria, conduct in the presence of road intersections and traffic signs, general driver attitude related to age, sex, mood, etc.

In general, macroscopic mobility describes gross quantities of interest, such as density or mean velocity of cars, treating vehicular traffic according to fluid dynamics, while microscopic mobility considers each vehicle as a unique individual, modelling its behaviour in a more precise but computationally more expensive way.

B. Traffic Simulators

To explore the correlation between the mobility and network connectivity, we need a traffic simulator for simulating the vehicular network environment. Several simulators such as ns-2 [11], QualNet [12], and OPNET [13] have been developed for generic ad hoc networks and modelling of the wireless channel. However, they do not support specific vehicle network topologies and traffic control models. VISSIM [14], Paramics [15] and SUMO [16] are microscopic traffic simulators that provide highly accurate traffic queuing and vehicle interaction models. They focus on transportation planning and road network design, but do not integrate any vehicle-to-vehicle communications.

The IMPORTANT tool [1] although can generate mobility traces to ns-2, however, as discussed above, the mobility models (Freeway and Manhattan models) are definitely too simple to represent realistic vehicular motion.

TranNS [17] aims at joining a traffic simulator SUMO and a network simulator ns-2. Using an interface to extract traces from SUMO to ns-2, and on the other hand, instructions from ns-2 are sent to SUMO for traffic tuning. As a result, interaction between vehicular traffic and communication network may be implemented.

GrooveNet [5;6], jointly developed by Carnegie Mellon University (CMU) and General Motors Corporation, is a hybrid simulator which enables communication between simulated vehicles, real vehicles and between real and simulated vehicles. By modelling inter-vehicular communication within a real street map-based topography, it facilitates protocol design and also in-vehicle deployment. GrooveNet's modular architecture incorporates mobility, trip and message broadcast models over a variety of link and physical layer communication models. It supports multiple network interfaces, GPS and events triggered from the vehicle's on-board computer. Through simulation, we are able to study the message latency, and coverage under various traffic conditions.

Overall, we found that GrooveNet has competitive capability in both the transport and communication aspects. Moreover, its open-source nature and modular architecture make it flexible for customization. In Section V, we exploit GrooveNet for the bus network simulation and analyze the results based on a set of node connectivity metrics which will be introduced in Section IV.

III. LIST OF PARAMETERS FOR A REALISTIC VEHICULAR NETWORK SIMULATION

As mentioned earlier, our studies on the relationship between mobility and network connectivity will focus on buses, which are a special type of vehicles on the road with unique characteristics. In this section, we are going to introduce various parameters which together form the mobility framework for realistic vehicular network studies. The proposed parameters fall in three categories: macro-mobility, micro-mobility and bus network features.

A. Macro-mobility

When considering macro-mobility, we do not only take into account the road topology, but also include trip generation, or traffic controls that will influence vehicles movement pattern on the topology. We therefore have the following components:

1. **Road Network/Topology:** The motion of vehicle is restricted to the geometry of the roads.
2. **Multi-lane:** The multiple lanes nature of the road gives rise to distinct connectivity graph in the communication network. Moreover, it allows certain micro-mobility criteria such as lane changing and overtaking.

3. **Traffic Signal Control:** Traffic light acts as a gate on the road, it causes bunching of vehicles, while at the same time, separates vehicles into clusters. It therefore has a strong impact on the node connectivity of communication network.
4. **Origin/Destination Position:** Every vehicle on the road has an origin and destination. The position may be either random, random restricted on a graph or based on a set of attraction points.
5. **Trip:** A trip may be generated randomly or with algorithms such as Dijsktra's Algorithm between the origin and destination points.
6. **Velocity:** The simulated velocity may be uniform, smooth or dependent on the speed limit of roads.

B. Micro-mobility

Micro-mobility or driving behaviour models captures drivers' tactical manoeuvring decisions in different traffic conditions. Aggregate traffic flow characteristics may be deduced from the behaviour of individual drivers. The literature on driving behaviour mainly focuses on acceleration and lane-changing models.

1. **Acceleration Models:** It can be classified into two groups: *car-following models*, which describe the acceleration drivers apply in reaction to the behaviour of the vehicle in front, and *general acceleration models*, which apply when drivers do not closely follow their leaders.

