Access Point Placement in Vehicular Networking [*]

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Abstract – Providing wireless networking to vehicles has been identified as a near-term goal by the automotive industry in the support of basic Internet access as well as an enabler to a variety of safety enhancement applications. Network connectivity to on-board computers can be provided via existing mobile telephony; however, these systems rely on both expensive infrastructure (cell towers) and a strongly hierarchical and high-latency network model. In contrast, a short-range, multihop mode of communication can exploit the localization of information generation/consumption of vehicular data applications, and the need for low-latency in safety ones. In practice, both models have their merits and we seek to understand the best mix of fixed roadside infrastructure ("access points") and use of multihop connectivity.

In this paper, we consider the problem of access point placement in a hybrid vehicular networking environment comprised of multihop communication over moving vehicles supported by access points. Particularly, we consider varying vehicular traffic densities and various access point separations, under the assumption of delay tolerant messaging. We extend previous work on analytical modeling of message propagation in delay tolerant vehicular networks absent any infrastructure to study the average delay in cases with fixed infrastructure. Our simulation results depict various design choices as a function of vehicular traffic density, physical radio characteristics and vehicle speed. We show that large access point separations are possible in a hybrid scheme that supports multihop networking. The performance is dominated by vehicular traffic density. We demonstrate that under delay tolerant networking assumption, minimum delay and and maximum propagation rates can be achieved for low vehicular traffic densities of 20 vehicles/km. A path based messaging scheme would achieve similar performance at 40 vehicles/km.

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1 INTRODUCTION

IEEE 802.11p – also called WAVE (Wireless Access for Vehicular Environments) [1] provides required standards and protocols to enable vehicle to vehicle and vehicle to infrastructure communication. Vehicle manufacturers aim to enhance the vehicle ownership experience by providing additional features such as remote diagnostics, in-vehicle Internet access, enhanced safety and the like. Future vehicle networks are envisioned to enable a variety of applications that will ease and possibly transform travel [2, 3]. Consortia such as PATH (The Partners for Advanced Transit and Highway), C2CC (Car-To-Car Consortium) and NOW (Networks on Wheels) [4, 5, 6] are leading efforts to integrate vehicles in the information and technology framework.

Infrastructure such as access points or cellular towers provide connectivity for vehicles to the backbone Internet. The deployment of infrastructure is essential to bridge the inherent network fragmentation that exists in any multihop network formed over moving vehicles. Our goal here is to understand the impact of vehicle traffic densities and multihop assumptions on access point separation. A large separation implies, on average, greater message transmission delay. While smaller separations would incur greater cost penalty in equipping the large network of roadways. Authors in previous works [7, 8, 9] have shown that there is a relationship between the vehicular traffic density and the message propagation rates. We build upon existing work to demonstrate that substantially large access point separations are possible under the assumption of delay tolerant and multihop networking.

In this paper, we model a scenario of delay tolerant networking between vehicles traveling on a highway equipped with road-side units. The authors in references [7, 8, 10] model message propagation in an infrastructure-less ad hoc network. We extend the model to include infrastructure such as access points that provide backbone connectivity to the vehicles. To this end, we model the average message transmission delay given there is possibly a lack of instantaneous connectivity between vehicles and access points. We describe the parameter transmission delay as the time taken by message originating at a vehicle to reach an access point. We demonstrate that under the assumption of delay tolerant networking, on average, minimum delay and maximum propagation rates can be achieved at a relatively low density of 20 vehicles/km. While path formation based schemes such as AODV (Ad hoc On-Demand Distance Vector routing) or DSR (Dynamic Source Routing) require 40 vehicles/km for comparable performance. We discuss the placement of access points in the context of delay constraints and vehicular traffic density. Our results show that the average delay is a function of access point placement, while the average propagation rate is independent of the access point placement and is a function of the vehicle traffic density. These results are significant in that they establish that substantial functionality can be provided even with low infrastructure cost if vehicles are enabled with multihop capability.

The remainder of the paper is organized as follows – Section 2 describes the related work. In Section 3, we describe the vehicular networking environment and the corresponding observations and assumptions to build our network model. In Section 4, we describe the simulation model and the parameters while the results are described in Section 5. We conclude the paper and summarize our results in Section 6.

