MDDV: A Mobility-Centric Data Dissemination Algorithm for Vehicular Networks

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ABSTRACT

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. A natural approach is to use vehicle-to-vehicle communications to disseminate information. In this paper, we propose MDDV, a mobility-centric approach for data dissemination in vehicular networks designed to operate efficiently and reliably despite the highly mobile, partitioned nature of these networks. MDDV is designed to exploit vehicle mobility for data dissemination, and combines the idea of opportunistic forwarding, trajectory based forwarding and geographical forwarding. We develop a generic mobile computing approach for designing localized algorithms in vehicular networks. Vehicles perform local operations based on their own knowledge while they collectively achieve a global behavior. We evaluate the performance of the MDDV algorithm using realistic simulation of the vehicle traffic in Atlanta area.

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design] - *Wireless communication*; **C.2.2** [Network Protocols]

General Terms

Algorithms, Design

Keywords

ad hoc networks, geographical forwarding, localized algorithm, opportunistic forwarding, trajectory based forwarding

1. INTRODUCTION

Intelligent Transportation Systems (ITS) have been deployed in the U.S., Europe, and Asia [14]. Existing ITS deployments are "infrastructure heavy" in that they rely on roadside sensors, cameras, networks, etc. While such systems provide substantial benefit, deployment is very costly. Further, it is often difficult for government agencies to obtain adequate funding to keep these systems completely operational, preventing them from reaching their fullest potential.

There has been increasing interest in the exploitation of advances in information technology (e.g., mobile computing and wireless communications) in surface transportation systems [2, 19, 23, 30, 33, 36, 40, 41]. An emerging trend is to equip vehicles with computing and communication capabilities, offering the potential to greatly lessen dependence on government-maintained IT infrastructures by exploiting equipment that will be continually upgraded and maintained as new vehicles are purchased and existing vehicles are enhanced. In-vehicle systems allow coverage to extend beyond areas where roadside equipment has been placed. Subject to privacy considerations, in-vehicle sensors offer the potential for much more detailed, accurate information (e.g., vehicle emissions) than would otherwise be possible, enabling new ways to improve and optimize the transportation system. In-vehicle computing systems facilitate the customization of information services to the needs and characteristics of individual travelers. Driver assistance and safety applications exploiting upstream traffic information to help users avoid congestion [41] [33] and the use of information concerning nearby vehicles to provide early warning of hazards [23] [36] are two examples that are being explored.

There are several possible network architectures to organize and connect these in-vehicle systems. Three alternatives include a pure wireless vehicle-to-vehicle ad-hoc network (V2V), a wired backbone with wireless last-hops, or a hybrid architecture using V2V communications that does not rely on a fixed infrastructure, but can exploit it for improved performance and functionality when it is available.

Deployment of applications on these architectures 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. Both the "pure ad-hoc" and "hybrid" architectures require the use of vehicle forwarding to realize data dissemination. While data dissemination in fixed infrastructures can utilize well-established routing protocols for wired networks, the best approach to data dissemination using vehicle forwarding remains an open problem. In this paper, we present MDDV, a Mobility-centric Data Dissemination algorithm intended for Vehicular networks. We discuss the algorithm design 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 remainder of this paper is organized as follows. In Section 2, we discuss the context for this work. MDDV is described in Section 3. In Section 4, we summarize some implementation considerations. In Section 5, we discuss design alternatives. Performance evaluation is presented in Section 6.

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Related work is described in Section 7. We conclude this paper in Section 8.

2. BACKGROUND

2.1 V2V Networks

A good data dissemination algorithm must address the characteristics of the network in which it will operate. Let us therefore consider the characteristics of V2V networks. We assume instrumented vehicles are equipped with on-board computing and wireless communication devices, a GPS device enabling the vehicle to track its geographical-temporal trajectory, a pre-stored digital map, and other sensors reporting crashes, engine statistics, etc. We do *not* assume all vehicles have this capability. Due to the gradual nature of market penetration, only a fraction of the vehicles on the road will 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 remaining of this paper, the term "vehicles" refers to instrumented vehicles only.

Vehicles exchange information with other vehicles within their short 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 [30] that differentiate it from other types of ad hoc networks include: (1) predictable, high mobility that can be exploited for system optimization; (2) dynamic, rapidly changing topology (due to high mobility); (3) constrained, largely one-dimensional movement due to static roadway geometry; (4) potentially large-scale; (5) partitioned — 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 ad hoc networking research; (6) vehicles are not completely reliable; (7) no significant power constraints, unlike sensor and other types of mobile networks where limited battery life is a major concern.

These properties make V2V networks different and significantly affect their design. The impact of network partitioning on information propagation is analyzed in [34]. Also due to the partitioned, highly dynamic nature of these networks, large-scale logical structures (e.g., trees) are undesirable; rather, localized algorithms based on vehicles interacting with neighbors are preferred. Further, unreliable communication channels, vehicle failure, high mobility, and network partitioning introduce uncertainty in V2V networks. Data replication and diversity [9] can be employed to improve performance or increase reliability and data availability.