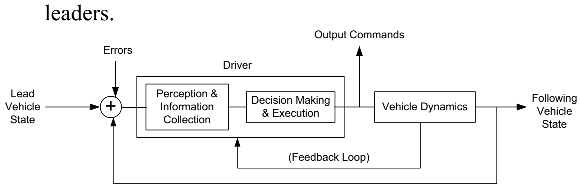

Figure 2. General schema of car-following models.

Car-following Models: The car-following model is one of the microscopic models that adapts a following car's mobility according to a set of rules in order to maintain a safe distance and avoid collision with the lead vehicles. A generalization of car following in a conventional control theory block diagram is shown in Figure 2.

Brackstone [7] classified car-following models into five classes: GHR Models, Psycho-Physical Models, Linear Models, Cellular Automata, and Fuzzy Logic Models. For the details of various classes of car-following models, the reader is referred to [7].

2. **Lane-changing Models:** Modelling lane-changing behaviour is a more complex task. It is a two-step process including the *lane-selection process* (the decision to consider a lane change and the lane choice), and the *decision to execute the lane change*. Lane changes are either mandatory (MLC) or discretionary (DLC). MLC are executed when driver must leave the current lane. DLC are executed to improve driving condition. *Gap-acceptance* models are used to model the execution of lane changes. Some widely used models in transport studies include the Gibbs Model [8] and Wiedeman Psycho-Physical Model [9] for lane changing.

C. Bus Network Features

The type of vehicles that we are interested to study is buses. Given that buses have a number of characteristics that distinguish their traffic patterns from other vehicles on the road, we need to consider extra features for the bus network, which could have potential impacts on node connectivity in the communication network.

1. **Bus Signal Priority (Bus SCOOT):** The Split Cycle Offset Optimisation Technique (SCOOT) [18] is an urban traffic control system. The Transport Research Laboratory (TRL) developed SCOOT in collaboration with UK traffic system suppliers. Today, TRL, Peek Traffic and Siemens Traffic Control jointly own SCOOT.
   Bus SCOOT is a facility incorporated into SCOOT to give priority to buses. Since traffic lights cause bunching of vehicles, bunching of buses will not be a desirable phenomenon, especially from the perspective of bus passengers. The main objective of bus signal priority is to evenly distribute buses on the road. Some strategies of Bus SCOOT include:
   i) *Bus SCOOT with extensions only*: if traffic signals are on green when a bus arrives, the time the signals are on green is extended to allow the bus to proceed;
   ii) *Bus SCOOT with extensions and low/high degree of saturation recall*: if traffic signals are on red when a bus arrives, Bus SCOOT looks at the other signal arms and decides whether to recall the green for the bus. Whether the green is recalled depends on the priority (low or high) assigned for this to occur.
2. **Bus Lane:** A bus lane is a lane on a road restricted to buses. The aim of a bus lane is to give priority to buses and save journey time in places where roads are congested with other traffics. In general, buses move with a higher speed in bus lane than in regular lane.
3. **Bus Route:** Unlike other vehicles, the motion of buses on the road is governed by bus routes, which include fixed origins and destinations, and the trips taken by buses. Moreover, communications seldom exist between buses moving on the same route and in the same direction, since there is usually at least a several minutes of headway between consecutive buses on the same route, which is enough for them to move beyond the communication ranges of each other. Indeed, most of the communications exist between buses moving in reverse directions or on different routes. As a result, the inter-arrival time of buses and also the topologies that bus routes intersect will greatly define the density of nodes and thus the network connectivity.
4. **Bus Stop and Passenger Modelling:** Buses stop at bus stops to load and unload passengers. Different levels of demand (distribution of bus passengers) cause different degrees of delay on the bus journey, and the demand grows when there are traffic congestions. It can be simulated by modelling the distribution of waiting time at bus stops.
5. **Background Traffic:** Traffic of other vehicles (non-buses) may cause congestions on the road and thus incur delay on the bus journey. Background traffic can be simulated with vehicles with random origins and destinations following a random walk or sight-seeing trip models.

IV. NODE CONNECTIVITY METRICS

To characterize the effect of mobility on the connectivity graph (topology) and thus explain the effects of mobility on protocol performance, we develop based on [1] the *Number of Connected Node Pairs*, *Path Duration*, *Number of Connected Periods*, and *Fraction of Connected Time* metrics for evaluation of node connectivity.

