Ad Hoc Peer-to-Peer Network Architecture for Vehicle Safety Communications

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ABSTRACT

This article addresses the design of an architecture for ad hoc peer-to-peer networking of neighboring vehicles to help achieve near-instantaneous communication for safety applications such as collision avoidance warnings. We propose a local peer group (LPG) architecture to organize neighboring vehicles that have frequently changing neighbors and have no inherent relationships with one another. We study two architectural alternatives for LPG in this article, and consider areas of improvement for ad hoc vehicle networking protocols to support safety communications including multihop throughput, connection setup time, and configuration.

INTRODUCTION

Traffic deaths and injuries remain a major health and social issue. While industrialized nations (e.g., the United States) have continuously reduced annual traffic deaths since 1970, annual traffic-related fatalities and injuries remain high (in the United States alone there were over 41,000 deaths and 5 million injuries in 2000, according to the NHTSA). The economic impact of vehicle crashes in the United States exceeded US$230 billion or 2.3 percent of the U.S. GDP in 2000 [1]. While passive safety technologies to survive crashes (e.g., seat belts, airbags) are crucial, there is need for active safety technologies such as vehicle safety communications (VSC) to avoid crashes.

Significant activities are underway worldwide to develop VSC technologies. These include, for example, in the United States, the ITS America VII (Vehicle-Infrastructure Integration) effort on 5.9 GHz Wireless Access in Vehicle Environment (WAVE) communication for all vehicles, the U.S. Department of Transportation Intelligent Vehicle Initiative (IVI) program to accelerate R&D of crash avoidance technologies, and initiatives such as the Crash Avoidance Metrics Partnership (CAMP) VSC Consortium (VSCC). Similar examples include, in the European Union, the e-Safety and ADASE2 (Advanced Driver Assistance Systems in Europe) efforts, and in Japan efforts in the ITS Infocommunications Forum, Japan Automobile Research Institute/ITS Center (JARI/ITSC) and Advanced Cruise-Assist Highway System Research Association (AHSRA).

VSC may be broadly categorized into vehicle-to-vehicle and vehicle-to-infrastructure communications. In vehicle-to-vehicle communications, vehicles communicate with each other without support from the infrastructure. Vehicles communicate with each other when they are covered within the same radio range, or when multiple-hop relay via other vehicles is possible. In the vehicle-to-infrastructure communication case, vehicles communicate with each other with the support of infrastructure such as roadside wireless access points. In this case, vehicles may also communicate with the infrastructure only.

Examples of vehicle-to-vehicle safety communication may include collision warning, road obstacle warning, cooperative driving, intersection collision warning, and lane change assistance (Table 1). Examples of vehicle-to-infrastructure safety communication may include hidden driveway warning, electronic road signs, intersection collision warning, railroad crossing warning, work zone warning, highway merge assistance, and automated driving.

While potential VSC applications are numerous, the key bottom line VSC requirements are low latency and sustained throughput (or equivalently, the percentage of neighboring vehicles that successfully receive warning messages). For latency, the one-hop message transfer latency among vehicles is generally required to be less than 100 ms; and for throughput, the end-to-end multihop throughput should not deteriorate significantly with the number of hops. Separately, the roadway traffic environment is dynamic with uncoordinated vehicles. Vehicles do not have inherent relationships with each other, and