2.2 Data Dissemination Services

Data dissemination concerns the transport of information to *intended receivers* while meeting certain *design objectives*. The design objectives we consider include low delay, high reliability, low memory occupancy, and low message passing overhead. The intended receivers are those specifying interest in the information. Users may define arbitrary interests: "all vehicles going to the football stadium", "police cars that are close by", etc. Here, we are only concerned with those interests that can readily be exploited by data dissemination algorithms, e.g., time and location.

An important question concerns the semantics of data dissemination services, and their suitability for ITS applications. Four services that have immediate application are unicast, multicast, anycast and scan. Unicast with *precise* location means a message should be delivered to node *i* in location *l* before time *t*. Unicast with *approximate* location means sending a message to node *i* before time t_1 while that node was last known to be at location *l* with mobility *m* at time t_2. Multicast means disseminating a message to all receivers in region *r* before time *t*. Anycast means disseminating a message to one among a set of possible destinations (e.g., send to any police car) in region *r* before time *t*. Scan is to have a message traverse region *r* once before time *t*. In these services, location *l* and region *r* are used to direct the message to a geographical area. Time *t* is determined by the nature of the message, e.g., when the information becomes obsolete, and serves to avoid the infinite looping of messages in the system. Other services can also be designed as variations or combinations of the above services.

To illustrate an application using these services, consider a vehicle (or a traffic signal controller) wishing to obtain information concerning some remote region. The vehicle/controller needing the information first queries its own proximity (*multicast*) to determine if a near-by vehicle happens to have this information. Any vehicle having such information can respond (*unicast with approximate/precise location*). If no one replies within a certain amount of time, the vehicle/controller sends a query to any vehicle in the remote region (*anycast*). Receivers in the remote region with this information can respond. The response can be disseminated as *unicast with approximate/precise location*, or *multicast* if caching is desired. This scenario describes a pull approach. A push approach could also be used, e.g., vehicles encountering a crash or traffic congestion may send this information to a region using *multicast*.

Another application is mobile Internet access. Fixed-location Internet gateways may be placed along roads. A vehicle wishing to access the Internet first propagates a query through a region for gateways (*scan*). Gateways receiving the query can respond to the requesting vehicle (*unicast with approximate location*). The requesting vehicle picks one responder and begins to interact with it. The communication from the vehicle to the gateway is *unicast with exact location* while the reverse direction is *unicast with approximate location*.

2.3 Data Delivery Mechanisms

Data delivery mechanisms define the rules for moving information through the network. Conventional data delivery services often implicitly assume that the network is connected. The "node centric" approach [15] specifies the routing path as a sequence of connected nodes. However the high vehicle mobility in V2V networks will quickly render inter-node connections invalid. The "location centric" approach [22] decouples the routing path from the intermediate nodes and the message is forwarded to the next hop(s) closer to the destination geographically. If a hole is encountered, efforts are made to find a path around it [17]. When the network is partitioned (or at least non-continuously connected) and no immediate end-to-end path is available, this approach also fails. Even broadcast protocols, e.g., gossip protocols [10, 21], do not ensure reliable delivery in partitioned networks. "Opportunistic forwarding," as suggested in [3, 6], targets networks where an end-to-end path cannot be assumed to exist. Messages are stored and forwarded as opportunities present themselves. When a message is forwarded to another node, a copy may remain with the original and be forwarded again later to improve reliability. Some simple implementations, e.g., two nodes exchange data whenever they can communicate [12, 18, 26], work well if the data needs to be propagated to everybody. But they are inefficient if a message is to be delivered to some specific receivers, e.g., those in a certain region. In this case, it is more efficient to forward messages in a way that they migrate closer to the eventual destination, and not to others. "Trajectory based forwarding" [25] directs messages along predefined trajectories. It was presented to work well in a dense network. Despite their sparseness, V2V networks should be a natural application of trajectory based forwarding because messages are moving along the road graph. Trajectory forwarding can help limit data propagation along specific paths and thus reduce message overhead.

3. MDDV

In this section, we present the MDDV algorithm. In V2V networks, opportunities to forward messages are created by vehicle movement, so it is natural to focus on vehicle mobility. MDDV is a "mobility centric" approach [20] that combines opportunistic forwarding, geographical forwarding, and trajectory based forwarding. A forwarding trajectory is specified extending from the source to the destination (*trajectory base forwarding*) (Section 3.2), along which a message will be moved geographically closer to the destination (*geographical forwarding*). With an opportunistic forwarding approach, rules must be defined to determine who is eligible to forward a message, when a copy of the message should be passed to another vehicle (Section 3.5), and when a vehicle should hold/drop a message (Section 3.6). To support its decision-making, a vehicle needs some approximate knowledge about the status of the dissemination (Section 3.4).

We motivate the design by reference to a test scenario, geographical-temporal multicast. Later we will show how to extend MDDV to cover all the services defined in Section 2.2. 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*. A region is defined as a set of connected road segments (for two-way roads, both directions are included). Two road segments are connected if they share an intersection (see Figure 1 for an example). We place the source outside of the destination region to make the problem non-trivial.

