Analysis and Design of Vehicular Networks

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by

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Contents

Summary

There has been increasing interest in the exploitation of advances in information technology in surface transportation systems. One trend is to exploit on-board sensing, computing and communication capabilities in vehicles, e.g., to augment and enhance existing intelligent transportation systems (ITS). There are several possible network architectures to organize these in-vehicle computing systems. Three alternatives include a pure wireless vehicle-to-vehicle (V2V) ad-hoc network, a wired backbone with wireless last-hop, or a hybrid architecture using V2V communications to augment roadside communication infrastructures for improved performance, reliability, and functionality. An understanding of network properties, e.g., delay, loss rate, throughput, etc., is necessary to evaluate alternate network architectures before new applications can be successfully deployed. Based on this understanding, data services (e.g. dissemination services) can be designed to accommodate application requirements.

Disseminating information using V2V communications is required by both the “ad hoc” and “hybrid” architectures. In this research, we first study performance limits of spatial propagation of information using V2V communications. Analytical models are developed to study relatively simple vehicle traffic scenarios in order to discover the important characteristics influencing information propagation. Simulation studies using realistic traffic models are used to evaluate more complex vehicle traffic scenarios. Based on these studies, we argue that opportunistic forwarding is a viable approach for data dissemination in applications that can tolerate some data loss and delay. We develop a generic approach for designing opportunistic forwarding in vehicular networks. Based on this generic approach, two opportunistic forwarding algorithms, MDDV and optimistic forwarding, are derived. MDDV leverages vehicle traffic information to identify a group of vehicles to actively forward the message in order to improve reliability. Optimistic forwarding designates a message owner to forward the message. Experiments with proof-of-concept in-vehicle systems are planned to validate simulations and demonstrate the viability of the proposed approach.

The limitations of V2V communications lead us to consider infrastructure-based wireless network architectures, e.g., hybrid and wireless last hop (only) architectures. Work is planned to compare various design options through simulation studies using realistic traffic models.

1 INTRODUCTION

1.1 Vehicular Networks

Interest in the exploitation of advances in information technology (e.g., mobile computing and wireless communications) in surface transportation systems [3, 11, 12, 15, 19, 26-28] has been growing in recent years. An emerging trend is to equip vehicles with computing and communication capabilities, e.g., to augment and enhance existing intelligent transportation systems (ITS). For example, the FCC has allocated 75MHz of spectrum at 5.9GHz for Dedicated Short-Range Communications (DSRC) [2] between vehicles and from vehicles to roadside facilities.

In-vehicle computing systems allow the coverage of monitoring systems to extend beyond the extent of infrastructure-based sensors, e.g., roadside cameras that are expensive to deploy and maintain. Subject to privacy considerations, in-vehicle sensors offer the potential for much more detailed, accurate information (e.g., on-road vehicle activity and emissions) than would otherwise be possible, enabling new ways to improve and optimize the transportation system as well as support a variety of commercial applications. In-vehicle computing systems facilitate the customization of information services to the needs and characteristics of individual travelers. Cooperation between vehicles can reduce the end cost of user services. Possible applications designed to benefit from these in-vehicle computing systems can be generally classified as safety and non-safety applications. Safety applications include, e.g., collision avoidance and cooperative driving [12] [26]. Non-safety applications include traffic information propagation [28] [19], toll service, Internet access [3], tourist information, cooperative gaming and entertainment, etc.

1.2 V2V Networks

A V2V network consists of instrumented vehicles equipped with on-board computing and wireless communication devices, a GPS device enabling the vehicle to track its spatial and temporal trajectory, a pre-stored digital map, and optional sensors for reporting crashes, engine operating parameters, etc. *Not* every vehicle is assumed to have this capability. Due to the gradual nature of market penetration, only a fraction of the vehicles on the road may be instrumented. Specifically, the term “penetration ratio” is defined as the fraction of vehicles on the road that are instrumented. Only instrumented vehicles participate in the V2V system. In the remainder of this thesis, by default the term “vehicles” refers to instrumented vehicles only.