2 RELATED WORK

Consortia such as PATH (The Partners for Advanced Transit and Highway), C2CC (Car-To-Car Consortium) and NOW (Networks on Wheels) [4, 5, 6] have been formed to organize government, industrial and academic efforts to improve safety, enhance travel experience and bring information services to the traveler. WAVE (Wireless Access for Vehicular Environments) [1] is the IEEE 802.11p draft under development to define standards and protocols to enable communication between vehicles (V2V) and between vehicles and other infrastructure (V2I).

Delay tolerant networks (DTNs) [11], also known as Intermittently Connected Mobile Networks or Opportunistic Networks, are characterized by periods of connectivity interspersed with periods where nodes are largely disconnected. Delay tolerant networking has found several applications in inter-planetary space communications, mobile ad hoc networks and sensor networks. Performance modeling in the context of ad hoc networks, particularly delay and throughput effects is of particular interest. An important observation is the absence of end-to-end connectivity in vehicular networks owing to the unique characteristics of vehicle mobility and time-varying vehicular density. While existing mobility models such as the Freeway and Manhattan model capture the mobility of vehicles along restricted pathways, they do not adequately reflect the fragmented connectivity.

In the context of vehicular networks, DTN messaging has been proposed in previous work [8, 9, 12, 13]. The authors in refs. [7, 10] propose a model for evaluation of delay tolerant networking in vehicular networks. The model gives bounds on the performance of messaging in a vehicular network absent any infrastructure. The work demonstrates the gains achieved by delay tolerant messaging and the minimum density requirements. The model is essentially an infinite linear network and evaluates long-run average performance. In contrast, a network with access points is a finite case with unique messaging. In ref. [9], the authors have evaluated vehicle traces on the highway and demonstrated that they closely follow exponential distribution of nodes. The work demonstrates network fragmentation and the impact of time varying vehicular traffic density on connectivity and hence, the performance of messaging.

The UMass DieselNET project explores the deployment of communication infrastructure over campus transportation network and records measurements on opportunistic networking [14]. Wu et al. have proposed an analytical model to represent a highway-vehicle scenario [8]. In their approach, they investigate speed differential between vehicles traveling in the same direction to bridge partitioned network of vehicles. An important distinction in our work is that we consider bidirectional connectivity which is intuitively faster due to the speed differential in traffic moving in opposing directions. In our work, we evaluate the impact of access point placement on the average delay in messaging between vehicles and access points deployed at fixed points.

3 NETWORK MODEL

There are three main models for communication in a vehicular network. The first is the ad hoc model in which vehicles form nodes of an ad hoc network; an infrastructure model in which nodes are connected to infrastructure such as cellular towers; and a hybrid model where vehicles form an ad hoc network supported by infrastructure such as road-side units (access points). In this paper, we consider the hybrid model in which access points are placed at fixed positions in the network.

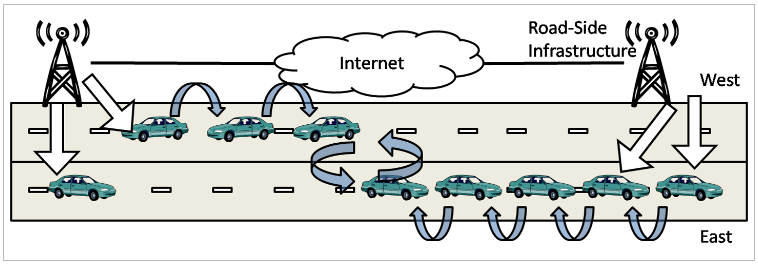

Figure 1: Hybrid model of vehicular network

The access points provide connectivity to the backbone network. Note that here we generalize the access point concept to cellular towers, WiFi, or other emerging technology. However, we parametrize the performance of the access point in terms of radio characteristics. We concentrate on the low traffic density, low data rate scenario and consider high density, high data rate as future work. Thus, nodes are assumed to be perfect relays and there is no delay associated with data buffering.