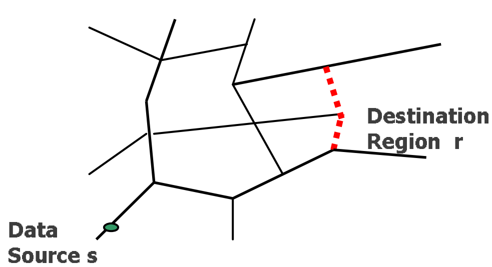

Figure 1. Geographical-Temporal Multicast

3.1 Assumptions

We assume a vehicle knows the road topology through a digital map and its own location in the road network via a GPS device. We assume vehicles know the existence of their neighbors through some link level mechanism. But we do *not* assume a vehicle knows the 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. Further it is assumed that all instrumented vehicles communicate using the same wireless channel. The message dissemination information, e.g., source id, source location, generation time, destination region, expiration time and forwarding trajectory, etc, is specified by the data source and is placed in the message header.

3.2 Forwarding Trajectory

A forwarding trajectory is specified as a path extending from the source to the destination region. The road network can be abstracted as a directed graph with nodes representing intersections and edges representing road segments. Geographical forwarding attempts to move the message geographically closer to the destination. For an ad-hoc network deployed in a two-dimensional area, geographical distance is often defined as Cartesian distance [22]. However, in V2V networks, geographical distance has to be defined as graph distance [31].

One of the MDDV objectives is to deliver messages to their destination regions as soon as possible. A naive approach would be taking the path with the shortest distance from the source to the destination region. However, information propagation along a road depends largely on the vehicle traffic on it, e.g., vehicle density. A short road distance may not translate to short information propagation delay. High vehicle density often leads to fast information propagation. Therefore both the road distance and traffic condition must be taken into account. But vehicle traffic conditions change over time and vary from one road segment to another. Here, we only explore the static road network topology information since road networks are typically engineered to match transportation demands. In the case where the traffic information is available, it can be utilized to generate more accurate metrics. The number of lanes gives some indication of the expected vehicle traffic. We define d(A, B) as the "dissemination length" of a road segment from road node A to B, which takes into account the static road information. Let r(A, B) be the road length between A and B, i/j the number of lanes from A/B to B/A. We use the following heuristic formula:

$$d(A,B) = r(A,B)(m-(m-1)(i^p + cj^p)) \quad 0<c<1$$

From [34], we know that the vehicle traffic in both directions on a two-way road can help propagate information. But the traffic in the opposite direction of the desired information flow is less helpful than the traffic in the same direction of the information flow. Constant c is used to discount the opposite traffic flow. When i = 1 and j = 0, d(A, B) = r(A, B). In our study, we set m = 5, p = 0.1 and c = 0.05.

The dissemination length of a road segment is used as the weight for the corresponding link in the abstracted road graph. Our current MDDV implementation uses a forwarding trajectory that is specified as the directed path with the smallest sum of weights from the source to the destination region in the weighted road graph.

3.3 A Generic Mobile Computation Approach

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. This is also consistent with the lack of central facilities in peer-to-peer (P2P) systems. It scales well as the system size increases and also helps the system cope with network non-determinisms. We develop a generic approach for designing localized algorithms in V2V networks that consists of four components: global behavior, ideal scenario, approximation and local operations. The global behavior is the objective we want to achieve. The ideal scenario characterizes algorithm behavior by assuming every participant has perfect knowledge. Approximation is the practical scheme used to approach the ideal scenario where the perfect knowledge assumption is relaxed. Local operations are designed to realize the approximation.

Global Behavior. The dissemination process consists of two phases: the forwarding phase and 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 and the message is propagated to every vehicle in an area centered on the destination region before the message time expires. This area covers the destination region and is usually larger in order to deliver the message to intended receivers before they enter the destination region in order to reduce delay.

Ideal Scenario. Let us assume, for the moment, every vehicle has perfect knowledge concerning the global status of the data dissemination. During the forwarding phase we call the message holder closest to the destination region along the forwarding trajectory 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. Only the message head tries to pass the message to other vehicles that may be closer to the destination region. During the propagation phase the message is propagated to vehicles without the message in the specified area.

Approximation. The above ideal scenario cannot be implemented due to the lack of perfect knowledge for participating vehicles. Specifically, individual vehicles do not know which vehicle is the message head in real time. For example, as illustrated in Figure 2, in a two-way traffic road, the current message head is vehicle 1. In (a), vehicle 1 may run out of the trajectory or may become inoperative, of which vehicle 2, the immediate follower, may not be aware because the network is partitioned. In (b), vehicle 1 is moving away from the destination region (note the road is bi-directional). Once vehicle 1 passes vehicle 2, vehicle 2 should become the new message head. However, vehicle 2 does not know this unless it receives an explicit notification from vehicle 1. With our assumption that vehicles do not know the location of others, this is difficult to do. In both cases, the message is lost. To address this problem, we allow a *group* of vehicles near the real message head to actively forward the message instead of the message head vehicle only. The group membership changes as the actual message head moves toward the destination region. There is a tradeoff between delivery reliability and message overhead: larger groups mean higher delivery reliability but higher message overhead too. Vehicles have to locally determine their own actions based on their approximate knowledge of the global message dissemination status. Later we will discuss in detail how to design local operations for individual vehicles to realize the approximation.