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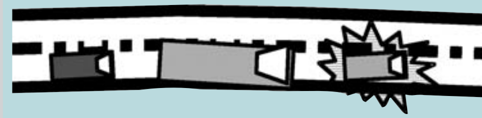
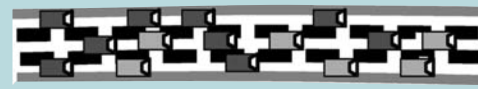
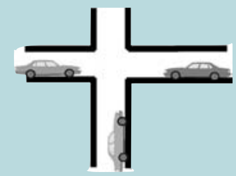
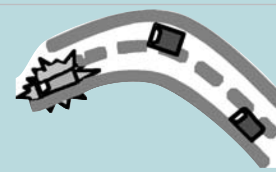
Example	Description	Image
Obstacle Warning	Stopped/skidding/slowing down vehicle warning, road obstacle/object-on-road warning	
Lane Merge/Lane Change Assistance	Merging/lane-changing vehicle communicates with vehicles in lane to safely and smoothly merge	
Adaptive Cruise/Cooperative Driving	Automatically stop and go smoothly, when vehicles are in heavy roadway traffic; cooperative driving by exchanging cruising data among vehicles	
Intersection/Hidden Driveway Collision Warning	Vehicles communicate to avoid collision at intersection without traffic light or hidden driveway	
Roadway Condition Awareness	Vehicles communicate to extend vision beyond line of sight (e.g., beyond a big turn or over a hill)	

Table 1. *Examples of vehicle safety communications.*

neighboring vehicles frequently change. This dynamic environment makes it difficult for vehicles to access key servers if these servers reside in designated vehicles (e.g., DHCP server, Mobile IP HA/FA, SIP server, DNS server) for functions such as address configuration, location or session management, and service lookup.

The stringent performance requirements and dynamic vehicular environment pose new networking challenges, including network architecture and communication protocols that are tailored to VSC. In this article, we focus on the architectural design of vehicle-to-vehicle safety communications. We also consider areas of improvement for ad hoc vehicle networking protocols to support VSC including multi-hop throughput, connection setup time, and configurations.

The article is structured as follows. We introduce the need for vehicle groups. We describe two architectural designs of local peer groups for safety communications. We then discuss the open issues of multihop throughput, connection setup time, and configuration, respectively. We also outline related work and then summarize the article.

The Need for Manageable Vehicle Groups

The autonomous safety systems on individual vehicles help, but are insufficient for many safety applications. This is particularly true in many situations where vehicles need to have an extended range of awareness beyond what drivers can immediately see or autonomous safety systems can detect (e.g., road obstacles beyond a turn, a truck or bus blocking the driver's view, or a road intersection). Autonomous safety systems may potentially interact with roadside infrastructure, if they are widely installed, to achieve an extended view. However, it will take a long time to build up roadside infrastructure everywhere. Vehicle-to-vehicle networking is thus a complementary alternative to autonomous safety systems for vehicle safety.

Simply installing wireless antennas on vehicles and starting uncoordinated communication among them will not suffice for safety. This kind of best effort networking cannot provide the stringent VSC requirements. Our benchmarking measurement results on state-of-the-art ad hoc technologies showed the limitations of this approach. The underlying reason is that the radio bandwidth is limited, and can easily be jammed when multiple neighboring vehicles try to flood the airwaves with warning messages in an uncoordinated manner.

Grouping neighboring vehicles into manageable units is crucial to achieve efficient and reliable safety communications. Without boundaries among vehicles:

- Too many vehicles can interfere with each other in contention for radio bandwidth for transmissions.
- All messages may propagate everywhere, flooding the system with messages.

Communication among vehicles will be inefficient and unreliable. By introducing appropriate boundaries among vehicles, we can group vehicles into manageable units to coordinate the vehicles in message transmissions and relaying, and control the range and direction of message propagation (Fig. 1). For example, we can focus on intragroup communication for extremely fast safety-related message delivery and stop the messages at the group boundary. We can also control how to pass the messages to neighboring groups for longer-range dissemination. More efficient and reliable vehicle safety communications may be achieved.