Vehicular Networking Environment

The network environment modeled is determined by the highway scenario – vehicles travel in either direction on bidirectional roadway. The highway is modeled as essentially linear. Vehicles are assumed to be equipped with communication, computation and storage capabilities such that they form nodes of a mobile ad hoc network (MANET). We consider a fixed transmission range radio model, of radius R, such that, two vehicles are able to communicate with each other, if their separation is less than R. Vehicles are assumed to be point objects, i.e., we do not consider the length of a vehicle in our analysis. For this work, we also do not consider the effect of mobility on the transmission range, rather we adopt a conservative approach in assigning the range R in our analyses. Vehicles are assumed to be traveling at a constant rate (v m/s). Vehicles leave and join the network at random, though we do not explicitly model this event. A roadway is annotated *eastbound* and *westbound* for convenience in the narrative. But much more complex scenarios such as curvature in the roadway and intersections are resolved using attributed (labelled) data as shown in related work [12]. Essentially, by embedding location information from GPS sensors in data packets the roadway can be simplified into a bidirectional linear model.

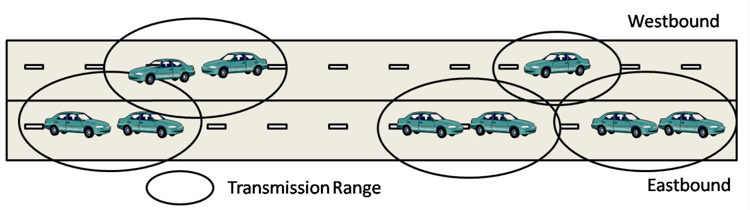

Figure 2: Illustration of fragmentation in the network

Access points in this model are deployed at regular intervals of L m such that $L > R$. Thus, vehicles are not always in direct contact with an access point. They can potentially connect to an access point using multihop connectivity over other vehicles located on the roadway. In the analysis, we model only the delay in messaging from a vehicle to an access point. The characteristics of the access point are not investigated in this paper. As data are attributed with location information, the direction of vehicle travel becomes irrelevant to the location of access point. A vehicle can forward data to an access point located in either direction relative to its location. This model is illustrated in Figure 1.

Fragmentation of the Network

Nodes in a vehicular network are highly mobile and thus, the network topology is highly dynamic especially when opposing lanes of traffic interact. Often the network will be fragmented into many disconnected sub-networks. However, the time-varying nature of the topology also indicates reconnection at future times. This characteristic is found to be both a hindrance and an opportunity.

Snapshots of real-time traffic data have shown that vehicles tend to travel in clusters that are disconnected from each other in terms of radio connectivity [15]. Furthermore, vehicular traffic density varies between the extremes of sparse and dense traffic scenarios depending upon the time of the day [9]. It can be shown analytically, that for an exponential distribution of vehicular traffic, there is a non-zero probability that consecutive nodes are disconnected.

In the event of fragmentation, consecutive nodes in one direction of the roadway are separated by a distance greater than transmission range, R. Under the assumption of constant velocity, this partition is constant. The traffic in opposing direction can be utilized to *bridge* this gap. It has been shown in [10] that expected time (delay) until the partition is bridged can be computed. The partition between two consecutive nodes *eastbound* is bridged when n consecutive nodes *westbound* are found, as shown in Fig. 3. This is analogous to the *pattern matching* problem as described in [16]. The expected number of trials until a pattern is found is given by:

$$E[N] = \frac{1 - p^n}{(1 - p)p^n} \tag{1}$$

where p is the probability that a single event is successful. It has been shown in [7] that the result in Eqn. (1) can be used to evaluate the time until connectivity to the next available hop is achieved.