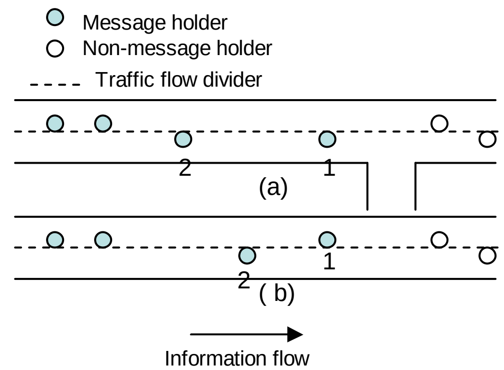

Figure 2. Lack of Perfect Knowledge

3.4 Message Head Pair

To realize the approximation, vehicles need to have some information concerning the message dissemination status. Specifically information concerning the message head is required. However, the message dissemination status changes over time. Vehicles can only expect approximate knowledge, at best. Also a vehicle's knowledge must be updated constantly. A convenient way to exchange such information is to place it in the message. As the message is propagated among vehicles, so does the message dissemination status information. Too much information in the message is cumbersome and expensive, however. To this end, a small amount of data, the message head location and its generation time, called the *message head pair*, are inserted to the message. Every holder of a message maintains a message record containing the message head pair along with other information concerning this message. The message head pair provides the best knowledge of a message holder concerning the message head location. It says "as far as I know, the message head was in that location at that time".

The actual message head can move either toward or away from the destination region along the forwarding trajectory within a short period of time. But it should move toward the destination region in the long run (remember the message head vehicle may change). For simplicity we require that the message head location installed by a message holder never moves backward, which means that a message holder can only install a new message head location closer to the destination region than its currently installed one.

To reduce the publication and dissemination of false information, only some vehicles are allowed to generate the message head pair. A message holder is allowed to publish its current location as the message head location if it believes it may be the real message head with some probability. In this sense, a message holder may assume either one of two roles: the message head candidate and non-message head candidate. Only a message head candidate can actively publish its current location as the message head location while a non-message head candidate can only learn from received messages.

There are rules for a message holder to transit between a message head candidate and non-message head candidate. Suppose the current time is t_c, a vehicle's current location is l_c, and a vehicle's installed message head pair is $<l, t>$ where l is the message head location and t is the generation time.

1. non-message head candidate -> message head candidate

During the forwarding phase, one important observation is that a vehicle passing its installed message location a shorter period after the generation time is more likely to be the message head because after a long period the message may have already been forwarded far away toward the destination region along the trajectory. Thus we stipulate that a non-message head candidate becomes a message head candidate if it passes its installed message head location toward the destination region before $t + T_1$, where T_1 is a system parameter.

During the propagation phase, message holders moving into the destination region assume the role of the message head candidate.

2. message head candidate -> non-message head candidate

During the forwarding phase, there are two transition rules: 1. if the message head candidate leaves the trajectory or moves away from the destination region along the trajectory, it becomes a non-message head candidate; 2. if a message head candidate moves toward the destination region along the trajectory, it stays as a message head candidate until it receives the same message with another message head pair $< l_n, t_n >$ where l_n is closer to the destination region than l_c.

During the propagation phase, a message head candidate becomes a non-message head candidate once it moves out of the destination region.

A message holder updates its installed message head pair with the information from received messages. Two messages differing only in the message head pair are two versions of the same message. One message version with message head pair $<l_i, t_i>$ is said to be newer than another message version with message head pair $<l_j, t_j>$ if: l_i is closer to the destination region than l_j; or $l_i = l_j$ but $t_i > t_j$. A vehicle always updates its installed message head pair with the received newer information. Therefore obsolete/false installations can be eliminated through data exchange.

3.5 Data Exchange

Data exchange can be structure-based [11] or peer-based [12, 26]. With a structure-base scheme, nodes are organized into some logical structure, e.g., clusters and trees, and data flows follow the logical order specified by the logical structure. With a peer-based scheme a node talks to encountered peers. Given the high vehicle mobility, peer-base schemes are more appropriate for the current context.

There are two possible data exchange sequences between two encountering peers as shown in Figure 3. The first is the three-way interaction in (a). Peer 1 first advertises the message metadata. Peer 2 decides whether it wants the message after processing the metadata. If it wants the message, peer 2 sends a request to peer 1. Peer 1, upon receiving the request, sends the message to peer 2. The second is the one-way transmission in (b). Peer 1 transmits the message. The former works better if the message metadata is much smaller than the message. The latter works better otherwise. In this paper, we use the second sequence by assuming that the message is not much larger than its metadata, which is usually true in traffic information applications. However MDDV does not depend on this choice. It can be easily adapted to accommodate the first sequence. To improve the transmission efficiency and exploit the broadcast nature of wireless communications, all transmissions are local broadcast so that multiple receivers can receive the same message sent by one transmission.