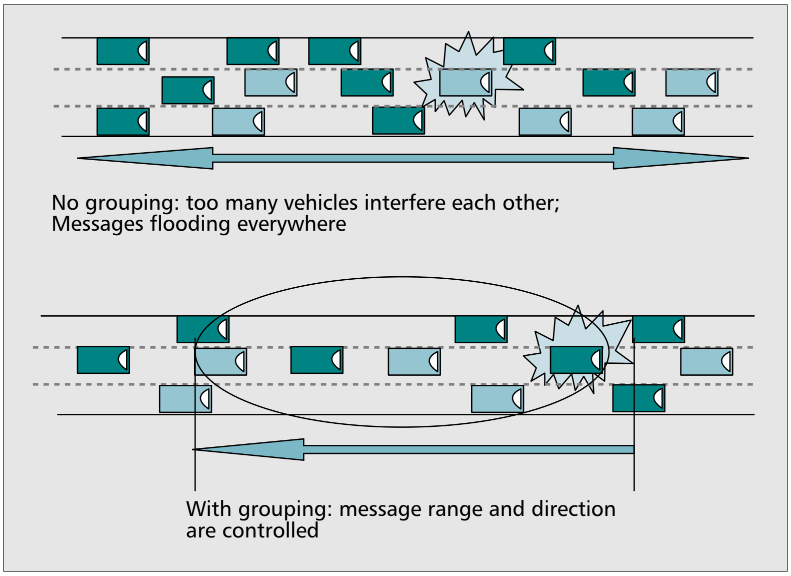


Figure 1. *The need for manageable vehicle groups.*

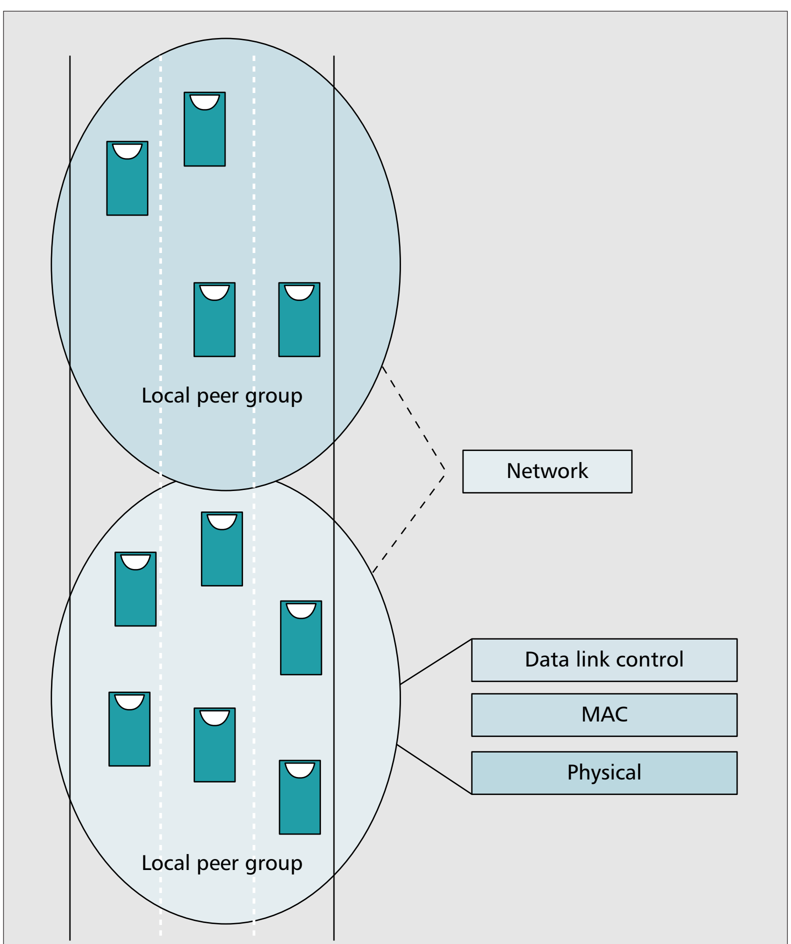


Figure 2. *Local peer group (LPG).*

Next we will briefly outline the key differences between vehicle safety and tactical ad hoc networking. In tactical applications, ad hoc networks among vehicles, soldiers, or rescue specialists, or even airplanes are formed to communicate without fixed infrastructure or real-time system administration support. Command and control is the primary application. To deal with the lack of fixed infrastructure and real-time system administration support, most tactical ad hoc networks are designed for organizational groups (e.g., rescue teams, platoons) where:

- The group's communication nodes and servers (e.g., mobile gateways/routers, configuration servers, mobility or location servers, and application server) are configured beforehand to communicate with each other.
- The network entities move together as a group during tactical operations.