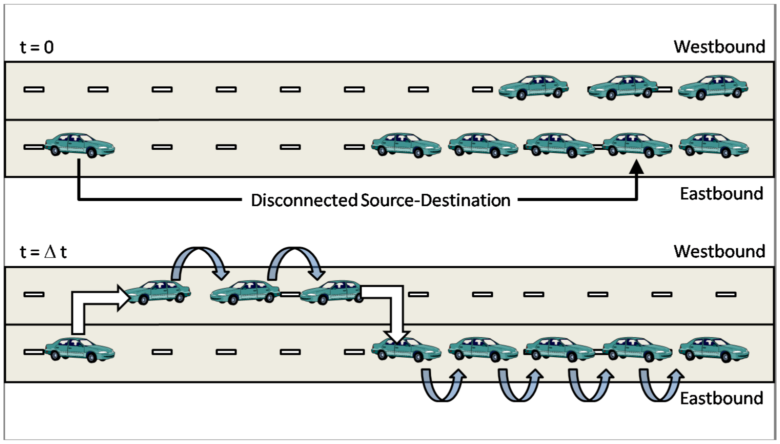

Figure 3: Illustration of delay tolerant messaging paradigm

We define the propagation rate as the time taken (delay) to cover the physical distance between a vehicle and an access point. As a result of delay tolerant messaging, the data propagation effectively alternates between two phases. In the absence of connectivity, the data are propagated as the vehicle travels at speed v m/s. When vehicles are connected multihop, data are able to propagate at the speed of the radio (v_{radio} m/s). We define a parameter radio speed (v_{radio}) as the rate at which a message is propagated by the radio. Given the radio range R, and considering propagation and transmission delays as τ, $v_{radio} = R/\tau$. In modeling the delay parameter τ, we account for latencies due to the link state and due to the protocol. Thus, the radio propagation speed is a value lessor than the theoretical speed which is comparable to the speed of light. For the purpose of the analysis, $v_{radio} >> v$.

Thus, the average propagation rate (v_{eff}) is a function of the time spent in these two phases. Analytically, denote T_1 as the time spent propagating as the vehicle travels and T_2 as the time spent propagating multihop at radio speed. The effective propagation rate is an alternating renewal process [16] where message propagation cyclically alternates between phase 1 and phase 2. The long-run fraction of time spent in each of these states is respectively:

$$p_1 = \frac{E[T_1]}{E[T_1] + E[T_2]}; \qquad p_2 = \frac{E[T_2]}{E[T_1] + E[T_2]}. \tag{2}$$

From Eq. (2), it follows that –

$$\begin{aligned} v_{eff} &= p_1 v + p_2 v_{radio} & (3) \\ &= \frac{E[T_1]v + E[T_2]v_{radio}}{E[T_1] + E[T_2]}. & (4) \end{aligned}$$

It has been shown in ref. [7] that $E[T_1]$ and $E[T_2]$ are functions of the vehicle traffic density on either direction of the roadway, the physical radio characteristics (R, v_{radio}) and the vehicle speed (v).

4 Simulation Model

We consider the highway model of the vehicular networking environment in which vehicles travel in either direction of a bidirectional roadway. The bidirectional roadway is annotated with *eastbound* and *westbound* directions. The vehicles are assumed to be exponentially distributed on the roadway in each direction with parameter λ_e and λ_w for *eastbound* and *westbound* respectively. The exponential distribution of nodes allows us to exploit the memoryless property. As vehicles travel with a constant velocity of $v = 20$ m/s, the separation between consecutive nodes remains constant. The access points are assumed to be placed at regular intervals of L m, where $L > R$.

We consider a fixed transmission range model for the radio. The radio range is considered to be $R = 125$ m. We define a delay factor τ over a single hop for the radio. The delay includes propagation and transmission delays. We use a representative value of $\tau = 125$ ms. The message can propagate a physical distance of $R = 125$ m in time $\tau = 125$ ms, thus, the radio speed (v_{radio}) is 1000 m/s.

We generate traffic on one direction of the roadway, say the *eastbound* direction. Given the density λ_e, we are able to generate distance between consecutive nodes $X_e = \{x_1, x_2, x_3, \ldots\}$.

If consecutive nodes are connected, $X_e < R$, the messages are able to propagate multihop. In the absence of connectivity along the *eastbound* direction, the traffic along *westbound* direction is generated $X_w = \{x_1, x_2, x_3, \ldots\}$ distributed with parameter λ_w. Here, we consider symmetric densities on each side of the roadway, asymmetric traffic is considered as future work. The connectivity along *westbound* to the next hop *eastbound* or an access point is sought. In the absence of instantaneous connectivity, the message propagates a physical distance as it is carried by the vehicle. Thus, we are able to compute the distance, the delay and the propagation rate associated with the message as it is propagated through the network.

For the purpose of the simulation, we consider traffic densities ranging from 1 vehicle per km to 100 vehicles per km which cover the range of low, medium and heavy vehicle traffic densities.Vehicles are assumed to be moving at a constant rate of 20 m/s. The access point placement is varied from 5000 m to 15000 m, with transmission range $R = 125$ m.