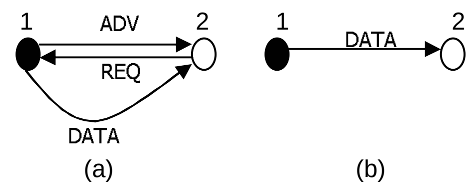

Figure 3. Data Exchange Sequence

Data exchange can be triggered by several types of events. It may happen as new messages are received. This is adopted by most structure-based routing protocols, bearing the benefit of fast delivery. For peer-based data exchange schemes, data exchange is triggered by new neighbors, having the merit of high delivery reliability. If the neighbor set information is not available to nodes, data exchange may happen as time events. Since MDDV assumes the knowledge of the neighbor set, we do not consider the third type of events. In MDDV, data exchange is triggered by: new messages, newer message versions or older message versions are received, or new neighbors appear. Transmissions triggered by new messages or newer message versions serve to quickly propagate messages or dissemination status. Transmissions triggered by older message versions can help eliminate false/obsolete information. This scheme has both the advantages of fast delivery and high delivery reliability. We call it the *full protocol*. However the full protocol is also expensive in terms of message overhead so that we have to set constraints on which part of the protocol one is allowed to execute at one instant.

The data exchange algorithm is defined as:

a) Forwarding phase

A message holder can be in either one of two dissemination states: the active state and passive state, or not eligible to transmit at all. A message holder in the active state runs the full protocol to actively propagate the message while a message holder in the passive state only transmits the message if it hears some older message version. The active propagation can help populate the message, move the message closer to the destination region or update dissemination status. The passive updating serves to eliminate false/obsolete information only. Given a message holder's installed message head pair $<l, t>$, its current location l_c and the current time t_c, it is in the active state if $t_c < t + T_2$ and l_c is within the distance L_2 from l, and otherwise it is in the passive state if $t_c < t + T_3$ and l_c is within the distance L_3 from l, while $T_2 < T_3$ and $L_2 < L_3$. Otherwise, the message will not be transmitted under any circumstance. T_2, T_3, L_2, L_3 are system parameters. In this way, the active data propagation is initiated by the fresh generation of a message head pair and is constrained near the message head location (through both geographical and temporal constraints). Data propagation caused by obsolete/false information will eventually stop when the time expires or it is suppressed by updates. Coupled with the effort in Section 3.4 to allow only message head candidates to generate message head pairs, this effectively results in the active message propagation near the actual message head location.

b) Propagation phase

A message holder can be either in the active state or not eligible to transmit. A message holder in the active state runs the full protocol. The active propagation serves to deliver the message to intended receivers. Using the same notations as before, a message holder is in the active state if $t_c < t + T_2$ and l_c is within the distance L_2 from l. Based on the rules to generate the message head pair in Section 3.4, every vehicle inside the destination region publishes its own location as the message head location. Thus this data exchange mechanism limits the active propagation in a region centered on the destination region.

3.6 Store and Drop Messages

An opportunistic forwarding mechanism must determine when to store/drop a message. The design decision can affect delivery reliability, memory usage and message overhead. The decision to store/drop messages can be based on a vehicle's knowledge of its future movement trajectory. For example, if we assume vehicles are aware of its own near future movement trajectory, a message holder may decide to drop a message if it knows that continually holding the message can no longer contribute to suppress unnecessary message transmissions based on its future movement trajectory. In MDDV every vehicle stores whatever it overhears since this is almost free except occupying memory buffers. A vehicle drops a message when the vehicle leaves the passive state during the forwarding phase, leaves the active state during the propagation phase or the message expiration time elapses.

4. IMPLEMENTATION

In this section, we first summarize two implementation issues: estimating MDDV algorithm parameters and exploiting local broadcast. We then present vehicles' transmission algorithm.

MDDV parameters, T_1, T_2, T_3, L_2 and L_3, should be estimated locally and dynamically by individual vehicles based on their knowledge about the vehicle traffic condition around the message head location. Based on vehicle traffic flow theory [8] mechanisms have been developed to monitor vehicle traffic, propagate the vehicle traffic information and applying the information to estimate MDDV parameters. Details will be presented in the future.

The nature of wireless transmission as local broadcast has been exploited to reduce the message overhead in MDDV. Multiple receivers can obtain the same message sent by one transmission. In addition message holders can learn from overheard messages to suppress redundant transmissions [24].

With the above discussion, we can now present the local transmission algorithm of vehicles.

Every vehicle maintains three lists as shown in Figure 4. The neighbors of the vehicle are stored in the neighbor list in increasing order of the time when they first appeared (*firstAppearTime*). A vehicle maintains a message record for every valid message overheard. Each message record contains *lastHeardTime, scheduledTime, messageHeadPair, and disseminationState*, among others. The meaning of these variables should be self-explanatory. The opportunistic message list stores messages not scheduled to transmit but can be transmitted when new neighbors appear. The messages in the opportunistic message list are ordered increasingly in the latest time they were transmitted or heard (*lastHeardTime*). The scheduled message list stores messages scheduled to transmit at some specific time. The messages in the scheduled message list are ordered increasingly in their scheduled time (*scheduledTime*).

Figure 4. Data Structure

Vehicles transmit messages in the opportunistic message list to new neighbors. The algorithm is described below:

```
Search for stored message m, the one with smallest lastHeardTime among those with disseminationState = Active in the opportunistic message list
Search for neighbor n, the one with largest firstAppearTime
If(m.lastHeardTime < n.firstAppearTime){
    Transmit m
    m.lastHearTime = now
    Insert m to the end of the opportunistic message list
}
```

A vehicle runs the above algorithm periodically to avoid dominating the wireless channel and also allow time to hear transmissions from others. During each pass, at most one message is transmitted. A vehicle only transmits a message if new neighbors appeared since the last time it heard/transmitted the message. Consider the following scenario. When a vehicle approaches a vehicle cluster, it becomes the neighbor of many vehicles. However, only one vehicle will transmit a message to the newcomer while others will suppress their transmissions of the same message upon overhearing the transmission.