Vehicles exchange information with other vehicles within their radio range, and ad hoc wireless networks are used to propagate information. A V2V network is a special type of ad hoc network. Some unique characteristics [15] [23] that differentiate V2V networks from other types of ad hoc networks include:

- Predictable high mobility - Vehicles often move at high speed, but once on the road their mobility is rather regular and predictable. Vehicles move along roads that are spatially constrained, and travel is constrained (at least to some extent) by traffic regulations, e.g., maximum and minimum speeds.

- Dynamic but geographically constrained topology - On the one hand, the interconnection between vehicles can change quickly due to their high mobility. But on the other hand, the road often limits the network topology to one dimension, and the road network is static. One can think of a V2V network as an overlay network on top of the road network. Roads are usually either located far away or close but there are obstacles (e.g., buildings), which generally prevents wireless signals from traveling between roads except near intersections.
- Potentially large scale - Unlike most of the ad hoc networks studied in the literature that usually assume a limited area, V2V networks can in principle extend as far as the road network provided there is a sufficient density of vehicles.
- Partitioned network - Dousse et al. [5] show that the probability of end-to-end connectivity decreases with distance for one-dimensional network topologies whereas end-to-end connectivity is often implicitly assumed in much of the research in ad hoc networking. The commercial success of V2V networks depends on gradual market penetration. The network is more likely to be partitioned with a low penetration ratio. This observation is also confirmed by our analytical models [23] and simulation studies [25].
- Vehicles are not completely reliable and dependable. They may fail in unpredictable ways.

- No significant power constraints - The power issue often assumed for mobile devices and sensor networks is usually not a constraint for V2V networks because vehicles can provide continuous power to computing and communication devices.

1.3 Wireless Technologies

Wireless communication is one of the enabling technologies for vehicular networks. Depending on their coverage, wireless technologies can usually be categorized as Wireless Wide/Metro Area Networks (WWAN/WMAN), Wireless Local Area Networks (WLAN), and Wireless Personal Area Networks (WPAN) in order of decreasing coverage.

WWAN often have large coverage areas (up to 20 km), and offer relatively low throughput. The second generation (2G) systems (AMPS, TACS) can provide less than 10 kbps of circuit switched data. 2.5G systems (GSM-GPRS, GPRS-136) offer less than 100 kbps packet switched data. 3G systems aim to offer data rates as high as 384 kbps outdoor and 2 Mbps indoors.

WLAN (e.g., IEEE 802.11x, HiperLan) are probably the most widely deployed wireless networks. They have limited cell coverage (~200 m) but relatively high bandwidth (e.g., 802.11g provides data rates of up to 54Mbps).

WPAN (e.g., Bluetooth) are primarily designed for networking personal devices and hence provide low data rates and transmission ranges (low power).

WWAN typically work in infrastructure mode with fixed base stations serving as access points, i.e. all communications must go through access points. WLAN can work either in infrastructure mode or ad hoc mode. In ad hoc mode, mobiles can relay packets for each other and no network infrastructure is needed, allowing them to be readily deployed in environments such as battlefields and disaster relief sites.

1.4 Vehicle Traffic Flow Theory

Vehicular networks consist of highly mobile computing devices. It is natural to study the impact of vehicle mobility, which is often addressed with vehicle traffic flow theory [9] in transportation research, in the design of vehicular networks. In this section, we introduce some of the basics of vehicle traffic flow theory.

The three most important characteristics of vehicle traffic are flow q (vehicles/hour), speed u (km/h) and density k (vehicles/km) [9]. The average values of these quantities can be related with the basic traffic stream model $u = q / k$. With few vehicles on the roadway, the density approaches zero and speeds approach the free flow speed. As additional vehicles use the roadway, traffic density increases and flows increase toward a parabolic maximum. As demand exceeds roadway capacity, traffic densities approach a “jam density” limit, where vehicles are very close together but barely moving. The actual relationships are much more complex, but can be readily modeled in simulation models such as CORSIM [8] and INTEGRATION. These and other simulation models employ car following theory to implement vehicle-vehicle interactions and track the motion of individual or platoons of vehicles. In cases where simulation models cannot be employed due to a lack of data, flows can be characterized with discrete distributions such as Poisson (for low-density traffic), negative binomial (for varying flow), and binomial distribution (for congested flow); time headways between the arrivals of vehicles may be represented with an exponential, shifted exponential, Erlang, or normal distribution; the distribution models for speeds are usually normal or lognormal.