5 PERFORMANCE RESULTS

The objective of this paper is to study the network formed by moving vehicles and to analyze the placement of access points in the network especially in the context of delay tolerant networking. The propagation rate alternates between vehicle speed and multihop radio speed, and the average is a function of time spent in each phase. Correspondingly, the average delay is a function of the vehicular density, the separation between the access points and the physical layer characteristics of the radio such as transmission range and multihop radio speed.

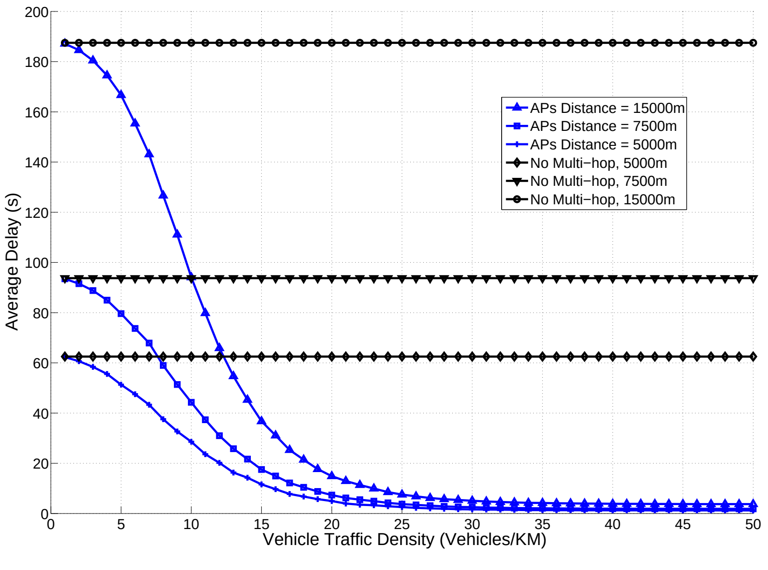

Figure 4: Simulation results – Average delay over various separations of access point placements

Fig. 4 shows simulation results for the average delay for a packet, originating at a vehicle, to reach an access point given the parameters of transmission range, vehicular speed and vehicular traffic density. When the traffic density is sparse, messages are unable to propagate multihop. The messages are stored and carried as the vehicle traverses the roadway, thus, the delay is of the order of time taken by vehicle to physically move to the access point. At the other extreme, when the

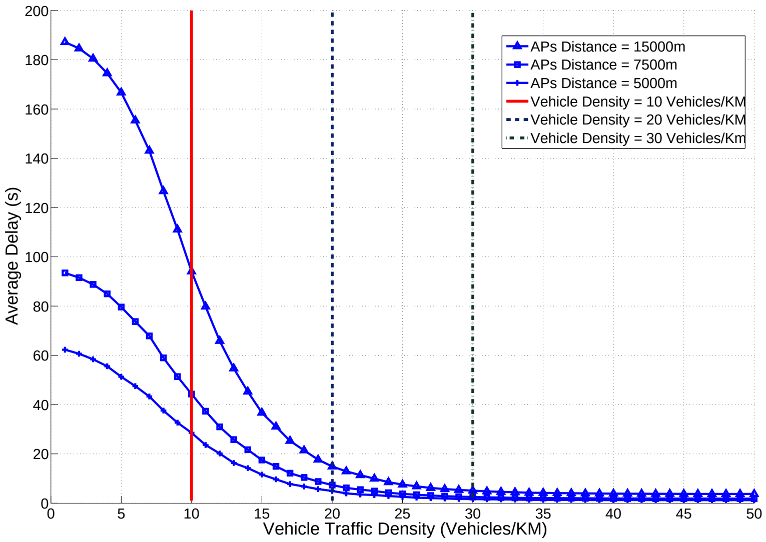

Figure 5: Simulation results – Average delay over various separations of access point placements

network is dense, there is end-to-end connectivity between the vehicle and the access point and the delay is of the order of time taken for the message to propagate multihop to its destination. In the intermediate density case, messages propagate along vehicles in the absence of connectivity and multihop whenever opportunistic connectivity is available.