A vehicle runs the following algorithm when receiving a message m':

```
    Search for stored message m which only differs m' in the message
head pair at most
    If(m does not exist){
        Create a message record m = m'
        m.lastHeardTime = now
        if(m.disseminationState = Active){
            m.scheduledTime = now + random backoff
            Insert m in the scheduled message list
        }else{
            Insert m to the end of the opportunistic message list
        }
    }else{
        m.lastHeardTime = now
        Compare m.messageHeadPair and m'.messageHeadPair
        if(m is significantly older than m'){
            m.messageHeadPair = m'.messageHeadPair
            if(m.disseminationState = Active){
                m.scheduledTime = now + random backoff
                Insert m in the scheduled message list
            } else{
                Insert m to the end of the opportunistic message list
            }
        }else if(m is significantly newer than m'){
            if(m has not already been scheduled)
                m.scheduledTime = now + random backoff
            }
            Insert m in the scheduled message list
        }else{
            Insert m to the end of the opportunistic message list
        }
    }
```

The above algorithm indicates that a transmission is scheduled when a new message or a significantly different message version is received. The transmission is delayed by a random amount of time to allow the vehicle to hear others. Receiving a similar message version will not trigger transmission.

5. DISCUSSION

5.1 Design Space

It can be seen that MDDV can fail to deliver a message to its destination if no vehicle is able to claim to be the message head after some stage during the message propagation. The estimation of MDDV parameters, especially T_1, is critical in the tradeoff between reliability and overhead. The vehicle failure model also needs to be taken into consideration if one is assumed. Alternatively, algorithm parameters can be readily replaced with probabilities, e.g., a message holder transmits a message with some probability. In this way, the number of vehicles actively propagating a message gradually declines as the geographical location leaves the installed message head location or the time ages. Intuitively this can help reduce wireless channel contention and redundant transmission as well.

Currently the data source specifies the global dissemination information, e.g., the destination region and moving trajectory. Intermediate vehicles have the flexibility of tuning local parameters based on their own knowledge, i.e. T_1, T_2, T_3, L_2 and L_3. This arrangement has the benefit of easy coordination between vehicles since a V2V system is a peer-based distributed system and there is no central facility. One area of future work is to allow intermediate vehicles more flexibility in manipulating messages. For example, intermediate vehicles may specify a better forwarding trajectory, change the destination region, or aggregate multiple messages based on application semantics. However, this will create coordination problems between peers. For example, one peer changes the forwarding trajectory, but not everyone else may be aware of or agrees with such a change. This will result in data propagation along multiple forwarding trajectories.

So far we have discussed specifying only one forwarding trajectory. Multiple diverse forwarding trajectories can be defined to increase system robustness or reduce delay. The specification of trajectories may follow criteria other than shortest delay, e.g., going through a specific region as required by a scan service.

It is shown [5] that the probability of connectivity increases as distance decreases or node density increases. An adaptive scheme would be to assume connectivity for short distances or high vehicle density and adopt opportunistic forwarding otherwise.

5.2 Extension

The data dissemination services mentioned in Section 2.2 can be easily covered with MDDV extensions.

Unicast. Unicast with precise location can be handled by the MDDV algorithm in the forwarding phase. Once the message reaches the destination location, the message will not be forwarded any longer. The algorithm for unicast with approximate location is an extension to the algorithm for unicast with precise location, beyond which intermediate vehicles must estimate the location of the destination as time elapses and determine whether the message has reached the destination.

Scan. It can be easily seen that MDDV scans over the moving trajectory when delivering the message to the destination region. Scan can be implemented as a special case of unicast with precise location. The destination location is set to the other end of the region to be scanned. The moving trajectory is set as going through the region.

Anycast. The algorithm for anycast is similar to the algorithm for scan. However the message does not have to traverse the entire destination region. A reply from any intended receiver will stop further propagation.

Multicast. The scenario that the source is inside the destination region is a special case of geographical-temporal multicast. When there are multiple disjoint destination regions, the moving trajectory can be specified as a dissemination tree with the location of the message originator as the root. Some implementation issues need to be addressed concerning branches.

6. EVALUATION

In this section, we present preliminary simulation results using a traffic model and data corresponding to a portion of the Atlanta metropolitan area. We explore the performance achievable with vehicle communications, study the sensitivity of MDDV parameters, and compare MDDV with two idealized schemes.

6.1 Simulation Methodology

We use the distributed simulation test bed for intelligent transportation system analysis developed by our group. It takes a federated approach to integrate simulations, applications and external data sources. In our experiments, the transportation simulation is performed by CORSIM, a microscopic transportation simulator [7]. CORSIM utilizes commonly accepted vehicle and driver behavior models to represent traffic networks. Extensive geometric and operational data are required to model an area in CORSIM. The wireless network simulation is performed by QualNet, a telecommunication network simulator [29]. Vehicles in CORSIM are mapped to mobile nodes in QualNet, whose movement will follow the simulated vehicle movement.