Traffic monitoring is commonplace in most major urban areas. Given the importance of minimizing congestion, major metropolitan areas expend millions of dollars per year to monitor freeway speeds and flows in an effort to identify and remove disabled vehicles from the roadway. Traffic characteristics can be measured at a spot, along a length, or by a moving observer.

Traffic density can be measured through the measure of *lane occupancy*, which is defined as $R_1 = \frac{\text{sum of lengths of vehicles along a roadway section}}{\text{length of the roadway section}}$. Given lane occupancy, density can then be computed using $k = \frac{\text{lane occupancy}}{\text{average vehicle length}}$. Because it is difficult to use on-line methods to measure the sum of the lengths of vehicles in a road section, time measurements are developed to estimate lane occupancy. Presence detectors, including induction loops, magnetometers, ultrasonic reflectors, and photo cells, are placed at a spot to count the time when the vehicle detector is occupied and the number of vehicles crossing the detector during the observation period: $R_2 = \frac{\text{sum of time vehicle detector is occupied}}{\text{time of observation period}}$.

From satellite imagery, it is possible to count the number of vehicles N on a road segment of distance l_s. Density can be obtained using $k = N / l_s$. With two (or more) aerial photos taken in sequence with a short time interval Δt between them, one can compute the speed of individual vehicles and then obtain the mean speed.

An old but effective method to measure traffic along an arterial is the moving observer method [17] [18]. An observer (or observers) in a moving vehicle first travels with the traffic flow being measured and then returns in the opposite direction along a road section. The traveling time in both trips is recorded. For the trip with the traffic flow, the number of vehicles that pass the observation vehicle and the number of vehicles passed by it are recorded. For the trip in the opposite direction, the number of vehicles encountered is recorded. Suppose t_c is the traveling time with the traffic flow, t_a is the traveling time against the traffic flow, x is the number of vehicles encountered while moving against the traffic, y is the net number of vehicles that pass the observer while moving with the traffic flow, and l_s is the road length, it can be shown that: $q = \frac{x + y}{t_a + t_c}$, $u = \frac{l_s}{t_c - y/q}$, and $k = \frac{q}{u}$.

A simplified moving observer method can be used for a vehicle to estimate the traffic flow in the opposite direction [13]. The observer counts the number of vehicles encountered in the opposite direction along a road section. Flow is calculated using $q = \frac{x}{l_s(\frac{1}{v_1} + \frac{1}{v_0})}$ where v_1 is the speed of oncoming vehicles, v_0 is the speed of the observer, l_s is the road length, and x is number of encounters.

1.5 Research Contributions

Through this research, we make several contributions:

- *Spatial propagation of information using V2V communications.* We study the propagation of information along roads. We have developed analytical models to predict information propagation speeds for relatively simple traffic scenarios. A simulation study using realistic traffic models was conducted to evaluate more complex traffic scenarios. The results show that information propagation relies largely on vehicle traffic conditions.

- *Data dissemination using V2V communications.* This is required by both the "ad hoc" and "hybrid" architecture. We argue that opportunistic forwarding is a viable approach for data dissemination in applications that can tolerate some data loss and delay to exploit vehicle mobility and address the problem of vehicular network partitioning. We have developed a generic approach for designing opportunistic forwarding in vehicular networks. Based on this approach, two opportunistic forwarding algorithms, MDDV [22] and optimistic forwarding [4], are derived. Evaluation and comparisons of these algorithms are conducted using simulations. Experiments with proof-of-concept in-vehicle systems are now beginning, and will be completed as part of this dissertation's research.
- *Comparison of various infrastructure-based design options.* The performance limits of V2V communications lead us to consider infrastructure-based options for designing vehicular networks, e.g., hybrid and wireless last hop (only) architectures. On-going work is evaluating these various design options using realistic vehicle traffic models.

1.6 Roadmap for This Document

The rest of the document is organized as follows. Section 2 describes the analytical models for spatial propagation of information using V2V communications. Section 3 describes a simulation study for the spatial propagation of information. In Section 4, we present the design of opportunistic forwarding for data dissemination using V2V communications. In Section 5, we identify several infrastructure-base wireless architectures and propose to evaluate their performance.