Synchronous movement of communication nodes and servers as a group ensures that the nodes can rely on the servers in the group during communication.

In VSC, neighboring vehicles frequently change and do not have inherent relationships with each other (i.e., neighboring vehicles just happen to be in that location at that time). The high mobility and lack of inherent relationships make prior configuration of the vehicles in the vehicle networks problematic (i.e., no vehicle knows anything about its neighbors beforehand): all information that is necessary for setting up safety communication must be exchanged in near real time among vehicles, and vehicles must configure themselves in near real time so that communication can take place. Speedy exchange of meta-data and organization is much more crucial for safety communications than for other types of applications. Also, there are new challenges to access support servers: which vehicles will act as mobility/IP address/name/media session servers, or where would vehicles get such support? Even if support servers can be somehow defined, the high mobility of vehicles implies frequent change of servers. These key differences make tactical ad hoc networking technologies not directly applicable to VSC. Other research has looked more closely at the case of uncoordinated nodes such as those that exist in the roadway environment [2]. However, that work focuses on reaching a particular destination (e.g., a roadside unit) or vehicles (in terms of their Global Positioning System, GPS, locations), and is not directly applicable to the more broadcast/multicast nature of safety traffic and its strict latency bounds.

Local Peer Group Architecture

We propose an architecture for ad hoc peer-to-peer networking that:

- Is specifically for neighboring vehicles
- Takes advantage of roadway characteristics, such as that vehicles frequently move in clusters, and in more or less structured patterns (e.g., lanes)

We propose to use local peer groups (LPGs) to build degrees of coordination among neighboring vehicles (Fig. 2). The degrees of coordination are:

- Tight coordination of vehicles in the immediate vicinity (i.e., intra-LPG communication) that supports near-instantaneous safety applications that typically require 100 ms latency
- Looser coordination of vehicles in the neighborhood (i.e., inter-LPG communication among interconnected LPGs) that supports roadway awareness applications (extending drivers' view)

Such coordination, among otherwise unrelated vehicles that happen to be in the same neighborhood, can be the basis for designing efficient protocols for wireless media access, routing, and multicasting.

Each LPG consists of vehicles in the immediate vicinity and performs intragroup networking to support near-instantaneous safety communications (e.g., sending urgent road obstacle warning so other vehicles can avoid the obstacle). Given the 100 ms latency requirement, we propose to push intra-LPG communication operations to the lowest layers possible (e.g., use link/MAC layer communication wherever possible). This is a reasonable approach since link layer detection of neighbors is on the order of milliseconds while the network layer detection time is on the order of seconds. Communication among the LPGs to disseminate safety information among vehicles in a larger neighborhood is performed via inter-LPG networking at the network layer. For near-instantaneous dissemination of safety information among vehicles, each LPG must be organized quickly and support timely reliable MAC and multicasting among vehicles.

Existing ad hoc clustering approaches achieve efficiency in grouping network entities in ad hoc environments. In the vehicle network, where nodes may be densely populated and lined on roadways, the conventional clustering strategies [3, 4] may not be effective to form LPGs and organize vehicles in LPGs. More efficient organizing methods need to be derived with consideration of the vehicular environment.

We propose two architecture alternatives: dynamic and stationary LPGs. The dynamic LPG approach seeks to coordinate vehicles based on the radio coverage of the neighboring vehicles. The stationary LPG approach uses preassigned group locations to partition vehicles on the road.