We simulate the traffic in the morning rush hour in the northwest quadrant of Atlanta, Georgia, approximately 12km of I-75 and approximately 160km of arterial surface streets. The data sources for geometric and traffic flow data used to develop the CORSIM model include traffic signal timings, speeds, travel times, and traffic flow data from local and state government agencies. A calibration effort, including field surveys, was undertaken to insure that the CORSIM model provides a reasonable representation of actual operations. Details on CORSIM model generation and calibration can be found in [35].

We implement MDDV in QualNet as an application layer data service to make it independent with network layer protocols, and to allow a data service layer to be augmented later that includes application layer functionalities, e.g., data aggregation. For comparison purposes, we also implement two idealized data dissemination schemes. The **central intelligence** scheme assumes the identity of the message head is always known to everyone so that messages will not be lost due to the lack of perfect knowledge, and only the message head actively propagates the message during the forwarding phase. The **P2P** scheme does not have the concept of the message head. Two encountering peers exchange data in the path extending from the source to the destination region. Both schemes, like MDDV, exploit the local broadcast nature of wireless transmission to reduce message overhead. All three schemes use the same algorithm during the propagation phase. We are also working on comparing MDDV with other data delivery schemes in vehicular networks, e.g., optimistic forwarding [3]. The results will be presented in the future.

We use a workload of 40 geographical-temporal multicasts. For each multicast, a message of size 512 bytes is sent from a randomly chosen source to a randomly chosen road segment. The average road distance from the source to the destination region is about 6.5km. We use a two ray propagation model since terrain data was not available for these experiments. Every instrumented vehicle is equipped with an omni-directional antenna. The radio range is set at 250m. This means that most of the time, data will only flow along roadways. The MAC protocol is 2Mbps 802.11 DCF.

Simulation runs were completed to examine the sensitivity of performance on various parameters, and to develop an approach to tune system parameters. Due to space limitations, the results are omitted here.

6.2 Feasibility Study

We use the central intelligence scheme to examine the best performance achievable using vehicular communications when only a single forwarding trajectory is specified for each geographical-temporal multicast. The message expiration time is set at 480 seconds. Figure 5 illustrates the delivery ratio, which is the fraction of the messages reaching their destination region before the message expiration time elapses. Figure 6 plots average, minimum and maximum delays for successful disseminations to reach destination regions. Note that unsuccessful disseminations require more than the message expiration time to reach destination regions. When the penetration ratio is below 0.2, the delivery ratio is less than 100%, so the average delay and the maximum delay should be inflated. In our experiments, the time for messages to reach destination regions varies from seconds to minutes due to path partitioning. Additional communication facilities such as roadside base stations may be required to reduce path vulnerability for some applications. More results can be found in [35].

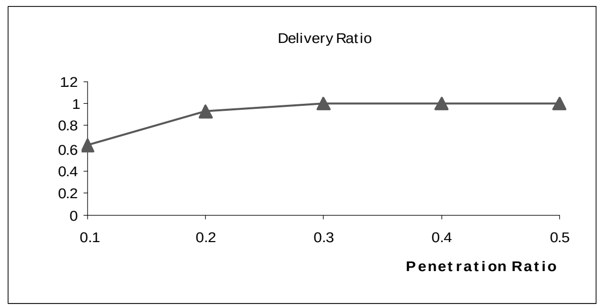

Figure 5. Delivery Ratio

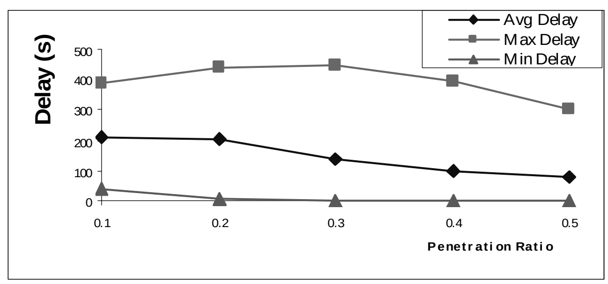

Figure 6. Dissemination Delay

6.3 Comparison

We compare MDDV with the two idealized schemes. Figure 7 plots the normalized MDDV delivery ratio over the value achieved by idealized schemes as a function of the penetration ratio. Even though we have conservatively set the parameters to reduce the overhead, more than 50% of those disseminations reaching destination regions with idealized schemes are also successful with MDDV, and the rest are lost due to the lack of perfect knowledge. Figure 8 illustrates the message overhead, the number of message transmissions in the forwarding phase, of MDDV and the central intelligence scheme normalized against that of the P2P scheme. It can be seen that the message overhead of both MDDV and the central intelligence scheme is a very minor portion of that of the P2P scheme since with the P2P scheme messages are propagating within the trajectory all the time. The MDDV scheme does not incur remarkably higher message overhead than the central intelligence scheme. These preliminary results are encouraging. We expect better performance after fine-tuning the system parameters.