2 ANALYTICAL MODELS FOR SPATIAL PROPAGATION OF INFORMATION

An understanding of network properties, e.g. delay, loss rate, throughput, etc., is necessary in alternate network architectures before new applications can be successfully deployed. As stated in [1], information theory research should be conducted to understand the performance limits of wireless networks, with the goal of designing systems to reach these performance limits. In this section, we examine the feasibility of V2V communications. Specifically we examine the spatial propagation problem: *how fast can information propagate along a specific road?* Stated another way, what is the average delay to propagate a message from location A to location B along a specific road using only V2V communications? The answer to this question can help address issues such as how far traffic information can propagate before becoming obsolete. We discuss this problem largely in the context of ad hoc V2V networks, but our analysis is also applicable in hybrid architectures when addressing data dissemination beyond the fixed infrastructure.

The spatial propagation problem requires special consideration in V2V networks because V2V networks are typically partitioned. However, information can propagate across partitions by exploiting vehicle mobility.

We employ a data propagation scheme in a general sense. We call a vehicle *informed* if it carries the information being propagated. When an uninformed vehicle enters the radio range of an informed one, it becomes informed after a time *tr*. The road is represented as a one-dimensional corridor. We study how a message propagates in the direction in which the vehicle is traveling along the road. The *message head* at time t refers to the informed vehicle with the largest position coordinate while the *partition tail* refers to the uninformed vehicle with the smallest position coordinate. We examine a free-flow vehicle traffic model: traffic passing an arbitrary point on the road follows a Poisson process; each vehicle travels with an average speed that is selected from a random distribution bounded by v_{max} and v_{min}, and vehicles move independently at their chosen velocity. This model is employed to enable closed-form solution of the quantities of interest. We believe that this model, though simplified, captures the dynamics of vehicle interactions and allows one to discover important characteristics that significantly influence the rate of information propagation.

Examination of the information propagation process reveals that a message propagates in either one of two modes termed the *forward mode* and *catch-up mode*. The forward mode involves the propagation of the message within a partition via multi-hop forwarding; the message travels quickly through a partition hop-by-hop until it reaches the frontmost vehicle in that partition. In the catch-up mode the message moves along with its carrying vehicle until it comes within the radio range of the tail of another partition. Due to limited vehicle speed, we expect the propagation speed in the catch-up mode to be much slower than in the forward mode. When information propagates along the road, it alternates between the forward and catch-up phases, resulting in a cyclic process.

We first design models for one-way vehicle traffic. In a sparse network (low instrumented vehicle density), the message propagation is modeled as solely depending on vehicle movement and we derive the distribution of the message propagation distance as a function of time t. For dense networks (high instrumented vehicle density), the message propagation process is modeled as a renewal reward process and we compute the long-term average message propagation speed. The catch-up phase and the forward phase are studied separately. During the catch-up phase, our model shows that the message head accelerates while the partition tail decelerates so that eventually the message head can catch up to the next uninformed partition that lies ahead. For networks between "sparse" and "dense", our models provide good bounds. The notational relationship between our models and expectations is illustrated in Figure 1.

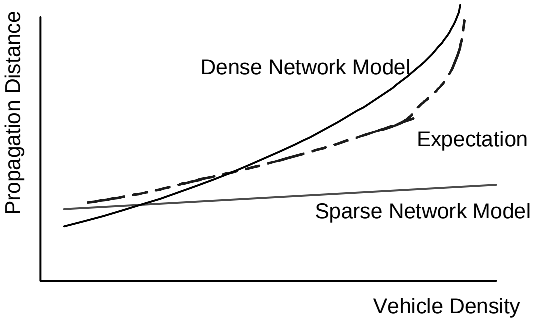

Figure 1: Model Relationship

We further extend one-way traffic models to cover two-way traffic and general road networks.

These models reveal several vehicle traffic parameters significantly influencing message propagation: vehicle density, average vehicle speed, and relative speed among vehicles. These models lead to some interesting discoveries, e.g. a message can propagate in the opposite direction as the traffic flow, and can propagate much faster than the movement of vehicles. They can also explain the observations made by Chen et al. [4].