Stationary LPG

The basic architecture feature of the stationary LPG is to use a GPS-based grid to partition roadways into *zip code areas* that define LPGs: if you are in area 1, you belong to LPG1; in area 2, LPG2; and so on (Fig. 3). This architecture assumes that GPS reception (or other positioning information) is available and can work with the in-vehicle navigation system to define the LPG by:

- Making the positioning process more accurate
- Integrating with the navigation system's map database

Stationary means that each LPG area is location-based and well defined. Members of LPG dynamically change as vehicles move. How to

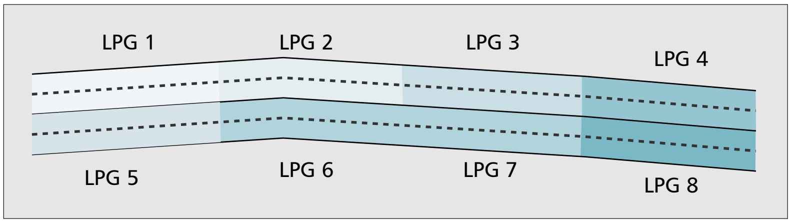


Figure 3. *Stationary (zip code area) LPGs.*

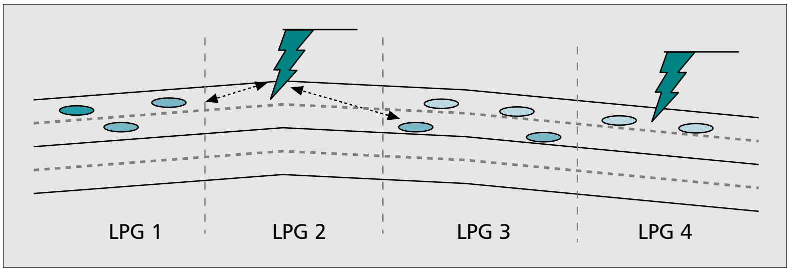


Figure 4. *Integration with roadside infrastructure.*

partition the stationary LPG areas is an issue that depends on road conditions, traffic patterns, and communication range.

The choice of a reasonable size for each LPG is a system design decision, depending on many factors such as the kind of radio technology used, communication range, number of vehicles we want to be in an LPG, road conditions (e.g., a curve), traffic pattern, and population density. Since vehicle traffic pattern and density are different at different places, sizes of LPGs will be different. Typically, the LPG size should be larger than the radio communication range so that we can maintain a relatively large size for each LPG and perform multihop communication. We may also need an overlapping area between adjacent LPGs to smooth the LPG changing process. The overlapping area size will depend on vehicle speeds and adaptation time for vehicles to switch LPGs.

Stationary LPGs may be integrated with roadside wireless infrastructure (Fig. 4), providing backbone access or inter-LPG communications even when some LPGs are empty (e.g., no vehicle in LPG2). We may set up special gateways to the LPGs that have the roadside wireless infrastructure, without any need to change the design and configuration of the LPGs.

Since each LPG area is well defined and stationary, we do not need to perform LPG forming, merging or splitting, dynamic LPG ID assignment, and IP address assignment. Since an LPG is related to geographic location, if we know a vehicle is in a particular LPG, we know its location and IP address range, and how to reach it. Stationary LPGs have some shortcomings:

- They require a positioning device (e.g., GPS). This adds cost and needs to deal with locations where the GPS signal is not strong enough.
- The LPG area is independent of radio coverage and thus cannot guarantee that vehicles within the same LPG can communicate with each other.