The connectivity graph is the graph $G = (V, E)$, such that $|V| = N$, where N is the number of nodes in the network. And at time t, a link $(i, j) \in E$ iff $D_{i,j}(t) \leq R$, where $D_{i,j}(t)$ denotes the Euclidean distance between nodes i and j at time t, R is the transmission range of a mobile node. Let $X_k(i, j, t)$ be an indicator random variable such that

$$X_1(i,j,t) = \begin{cases} 1 & \text{if } D_{i,j}(t) \leq R \\ 0 & \text{otherwise} \end{cases}$$

where $k \geq 1$ is an integer which denotes the number of hops of the communication path.

$X_k(i, j, t) = 1$ if and only if $X_1(i, r_1, t) = 1$, and $X_1(r_1, r_2, t) = 1$, … ,and $X_1(r_{k-1}, j, t) = 1$, where $r_1, r_2, \ldots, r_{k-1}$ are relay nodes; AND $X_1(i, j, t) = 0$, and $X_2(i, j, t) = 0$, … ,and $X_{k-1}(i, j, t) = 0$. Otherwise, $X_k(i, j, t) = 0$.

Specifically, $X_k(i, j, t) = 1$ means that nodes i and j are connected with at least one k-hop path at time t, given that they cannot be connected with less than k hops at time t.

1. **Number of Connected Node Pairs (*k*-hop):** We denote it as P_k. It is the number of node pairs i, j that have ever been connected with at least one k-hop path throughout the simulation period. Specifically, P_k is the number of node pairs i, j such that $X_k(i,j) = \sum_{t=0}^{T} X_k(i,j,t) \neq 0$.

2. **Number of Connected Periods (*k*-hop):** The number of connection periods of the k-hop path between a pair of nodes i and j is the number of times the path status between them change from 'down' to 'up'. Formally,

$$CP_k(i,j) = \sum_{t=0}^{T} C_k(i,j,t) \quad \textbf{(1)}$$

   Where $C_k(i, j, t)$ is an indicator random variable such that $C_k(i, j, t) = 1$ iff $X_k(i, j, t-1) = 0$ and $X_k(i, j, t) = 1$. That is, if the k-hop path between nodes i and j is down at time $t-1$, but comes up at time t.

   Average Number of Connected Periods (*k*-hop) is the average value of $CP_k(i, j)$ over the number of k-hop connected node pairs P_k. We have,

$$\overline{CP_k} = \frac{\sum_{i=1}^{N}\sum_{j=i+1}^{N} CP_k(i,j)}{P_k}$$

3. **Path Duration (*k*-hop):** It is the average duration of the k-hop path existing between two nodes i and j. It is a measure of the stability of the path. Formally,

$$PD_k(i,j) = \begin{cases} \dfrac{\sum_{t=0}^{T} X_k(i,j,t)}{CP_k(i,j)} & \text{if } CP_k(i,j) \neq 0 \\ \sum_{t=0}^{T} X_k(i,j,t) & \text{otherwise} \end{cases} \quad \textbf{(2)}$$

   Average Path Duration (*k*-hop) is the average value of $PD_k(i, j)$ over the number of k-hop connected node pairs P_k. We have,

$$\overline{PD_k} = \frac{\sum_{i=1}^{N}\sum_{j=i+1}^{N} PD_k(i,j)}{P_k}$$

4. **Fraction of Connected Time (*k*-hop):** It is the ratio between the total amount of time that a pair of nodes i and j are connected with the k-hop path throughout the simulation period and the amount of time that nodes i and j co-exist in the network. Formally,

$$FT_k(i,j) = \frac{\sum_{t=0}^{T} X_k(i,j,t)}{CT(i,j)} \quad \textbf{(3)}$$

   Where $CT(i, j)$ denotes the amount of co-existed time of nodes i and j in the network.

   Average Fraction of Connected Time (*k*-hop) is the average value of $FT_k(i, j)$ over the number of k-hop connected node pairs P_k. We have,

$$\overline{FT_k} = \frac{\sum_{i=1}^{N}\sum_{j=i+1}^{N} FT_k(i,j)}{P_k}$$

V. PERFORMANCE EVALUATION OF NODE CONNECTIVITY IN VEHICULAR NETWORKS

In this section, we present the VANET simulation of a bus network with GrooveNet, we installed GrooveNet on a machine running Suse Linux 10.1, and we have customized GrooveNet to output the set of metrics presented in the previous section for studies of node connectivity in vehicular networks.