Two simulations are conducted to validate our analytical models. In the first simulation, as a proof of concept, we apply the same assumptions as the analytical models. The second simulation is driven by the vehicle movement trace from a microscopic traffic simulator -- CORSIM. In both simulations, we model information propagating along a road segment with one-way traffic. The predictions from our models approximate those obtained from the first simulation while the results from the second simulation highlight the need to include other vehicle traffic models.

Details of this work are found in [23, 24].

3 A SIMULATION STUDY OF SPATIAL PROPAGATION OF INFORMATION

This section examines potential message propagation performance on a Freeway Corridor by exploring the rate at which messages may traverse a section of the I-75 corridor in Atlanta, Georgia, using V2V communications, under different traffic volumes and varying fleet penetration ratios. Details of this work are found in [25].

We build a distributed simulation test bed to perform this study, which consists of two different commercial simulation packages running in a distributed fashion over multiple networked computers. CORSIM [7] is a microscopic traffic simulator that simulates vehicle interaction, traffic flow, and congestion. The Run-Time Extension (RTE) facility available in CORSIM was utilized to extend the functionality necessary to operate the simulator in a distributed manner. For the wireless network simulation, QualNet [14] was used to model and simulate inter-networking aspects such as ad-hoc wireless protocols and radio propagation.

The study area for this research effort is the I-75 corridor in the northwest quadrant of Atlanta, Georgia, traversing I-75 from the I-85 interchange to the south to the I-285 interchange to the north. The research group led by Dr. Randall Guensler and Michael Hunter of Georgia Tech built two CORSIM models to model traffic conditions in the evening peak hour and midnight. These models incorporate extensive geometric and operational data from government partners. A general data propagation scheme as described in the previous section was adopted in this study. The spatial propagation of information southbound along I-75 for a distance of 6 miles is simulated for this research effort. Vehicle traffic in both directions is exploited in relaying the message. The primary metrics collected include end-to-end (E2E) delay and number of partitions (a partition is a collection of vehicles interconnected by wireless links) traversed.

Several observations may be made based on the simulation results:

- V2V communication is a feasible way for propagating information along the I-75 freeway in the Atlanta metro areas, as well as other roadway systems with similar traffic characteristics as Atlanta during peak or high traffic density periods. The propagation performance depends largely on the density of instrumented vehicles along the end-to-end (E2E) path, which is a function of the traffic flow rate and fleet penetration ratio. With a sufficient penetration ratio and traffic flow rate, information can quickly propagate through the system. Rapid message propagation during low traffic density periods, i.e. nighttime, present challenges and may require some additional mechanism to support communications, e.g., roadside relays.
- The simulation methodology described here allows one to determine a necessary penetration ratio for effective communication given the traffic density, and application requirements. For example, when rapid message propagation is desired during the evening peak, a penetration ratio of approximately 0.2 is sufficient for efficient information propagation.
- The message propagation delay is unpredictable except when vehicle density becomes saturated. A particular delay may be well below or above the average depending on traffic conditions. For applications requiring highly reliable, minimal

message propagation times, it may be necessary to design networks that provide extra support to avoid such variations. For example, to reduce path vulnerability roadside relays could supplement the communication infrastructure in critical areas. Or, a subset of vehicles could be equipped with cellular messaging systems, through which critical information could be reliably relayed. For applications where immediate data dissemination is not critical, other non-fixed-infrastructure based solutions may be explored. For example, vehicles can be instructed to cache information and when up-to-date information is not available, the most recently cached information can be used.

- E2E connectivity is possible with a high density of instrumented vehicles or a slightly lower density but a shorter propagation distance. This observation allows some insights for designing data dissemination algorithms. Algorithms assuming E2E connectivity [16] are suitable only for a high density of instrumented vehicles or short propagation distances. Opportunistic forwarding algorithms relaxing E2E connectivity [21] can adapt to a wider spectrum of traffic conditions.

In the previous section, our analytical models reveal several traffic characteristics, which significantly affect information propagation, e.g., (instrumented) vehicle density, average vehicle speed and relative speed among vehicles. Our work so far primarily focuses on the impact of traffic volume and fleet penetration ratio on information propagation. More scenarios will be examined in the future to study other characteristics and traffic conditions, e.g., vehicle speed, relative vehicle movement, crashes, etc.