The horizontal lines denote the delay in the absence of multihop connectivity. In a scenario in which there are no vehicles or the communication model does not allow multihop propagation, the delay is the time taken to cover the physical distance. For a separation of 5000 m, the average delay is 62.5 s as the vehicle travels at 20 m/s. Correspondingly, the delay for an access point separation of 15000 m, the average delay is 187.5 s. The contrast emphasizes the design choice for message delay as quality of service constraints demand limits over the delay.

Fig. 5 shows simulation results for the average delay for a message as the vehicular traffic density changes. However, in this graph we focus on the design choice of access point placement with respect to traffic density. The vertical lines signify the vehicular traffic density. As observed from the graph, the average delay for various access point separations varies significantly when the traffic density is between 10 vehicles/km and 20 vehicles/km. Correspondingly, the average delay is less discernible for vehicular traffic density between 20 vehicles/km and 30 vehicles/km. Thus, given prior knowledge about the traffic on a roadway, the access points can be placed farther apart.

Fig. 6 shows a comparison of the average propagation rates for different scenarios. The propagation rate is a long-run average of the physical distance covered by the message per unit time. As we described previously, the message alternates between multihop propagation rate and vehicle propagation rate, the average rate is the result of the proportion of time spent in each phase. The average propagation rate for different separations of access point placement is essentially the same. We compare the simulation results with analytical bounds for the network in the absence of infrastructure developed in previous work [12]. The results show that the propagation rate under the delay tolerant networking assumption is a function of vehicular traffic characteristics and the physical radio. Importantly, it is largely independent of the access point placement. Thus, the average rate for various access point separation remains the same.

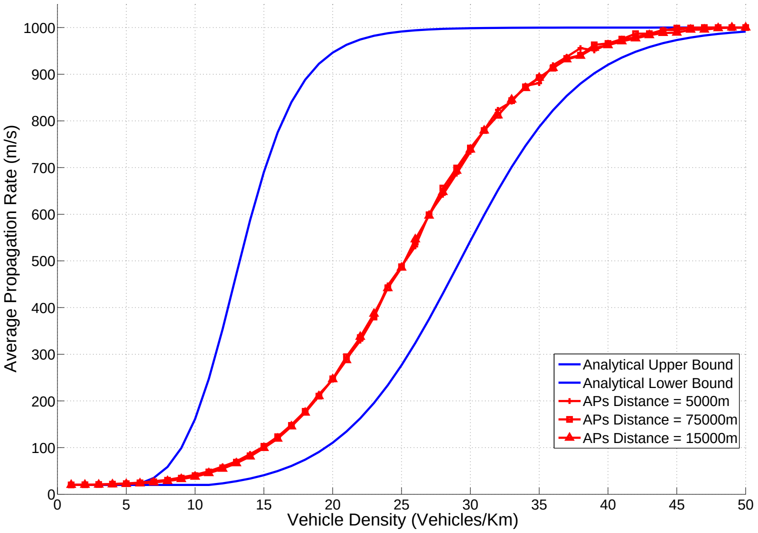

Figure 6: Simulation results – Average Propagation Rate

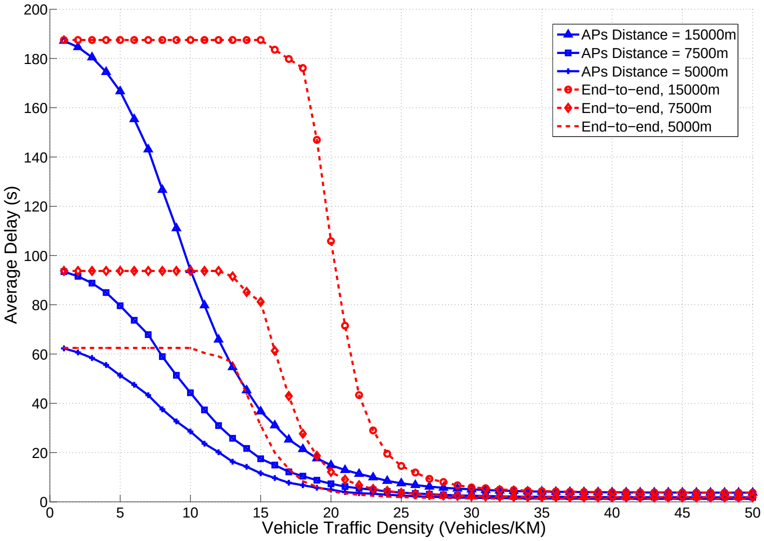

Figure 7: Simulation results – Comparing delay for DTN and end-to-end connectivity