In Subsection A, we begin from comparing the most commonly used random waypoint mobility model with a more realistic transport model with road constraints and car following. After that, we present results of the bus network simulation with different density of buses by varying the number of bus routes and inter-arrival time of buses in Subsection B. Furthermore, we consider in Subsection C the impact of traffic signals and background traffic on network connectivity, and finally we extend the transmission range of vehicles and see how much improvement in connectivity can be achieved in Subsection D.

Note that we do not include all parameters described in Section III in this simulation. Due to the space limit, we just extract parameters that would bring apparent impacts on the network connectivity in this paper. It is part of the future work to investigate the actual impact of other different traffic phenomena on vehicular network, in order to understand which elements must be considered and which can be neglected for a confident VANET study.

A. Comparison of Unconstrained Random Waypoint and Road-Constrained Car-following Models

In order to study the impact of road topology and car following, we compare them with the commonly used random waypoint model. The random waypoint model is implemented in the simulator as an unconstrained mobility model where vehicles choose a random direction, travel at a speed s for a duration d and paused for a duration p before choosing another random direction to traverse. We choose s to be uniformly distributed between 25 and 35miles/hour, d=20 seconds and p=1 second. On the other hand, vehicles using the car-following model [10] with road constraints are not permitted to go over each other. They use the random walk trip model and are constrained to drive on the streets at the speed limit which is between 25 and 35miles/hour. Initially, 80 vehicles are distributed randomly in a 4km^2 area, the transmission range of vehicles is fixed to be 200m.

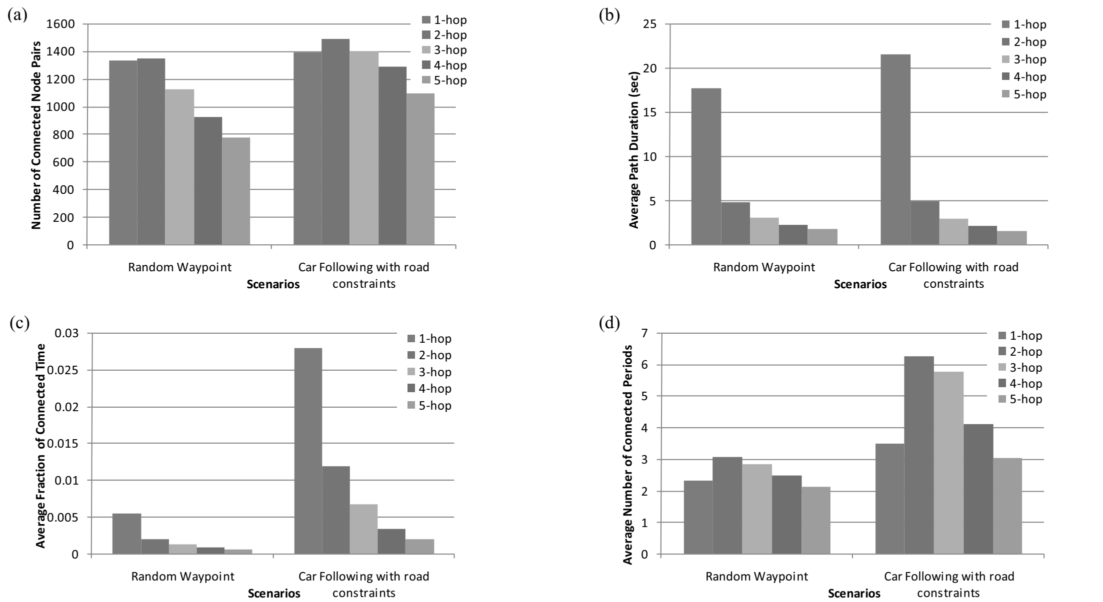

Figure 3. a) Total number of connected node pairs; b) average path duration; c) average fraction of connected time; and d) average number of connected period of unconstrained random waypoint model and car-following model with road constraints.

Figure 3 compares the node connectivity metrics of communication paths from one to five hops in the two scenarios. From Figure 3a, the constrained model has more number of connected node pairs than the unconstrained one, the difference is especially noticeable for paths more than three hops. We can see from Figure 3b that the two scenarios have similar results in terms of average path duration, except that the constrained model has about 20% longer path duration for single-hop links. However, there are significant differences in terms of the fraction of connected time and number of connected periods between the two according to Figure 3c and Figure 3d, the constrained model has an average fraction of connected time about 5.7 times larger than that of the unconstrained model. With respect to the number of path status changes, the constrained model has about 70% more number of connected periods than the unconstrained one.