4 OPPORTUNISTIC FORWARDING

Deployment of applications on vehicular networks requires the support of data dissemination services. Data dissemination concerns the transport of information to *intended receivers* while meeting certain *design objectives*, e.g., high delivery ratio. In this section, we study how to disseminate information using V2V communications. Because infrastructure-less vehicular networks are typically partitioned (or at least are not continuously connected), store-and-forward message switching is often adopted. In Delay-Tolerant Network research [6], store-and-forward message switching is proposed to overcome the problems associated with intermittent connectivity, long or variable delay, and high error rates. Since future vehicle contacts are usually unpredictable, vehicles must communicate during opportunistic contacts. This leads us to believe that opportunistic forwarding, i.e. vehicles buffer received messages until opportunities for forwarding present themselves, is a viable approach to disseminate information for applications that can tolerate some data delay and data loss. In vehicular networks, opportunities to forward messages are created by vehicle movement. Thus, it is natural to consider how to leverage vehicle mobility information, which is often addressed with vehicle traffic flow theory [9] in transportation research, in designing data dissemination services.

We first identify four types of data dissemination services: unicast, multicast, anycast and scan, which have immediate application in Intelligent Transportation System (ITS) applications. We address our design by reference to a test scenario, geographical-temporal multicast. All the services mentioned above can be easily covered with extensions of the design for this test case. Geographical-temporal multicast is formally defined as: *deliver a message to all vehicles* *in/entering region r before time t while the data source s is outside of r* (see Figure 2 for an example).

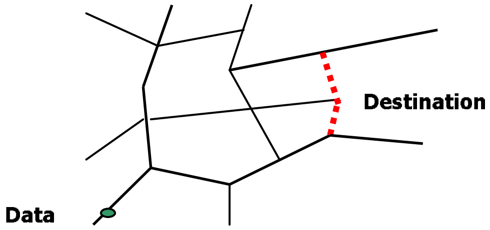

Figure 2.**Geographical-Temporal Multicast**

The data dissemination algorithms discussed in this section combine opportunistic forwarding, geographical forwarding, and trajectory based forwarding. A directed forwarding trajectory is specified extending from the source to the destination (*trajectory base forwarding*) in the road graph, along which a message will be moved geographically closer to the destination (*geographical forwarding*) during opportunistic contacts *(opportunistic forwarding)*.

Given the performance of current onboard ITS technologies, we assume a vehicle has knowledge of the road topology through a digital map and its own location in the road network via a GPS device. We also assume vehicles know the existence of their neighbors through some link level mechanism. But **we do *not* assume vehicles automatically share sufficient information such that each vehicle knows the exact identity spatial location of its neighbors** (unlike most geographic forwarding algorithms). In this way, a vehicle's knowledge of other vehicles is limited, in order to help alleviate privacy and security concerns.

Applications running on V2V networks are better to be designed using localized algorithms, i.e. nodes perform local operations and interact with neighbors while their collective behavior achieves some global objective. We develop a generic design approach for designing localized algorithms in vehicular networks. This design approach consists of four steps: specification of a desired global behavior, specification of an ideal scenario, definition of approximations to deal with incomplete and/or inaccurate information, and definition of local operations to implement approximations.

- **Global Behavior**. First, a directed moving trajectory is specified by the message source. The data dissemination process consists of two phases: the forwarding phase and the propagation phase. In the forwarding phase, the message is forwarded along the forwarding trajectory to the destination region. Once the message reaches the destination region, the propagation phase begins.
- **Ideal Scenario**. During the forwarding phase, the message holder closest to the destination region along the forwarding trajectory is called the “message head”. The vehicle taking the role of the message head may change over time as the message propagates or vehicles move. With perfect knowledge, every vehicle knows the message head vehicle in real time. In the ideal scenario, only the message head tries to pass the message to other vehicles that may be closer to the destination region.
- **Approximation**. The above ideal scenario cannot be implemented because vehicles do not have perfect knowledge of the entire system. Specifically, individual vehicles do not know which vehicle is the message head in real time. Some practical algorithm needs to be

designed to approximate the ideal scenario. MDDV [22] and optimistic forwarding [4] are two such algorithms.