Fig. 7 shows a comparison of the average delays for delay tolerant networking and a strategy involving end-to-end connectivity. In a strategy involving end-to-end connectivity, the network is considered disconnected unless there is an instantaneous end-to-end path between the access point and the vehicle. For low density scenarios, the network is mostly disconnected, the delay associated is the time taken by the vehicle to cover the distance between the access points. As density increases, however, the network becomes fully connected, the delay is equivalent to the multihop propagation delay. When averaged over several iterations and varying densities, we observe that as the access point separation increases, the density required to obtain end-to-end connectivity, on average, increases. For example, for an access point separation of 5000 m the network is likely to be fully connected at 20 vehicles/km, while for 15000 m, the network is not likely to be fully connected until there are 30 vehicles/km on either side of the roadway. In contrast in the delay tolerant networking paradigm, there are gains achieved in the absence of end-to-end connectivity and the corresponding density requirements are significantly lower. This is to support our argument for the application of delay tolerant networking when considering access points in the network.

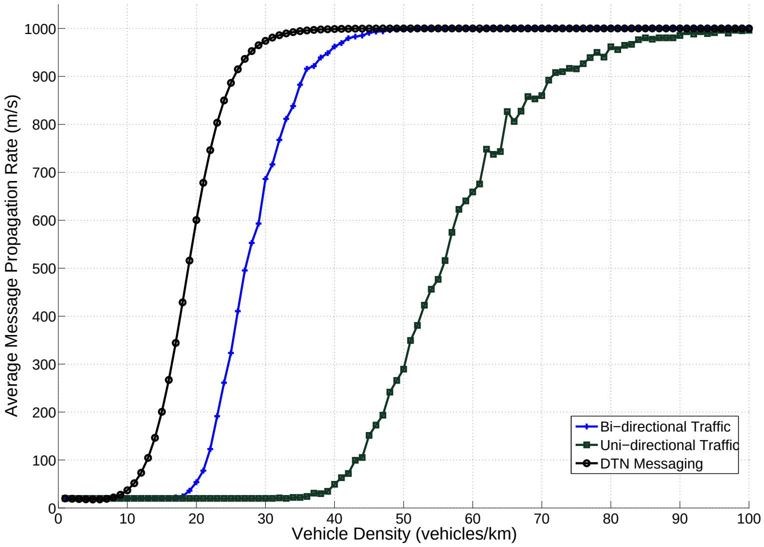

Figure 8: Simulation results – Comparing performance of DTN and end-to-end bi-directional and uni-directional messaging over a distance of 12.5 Kms

In Fig. 8, we show simulation results for the average propagation rate for a message, comparing the scenarios of end-to-end connectivity and delay tolerant networking paradigm. In the first scenario, we assume a network utilizes a routing protocol based on path formation strategies. Only nodes that are traveling in the same direction participate in forwarding messages to a destination that lies 12.5 km beyond the point of origin. Thus, the requirement is for a connected cluster of length 12.5 km, given exponentially distributed traffic. For sparse density cases, the network is likely to be disconnected, the average propagation rate is the vehicle speed 20 m/s. For high density of vehicular traffic, the network is likely to be fully connected and it is possible to achieve propagation at the rate of multihop propagation as defined by the radio-to-radio speed of 1000 m/s. It is noteworthy that the averaged results show that a traffic density of greater than 40 vehicles/km is needed to realize any connectivity in the average case, while a density of close to 90 vehicles/km