The above results imply that communication path between two vehicles is more likely to be re-connected once it got disconnected in the constrained car-following model than the unconstrained random waypoint model. This gives rise to the significant difference in the average fraction of connected time for the two cases. Therefore, *node connectivity in the unconstrained model is rather instantaneous and one-time, while for the constrained model, it is more sustainable and multiple-time.* As a result, the connectivity graph in conventional unconstrained random waypoint model is fundamentally different from that of the constrained car-following model. In addition, with the consideration of other transport-related elements such as traffic signals and background traffic, it may produce even more dramatic differences in the connectivity graph.

B. Intersection of Bus Routes

In Figure 4a, we can see the visualization of the road network in GrooveNet simulator with vehicles on it. The red vehicles denote buses with communication capability, they use a Dijkstra trip model to move from their origins to destinations. When background traffic is enabled, we can see the black vehicles which denote other vehicles without communication capability, they act as obstacles of the traffic flow of buses, and they use a sightseeing trip model to wander around the region.

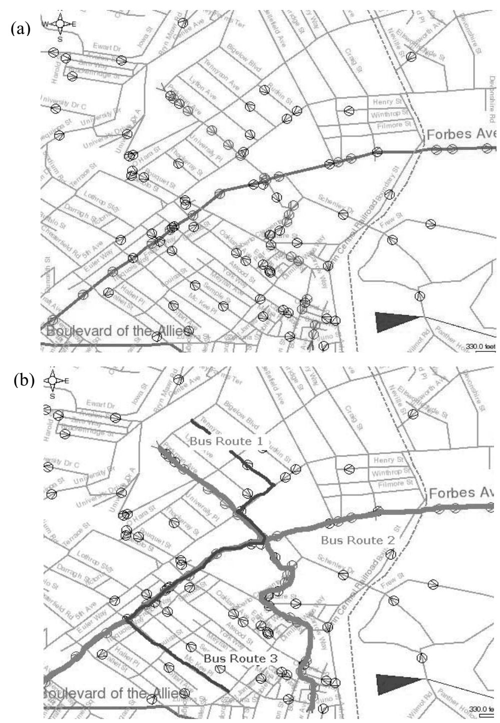

Figure 4. a) Map for bus network simulation; and b) simulated bus routes.

(a)

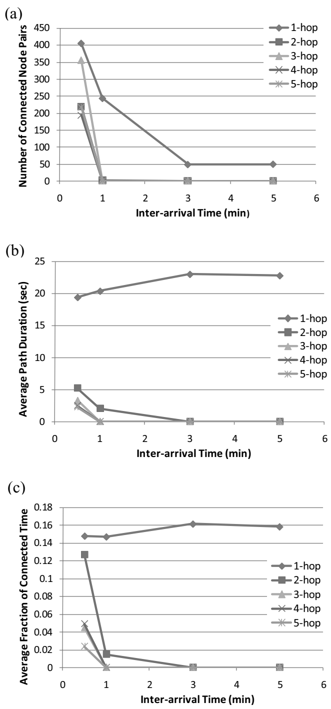

Figure 5. a) The total number of connected node pairs; b) average path duration; and c) average fraction of connected time for the scenario with one bus route.

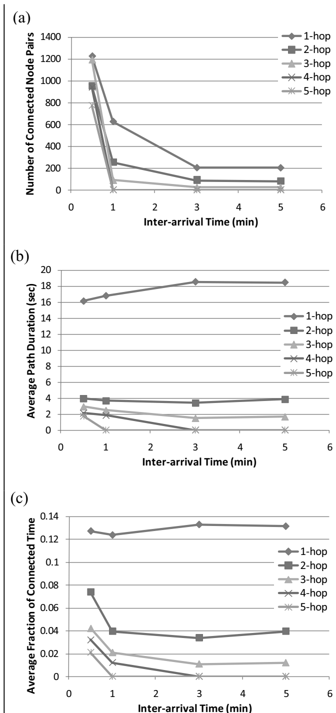

Figure 6. a) The total number of connected node pairs; b) average path duration; and c) average fraction of connected time for the scenario with two bus routes.