MDDV identifies a *group* of vehicles near the real message head to actively forward the message instead of the message head vehicle only in order to improve reliability. The group membership changes as the actual message head moves toward the destination region. The design issues include the group identification (every vehicle has to decide whether it belongs to this group), data exchange protocol (when a message should be transmitted), and the decision to store/drop messages. Two sets of information are designed to help a vehicle decide whether it belongs to the group. First, vehicles are provided with the vehicle traffic information in the area of the message head. For example, if vehicle density is high, the group should be very close to the message head, or the group may spread further than is necessary. To this end, we present a framework to exploit vehicle traffic information, including online methods to monitor vehicle traffic, propagate vehicle traffic information and apply this information in the algorithm design. Second, vehicles are provided with some approximate knowledge of the message head location. For this purpose, a small amount of information, the message head location and its generation time collectively referred to as the *message head pair,* is placed in the message header. As the message is propagated among vehicles, so does the message head pair.

Optimistic forwarding is designed to closely approximate the ideal scenario. Each message is assigned an owner during the forwarding phase. Efforts are made to try to make the message head the owner. Only the message owner may transmit the message. Unlike the ideal scenario, the owner cannot be identified automatically but has to be transferred explicitly through communications. Optimistic forwarding was first described by Chen and Kung [4]. It assumed a vehicle knows the location of neighboring vehicles. We develop a contention based scheme for optimistic forwarding while relaxing this assumption. The contention based scheme works as follows. The current message owner attaches its current location in the message and sends the message as a request for contention. Vehicles receiving the message compare their own locations with the location specified in the message. If their locations are closer to the destination region, they join the contention and set a backoff timer. If a contender does not hear the message again before its backoff timer expires, it assumes it wins the contention and becomes the new message owner. Otherwise it drops its contention. The backoff time is computed with $t_{backoff} = (1 - \frac{d}{r}) * t_{max}$ where d is the distance to the sender, r is the radio range and t_{max} is the maximum backoff time. This means that a vehicle farther away from the sender set a shorter backoff timer and is more likely to win the contention. Therefore the ownership is transferred in a way to make the greatest progress.

We have conducted an extensive simulation using a vehicle traffic model and data corresponding to a portion of the Atlanta metropolitan area. We compare dissemination schemes, and study the design considerations of MDDV. The major metrics that we are interested in include delivery reliability, message overhead, and propagation delay.

Details are found in [20, 22]. Our future work is in two directions. First, we are going to do some scenario-based evaluation of the algorithms, e.g., along highways and in situations involving crashes. Second, experiments with proof-of-concept in-vehicle systems are planned to validate simulations and demonstrate the viability of the proposed algorithms.

5 INFRASTRUCTURE-BASED DESIGN OPTIONS

In the previous sections, we have explored the performance limits of V2V communications and V2V ad hoc networks. These limits principally come from lack of sufficient vehicle density, reliance on high vehicle mobility, and unreliable in-vehicle systems. Algorithms (e.g., replication, diversity, and opportunistic forwarding) can be designed to mitigate some problems so that V2V networks are able to support certain applications (e.g., coordinated driving). But for other applications, e.g., multimedia applications, V2V networks may not be able to offer required Quality of Service (QOS). Infrastructure-based vehicular networks (e.g., wireless last-hop and hybrid architectures) can help alleviate these problems by providing reliable relaying paths.

Infrastructure-based wireless technologies can usually be categorized as WWAN, WMAN, and WLAN ordered in decreasing coverage area. One inherent characteristic of all these technologies is that larger coverage leads to higher cost per bit. Usually high coverage comes with low data rate. For example, 3G networks can provide data rate of 384Kbps outdoors and 2Mbps indoors while WLAN networks, e.g., 802.11x, HiperLan, can provide much higher data rates (e.g., 802.11a and 802.11g are designed for the data rates of up to 54Mbps).