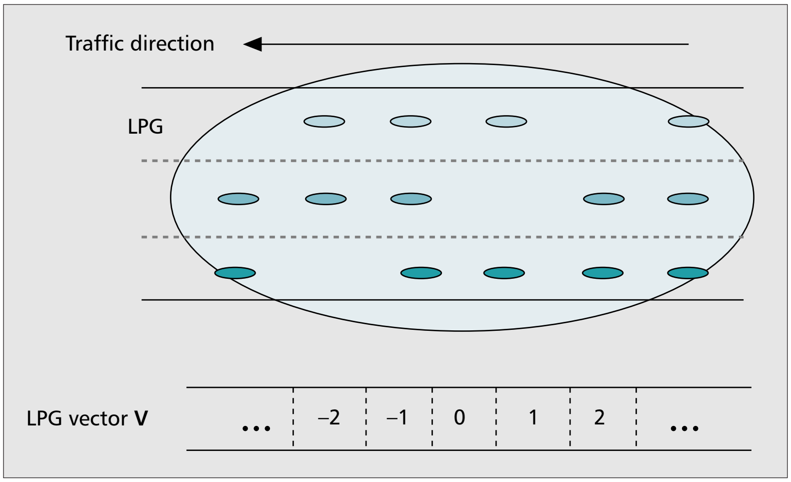


Figure 5. *LPG with relative ordering.*

- Defining and updating LPG areas can be difficult, given the likely large number of areas and the need to keep LPG databases up to date in all vehicles.

DYNAMIC LPG

The basic idea is for vehicles in the immediate vicinity to dynamically form a local peer group based on radio coverage so that they can tightly coordinate for near-instantaneous communications. Since LPGs are formed based on radio coverage, vehicles within an LPG can communicate with each other via single- or multihop. The baseline option is to simply form dynamic LPGs of neighboring vehicles for information dissemination without further internal structure. However, other options are possible to better control the message direction, wireless access prioritization, and bandwidth efficiency of multicast or message relay. We outline additional options below.

LPG with Relative Ordering — The sense and awareness of the direction in which each warning message is intended to propagate will enable more efficient communications in the roadway environment. For example, a vehicle may designate a warning message as going to the back of the LPG, and vehicles ahead of this vehicle in the LPG need not relay the message, thereby reducing the amount of relay traffic. The sense of direction may be derived from the relative ordering of vehicles. The relative ordering of vehicles may be estimated on demand or maintained periodically as described below.

On-demand estimation of relative ordering of vehicles: A vehicle (V_a) sending a message will include its GPS position and the timestamp in the message (along with the intended message direction). A vehicle (V_b) receiving this message may estimate the relative ordering with V_a by estimating V_a's current position based on its likely displacement and previous position. By comparing the estimated position of V_a with V_b's current position, V_b can determine the relative ordering of the two vehicles. V_b will try to forward the message (subject to coordination with other vehicles) only when V_b is along the path of the intended message direction. This approach requires that the vehicles' GPS devices are synchronized in time. The estimation error depends on the vehicle speeds, communication latency, update frequencies of the GPS devices, and accuracy of GPS readings. Mistakes can be made when mobility is high, or vehicles are close to each other (e.g., neighboring lanes).

Periodic maintenance of relative ordering of vehicles: The basic idea is to organize the LPG as a vector **V** (Fig. 5). Each vehicle in the vector has an ID, which is the position index of **V**. With this construct, vehicles can control the direction of information propagation. For example, information can go backward from the LPG if the sending vehicle (with index i) indicates that its message is meant for vehicles with indices larger than i, and only vehicles with indices $j > i$ will try to relay the message (subject to coordination with other vehicles). Furthermore, position index provides possibilities to prioritize MAC by associating the access priority of a vehicle with its position index (e.g., giving higher priority to vehicles at the front of the LPG since they may be more likely to observe warning events).

The position index i of a vehicle can be initialized in a straightforward manner. When a vehicle (N) is joining the LPG, it makes first contact with some vehicle (L) that is already in the LPG. N learns the position of L, and inserts itself into **V** based on the GPS readings of N and L. For example, if N is ahead of L and L is the current front-end position with an index n, N assigns $n - 1$ as the position index to itself and becomes the new front-end. If N is behind L and L is in the back-end position with an index n, N assigns $n + 1$ as the position index for itself and takes over as the new back-end. If L (with index n) is in neither the front-end nor the back-end position, N joins in the middle: N inserts itself into **V** by comparing GPS readings with L, and triggers an update of the indices of the vehicles behind the insertion point. The relative ordering of vehicles may be maintained via periodic updates. The basic objective is to swap the indices when two vehicles swap their relative positions. At periodic intervals, vehicles exchange GPS readings and swap their position indices if their relative positions have been swapped. The overhead to maintain ordering consistency can be reduced by increasing the update interval; as a result, the relative ordering is approximate or statistical between updates.