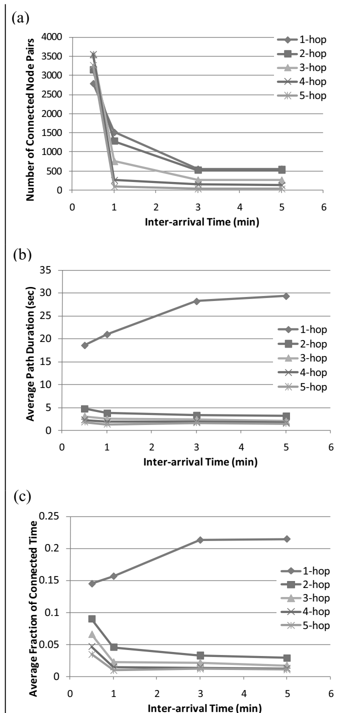

Figure 7. a) The total number of connected node pairs; b) average path duration; and c) average fraction of connected time for the scenario with three bus routes.

All vehicles on the road employ a car-following model [10], where a vehicle will not exceed the speed of a vehicle in front. A vehicle that is determined to be a leader vehicle will use a general acceleration model such as street speed model. With the street speed mobility model, vehicles always move within user defined range (e.g. +25%, -25%) of the speed limit of the road, where the speed limit of roads varies from 20 to 40miles/hour.

We try to increase the number of bus routes from one to three to study the effect of bus routes intersection on network connectivity. As indicated in Figure 4b, Bus Route 1 runs from north to south, Bus Route 2 runs from west to east, and Bus Route 3 runs in such a way that it has intersections with both Bus Routes 1 and 2. All of the bus routes are running bi-directionally, and for each direction of the bus route, we generate 50 buses and vary the inter-arrival time of buses from 30sec to 5min, and record the node connectivity metrics in the network. The transmission range of buses is fixed to be 200m.

Figures 5, 6, 7 show a) the total number of connected node pairs; b) the average path duration; and c) average fraction of connected time for scenarios with one bus route (Bus Route 1), two bus routes (Bus Routes 1 and 2), and three bus routes (Bus Routes 1, 2 and 3) respectively. Note that traffic lights and background traffic are not considered in this simulation, they are studied in the next subsection.

From Figures 5a, 6a and 7a, we observe that as the inter-arrival time of buses increases (node density decreases), the number of connected node pairs decreases for all scenarios, which aligns with our general understanding. However, in Figures 5b, 6b, 7b and 5c, 6c, 7c, we find that longer inter-arrival time gives longer average path duration and larger fraction of connected time for single-hop links. This implies that the additional paths formed in high density cases (e.g., for inter-arrival time of 30sec) are relatively unstable (i.e., with short path duration), which pull down the average value of path duration in the network. From Figure 5b (the one-bus-route case), we can also know that the average duration of paths established between buses moving in reverse directions is about 23 seconds (where speed limit of streets is between 20 and 40miles/hour), since communications between buses in the same direction is not possible when the bus density is low (e.g., for inter-arrival time of 3min or 5min).

Furthermore, the number of connected node pairs increases significantly as the number of bus routes increases from one to three. For example, the number of single-hop links increases from around 50 to 500 (ten times more) for inter-arrival time of 3min or 5min. However, additional paths formed with more bus routes may not be stable, *the path stability depends highly on the topological nature of the bus routes*. For example, the average path duration and average fraction of connected time of single-hop links decrease when we increase the number of bus routes from one to two. This is because Bus Routes 1 and 2 intersect only at a junction (according to Figure 4b), paths established between buses in the two routes is relatively short-lived, which pull down the average duration of communication paths in the network. While with Bus Route 3 added, both parameters increase, this is because the intersections of Bus

Route 3 with Bus Routes 1 and 2 provide capacities to buses to establish paths with longer life time.

In general, *we can see a dramatic drop in the average path duration and average fraction of connected time when the path is more than one hop*. For example in the three-bus-route scenario, the average path duration and average fraction of connected time of single-hop links are respectively about seven times and four times larger than those of two-hop paths. With number of hops more than one, we can only achieve an average path duration of no more than 4 seconds, and the average fraction of connected time is below 5%.