We use the following metrics to compare different design options for vehicular networks: continuous connectivity to infrastructures, throughput, investment and service cost. Hsieh et al. [10] address the wireless infrastructure design options for mobile users in general. Here we summarize the design options for vehicular networks:

- **WWAN last-hop.** Cellular-based WWAN are deployed to cover large areas. This deployment can provide continuous connectivity. The drawback of this approach is the limited data rates that can be provided to users. Thus it may not be able to offer the required throughput for a high density of vehicles. The service cost is also high since all the data traffic has to go through the WWAN infrastructure.

- **WLAN last-hop.** High-speed WLAN base stations are placed along the road. Users can experience high throughput within the coverage of WLAN base stations with low service cost. However this design has several drawbacks. First, the reach of WLAN base stations is usually limited. Thus such deployment typically cannot provide continuous connectivity (e.g., it may not be practical to set up WLAN base stations to provide complete coverage). Second, even though the cost of individual WLAN base stations is cheap the maintenance cost of large number of base stations is quite large.
- **Multi-hop WLAN.** This is an extension of the previous design. V2V communications are used to extend the reach of WLAN base stations. It is able to provide better coverage than the WLAN last-hop approach. But, due to the uncertainty of V2V communications, no continuous connectivity can be guaranteed.
- **WWAN last-hop + WLAN last-hop.** This is the combination of the two designs. WWAN can offer continuous connectivity and WLAN can provide users with high bandwidth with low service cost. With the added capacity provided by WLAN, this design can support more users than the WWAN last-hop approach.
- **WWAN last-hop + Multi-hop WLAN.** This is an extension of the previous design. V2V communications reduce the data traffic going through the infrastructure and also extend the coverage of WLAN base stations. Vehicles access these WLAN base stations either

directly or through the forwarding of other vehicles (we could limit the number of forwarding hops). For data traffic needing to go through the infrastructure, a vehicle tries to access WLAN base stations first to reduce the cost. When the connectivity with base stations is not there or the number of hops exceeds some threshold value, a vehicle will access the WWAN infrastructure directly. WWAN and WLAN facilities together provide a low cost solution to meet the collective communication demands of a large number of vehicles.

Next, we focus on evaluating the three design options that can provide continuous connectivity: WWAN last-hop, WWAN last-hop + WLAN last-hop and WWAN last-hop + WLAN multi-hop. Figure 3 illustrates notionally the expected throughput comparison of these three design options. WWAN can meet the demands of vehicle traffic at low density. WWAN + Single-hop WLAN can satisfy higher vehicle density. WWAN + Multi-hop WLAN would by far provide the most desirable properties. The service cost of these three options also decreases (Figure 4).

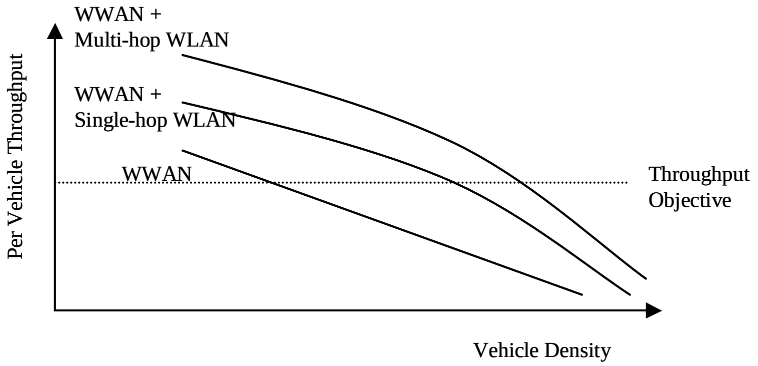

Figure 3. Throughput Comparison

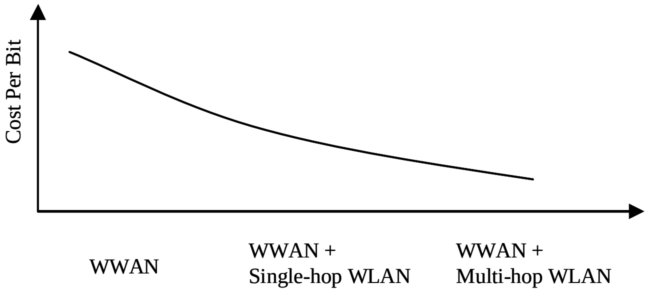

Figure 4. Cost Comparison

As the future work, we plan to use realistic traffic models to evaluate these different design options.

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