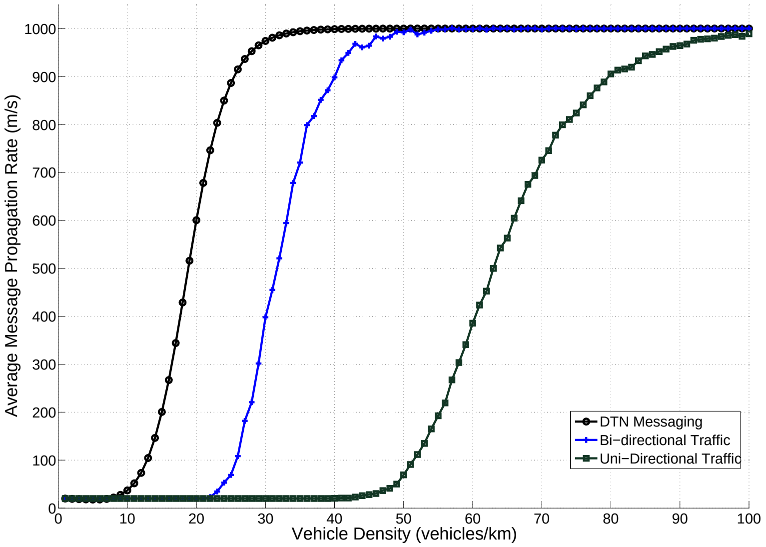

Figure 9: Simulation results – Comparing performance of DTN and end-to-end bi-directional and uni-directional messaging over a distance of 30 Kms

is needed, on average, to be fully connected. The results are averaged over several iterations. We consider random distribution of nodes along the roadway, some scenarios yield connectivity while others do not.

The second scenario models end-to-end connectivity assuming traffic on both sides of the roadway participate in connectivity. Consequently, the traffic density requirements in each direction are approximately halved. However, the connectivity over bi-directional traffic is transient as vehicles are moving in opposite directions. Thus, a path is extremely short-lived. In the delay tolerant networking paradigm, gains are achieved at relatively low density of 15 vehicles/km and maximum propagation rates are achieved at traffic density of 30 vehicles/km. The gains are achieved by virtue of the store-carry-forward scheme that exploits opportunistic connectivity and does not rely on end-to-end connectivity.

Fig. 9 shows the same three scenarios, however, in this graph the distance of separation is increased to 30 Km. For a larger separation the density requirements are significantly increased for the end-to-end connectivity constraint. In this case, the network, on average, is not fully connected unless there are 50 vehicles/km on each side of the roadway. For Fig. 8, the separation is 12.5 km, the network is connected at 40 vehicles/km, either side of the roadway. However, considering the delay tolerant networking paradigm, the extended distance has little effect over the fragmentation and opportunistic connectivity, hence, the density requirements are the same. Thus, in this scenario the gains offered by delay tolerant networking paradigm over end-to-end connectivity are even greater when the source-destination pairs are separated by a larger distance. This strengthens our argument for the application of delay tolerant networking in the context of vehicular networks.

6 DISCUSSION AND CONCLUSION

We considered a highway with regularly-placed roadside network access points bridged by multihop in-vehicle networking. We demonstrate performance gains under the assumption of delay tolerant networking paradigm versus path-based topology formation schemes that require end-to-end connectivity. The gains are due to exploitation of intermittent connectivity. Path formation based schemes require end-to-end connectivity which is hard to achieve given the fragmented network and the high mobility rates. The DTN scheme is able to perform well at low densities of 20 vehicles/km. Maximum propagation rates are achieved at densities of 40 vehicles/km. For comparable performance, path-based strategies require much higher density, a requirement that increases with greater access point separation. Thus, larger access point separations are possible in a cost effective, yet efficient, network.

Our results demonstrate delay as a function of vehicular traffic density, vehicular speed, physical radio characteristics and access point separation and are suitable for evaluating network design strategies. Based on knowledge of traffic density one can design to achieve specific delay or infrastructure cost targets. Moreover, parameters in the messaging protocol, such as TTL (time-to-live), can be suitably modified given knowledge of expected delays or access point separation. The impact on vehicular network applications is beyond the scope of this work. We concentrate on modeling messaging, while the performance of applications is dependant on several factors such as application scope, range and data exchange.

Finally, we demonstrate that the results are consistent with previous work involving pure multihop message propagation in the absence of access points. The average propagation rate is largely independent of the access point placement for most cases, except for very low density of vehicular traffic. The difference is attributed to the finite distance between access point placement. This correlation between the two results allows us to extend our analytical model for the finite case including infrastructure.

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