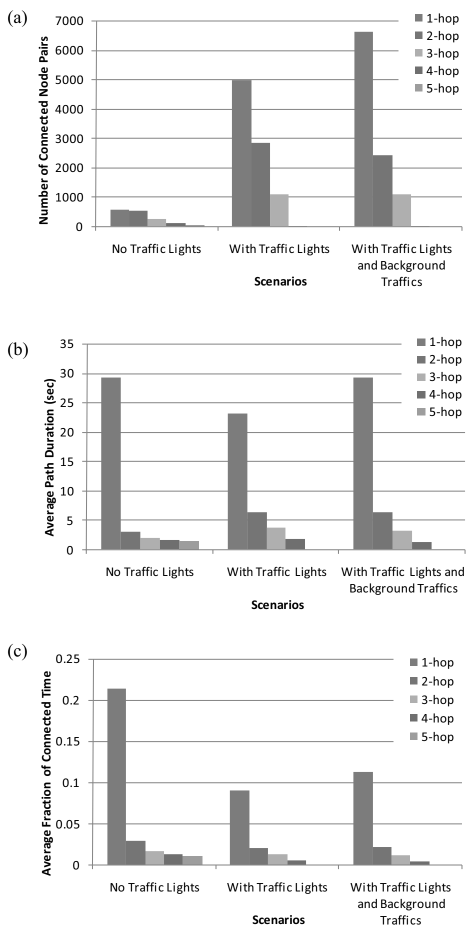

Figure 8. The influences of traffic lights and background traffic on a) total number of connected node pairs; b) average path duration; and c) average fraction of connected time for the simulation scenario with three bus routes, bus inter-arrival time of 5min.

C. Traffic Lights and Background Traffic

Other than the intersection of bus routes, we would also like to look at the influences of traffic lights and other background traffic on network connectivity.

Figure 8 shows the simulation results of the three-bus-route network with bus inter-arrival time of 5min. They include the scenarios with i) no traffic lights nor background traffic; ii) with traffic lights only; and iii) with both traffic lights and background traffic. Traffic lights are located at road junctions, and the mechanism of the traffic signal used is a simple one at this stage, it consists of 30 seconds of green period followed by 30 seconds of red period. For background traffic, we generate 100 vehicles moving with sight-seeing model around the bus routes region as shown in Figure 4a. For sight-seeing model, vehicle randomly walks until it is a certain distance (e.g., 1km) from the starting point; the vehicle then takes the shortest path back to the starting point and starts again along a different path.

With traffic lights, we can see that the number of connected node pairs increases significantly (more than nine times for single-hop links), this is due to the bunching of vehicles caused by the traffic signals. We can also observe that the average fraction of connected time decreases by a much larger amount than the average path duration. For multi-hop paths, the average fraction of connected time decreases even if the average path duration increases. This implies that the amount of delay incurred on the bus journey by traffic signals is longer than the amount of connected time lengthened due to the bunching of buses at traffic lights.

With the presence of background traffic, further delay will be incurred on the bus routes by other vehicles. We can see that it favours the connection of single-hop links, the number of single-hop links further increases by 33%, and the average path duration and average fraction of connected time for single-hop links also increase by more than 25% when background traffic is introduced. But its influence on multi-hop paths seems negligible.

However, even considered traffic signals and background traffic, there is still a great degradation in performances (in terms of average path duration and average fraction of connected time) when the communication path is more than one hop. Specifically, the average path duration and average fraction of connected time are reduced by respectively four times and three times when the number of hops increases from one to two. On average, we can only achieve less than 9 seconds of average path duration for two-hop paths and less than 4 seconds for paths with three or more number of hops in the scenario with traffic lights and background traffic.

D. Variation of Transmission Range

We try to increase the transmission range of vehicles, and see if this can improve the node connectivity. Figure 9 shows the results of the three-bus-route network with bus inter-arrival time of 5min, we increases the transmission range from 200m to 500m. From Figure 9a, the number of connected node pairs does not further increase when we increase the transmission range beyond 350m. This is because the total number of buses that co-exist in the network is restricted by the bus inter-arrival time and distances of the bus routes, increasing the transmission range beyond certain point therefore cannot cover more number of nodes.

We can see from Figure 9b and Figure 9c that both the average path duration and average fraction of connected time of single-hop links increase linearly as the transmission range increases. With a transmission range of 500m, single-hop links can achieve an average path duration of more than 50 seconds. However, those parameters for multi-hop paths are not scalable with the transmission range, both the average path duration and average fraction of connected time get saturated when we increase the transmission range beyond 350m. According to Figure 9b and Figure 9c again, for paths with two hops or more, even if we increase the transmission range to 500m, we can only achieve less than 6 seconds of average path duration and less than 8% of connected time.