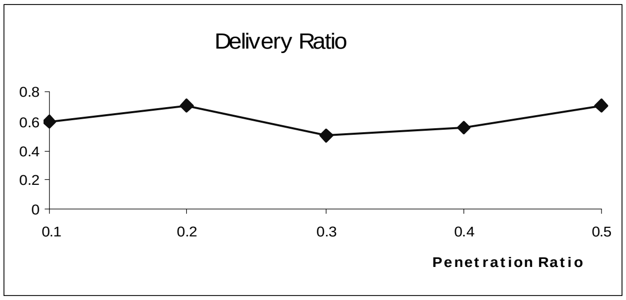

Figure 7. Normalized Delivery Ratio

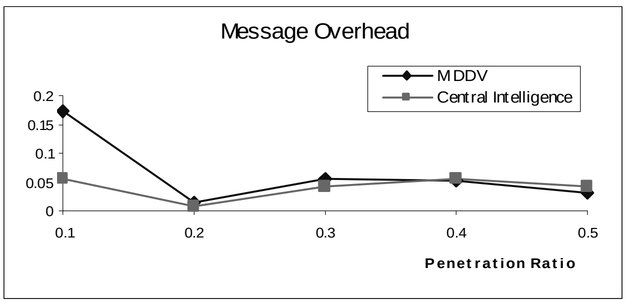

Figure 8. Normalized Message Overhead

7. RELATED WORK

There is much research in the area of wireless ad-hoc networks. Conventional practices focus on the network in a small two-dimensional area. Studies concerning data dissemination in ad-hoc networks assume either that mobile nodes move randomly and any two nodes can be expected to be close to each other from time to time because they are confined in a limited area [12, 18, 26], or alternatively, slow or zero node mobility so that topology information can be maintained with low cost [13, 28]. In the V2V system, due to the high mobility, maintaining inter-vehicle connection based topology knowledge will be expensive, infeasible or unnecessary in some cases. Neither is it acceptable to assume that two encountering vehicles will meet again with any certainty. Geographical forwarding [22] [17] is proposed to address the issue of high mobility. Most geographical forwarding algorithms require a node to know the location of its neighbors. This requirement is relaxed in our study due to privacy and security concerns.

A partitioned network can exploit node movement to deliver information opportunistically. In [4, 32], mobile hosts exchange information when they meet. In [20], mobile nodes proactively change their movement to deliver messages. Message Ferry [38] [39] provides a common communication channel via a node of a known fixed moving trajectory for disconnected mobile nodes. The Zebra project [16] and the MULE architecture [27] are intended to provide intermittent connectivity in a disconnected ad hoc network. Fall [6] proposes a network architecture for supporting challenged internets. Compared to these works, MDDV specifically addresses vehicle mobility.

Some recent work on routing in vehicular networks assume end-to-end connections [31]. Optimistic forwarding [3] is introduced as another opportunistic scheme for vehicular networks. Optimistic forwarding dictates that a message can have one owner at one time instant and the ownership has to be transferred from one node to another. In MDDV, we employ the concept of "group ownership", e.g. a group of message holders can actively propagate the message and the group membership varies with time. Optimistic forwarding is inherently more efficient and less robust than MDDV.

The general routing problem in a hybrid vehicular network is considered in [19]. No detailed implementation is given there. We are currently considering an integrated data dissemination scheme combining MDDV and some wired routing scheme to address this issue.

MDDV employs many techniques for reducing message overhead. Specifically it borrows heavily the techniques to solve the broadcast storm problem [24].

Most mobility models, as in [37], allow nodes to move randomly. In the Manhattan mobility model [1], nodes are moving along streets, but wireless signals can still travel across streets as if there is no building between them. Instead of synthesizing some mobility model, we let the node movement be driven by the microscopic transportation simulation to improve realism.

8. CONCLUSION AND FUTURE WORK

MDDV is designed to address the data dissemination problem in a partitioned and highly mobile vehicular network. Messages are forwarded along a predefined trajectory geographically. Since no end-to-end connectivity is assumed, intermediate vehicles must buffer and forward messages opportunistically. As an opportunistic algorithm, MDDV answers the questions about who can transmit, when to transmit, and when to store/drop messages. Using a generic mobile computing approach, vehicles perform local operations based on their own knowledge while their collective behavior achieves a global objective. Message delivery reliability is improved by allowing multiple vehicles to actively propagate the message. Two key MDDV design considerations improve the delivery efficiency: 1. vehicles are fed with some approximate message dissemination status information, and apply the data propagation analysis and vehicle traffic flow theory to act accordingly; 2. active propagation is limited to an area near the actual message head location. The local broadcast nature of wireless transmission is exploited to reduce the message overhead further. MDDV parameters depend on vehicle traffic conditions and can be estimated by applying vehicle traffic flow theory.

Future work includes exploration in several directions. Based on our preliminary analysis and experiments, MDDV parameters should be tuned by applying vehicle traffic flow theory. Much research can be motivated by the discussion in Section 5.1, e.g., a thorough analysis of the failure modes of delivery, and an adaptive data dissemination algorithm that assumes connectivity for short distances or high vehicle density and adopts opportunistic forwarding otherwise. A comparison of data delivery schemes in vehicular networks under various traffic conditions and vehicle failure models is also needed. An integrated data dissemination scheme combining MDDV and some wired routing scheme could be designed to address hybrid vehicular networks. Applications built on top of MDDV must be designed and evaluated.

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