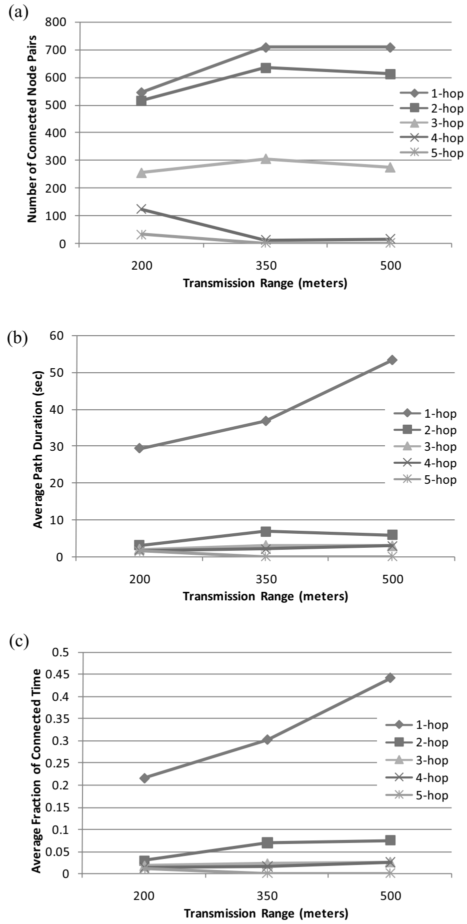

Figure 9. The influences of transmission range on a) total number of connected node pairs; b) average path duration; and c) average fraction of connected time for the simulation scenario with three bus routes, bus inter-arrival time of 5min.

VI. CONCLUSION AND FUTURE WORK

Predominated mobility models in MANET studies are not appropriate in VANETs. These models can generate unreliable results as they do not adequately model real-world vehicular macroscopic and microscopic motions. To facilitate cross-layer designs for VANETs, deriving mobility model that captures realistic vehicle motions and understanding its impact on network connectivity is of paramount importance. Overall, the main contributions of this paper are three-fold:

1. We have presented an analytical framework for realistic VANET studies, including a list of parameters that capture vehicular macroscopic and microscopic motions, elements for bus network studies, and metrics for evaluating node connectivity in vehicular networks.
2. We have shown by simulation that commonly used mobility models, such as random waypoint, produce dramatically different node connectivity metrics in the network than mobility model that captures road constraints and car following. Moreover, we have demonstrated through a bus network simulation the impact of the topology of bus routes, traffic signals and background traffic on network connectivity. Specifically, the number of connected node pairs increases significantly by more than nine times when traffic lights are introduced.
3. We have shown by simulation that multi-hop paths have much poorer connectivity statistics than single-hop links in vehicular networks. Using the statistics of the bus network simulation with three bus routes, traffic lights and background traffic as benchmark (Table 1), single-hop links have relatively stable performance with an average path duration of 30 seconds and average fraction of connected time of 13%. While for multi-hop cases, two-hop and three-hop paths can only achieve respectively 8.1 seconds and 3.8 seconds of average path duration, and 4.3% and 1.8% of average fraction of connected time. Even if we increase the transmission range of vehicles, multi-hop connectivity cannot be improved.

Table 1. Degree of connectivity of communication paths with different number of hops for the scenario with three bus routes, traffic lights and background traffic. Speed limit of streets varies between 20 and 40miles/hr.

	1-hop	2-hop	3-hop	4-hop
Average path duration (sec)	29.98	8.10	3.78	2.74
Average fraction of connected time	12.72%	4.27%	1.77%	1.55%

Given the relatively short link duration, a key message is that *it is inappropriate to rely on using multi-hop links to support real-time applications in the mobile platform networks*. Such kind of knowledge of the performance of multi-hop transmission will be significant for the studies of routing algorithm and other networking functions in vehicular networks. Moreover, it is part of the future work to investigate non-real-time node connectivity as well, since certain routing algorithms may allow buffering of packets for transmission upon the communication path is available. Multi-hop transmission may be feasible for such kind of delay-tolerant applications (e.g., collection of sensor data in a day).

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