LPG with Linked Equivalent Cells — Maintaining ordering consistency in LPG with relative ordering (LPG-RO) may incur high overhead when the number of vehicles in LPG is large. In dense vehicle networks, it probably makes sense to assign one position index to several neighboring vehicles that are within the same radio coverage and form an equivalent cell (EC). An EC thus corresponds to a segment of LPG-RO's vector: a collection of vehicles with contiguous indices in the LPG-RO is represented as an EC, and a single message transmission within an EC can be received by all vehicles in the EC. In dense vehicle networks, it probably makes sense to have only selected vehicles to relay warning messages, instead of all vehicles trying to relay and result in channel scheduling and collision problems for the underlying MAC.

The basic idea of LPG with linked ECs (LPG-LEC) is thus to form linked ECs and disseminate information using the ECs as base units (Fig. 6). In LPG-LEC, relative ordering is maintained only among ECs (reducing ordering-maintenance overhead), and each message is relayed once per EC (improving bandwidth efficiency). ECs are connected via radio links.

Specifically, each EC has one EC header (ECH). Each ECH is linked with its neighboring ECHs; thus, all ECHs in an LPG are serially linked. This implies that they are connected on the order of radio hop count and represented as the forwarding nodes of an efficient broadcasting tree. Only the ECHs are responsible to relay messages, so unnecessary traffic is minimized. Every ECH periodically advertises its list of linked ECHs (i.e., comprising the one-hop ECHs, two-hop ECHs, etc.), and every vehicle (either ECH or non-ECH) updates its list of linked ECHs. Thus, all linked ECH lists can be consistent with each other. With such a consistent list, every vehicle is able to detect its own and its ECH's mobility, engage in ECH election and ECH swapping, and also determine the direction of traffic. Details of the LPG-LEC organization protocol is beyond the scope of this article and will be reported in a future paper.

Next we focus on several key open issues, identified through our benchmarking and design work, that require more improvement in order for ad hoc networking technologies to be used in VSC. These are multihop throughput, connection setup time, and configuration issues.

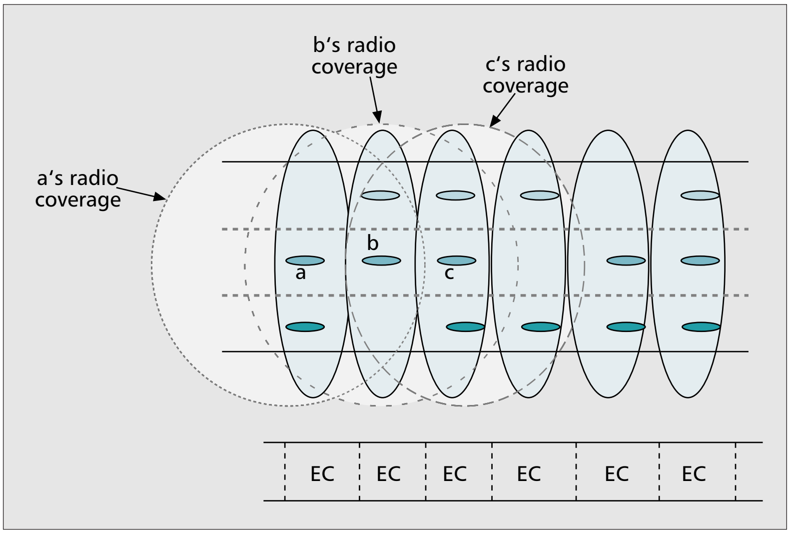


Figure 6. *LPG with linked equivalent cells.*

OPEN ISSUE: MULTIHOP THROUGHPUT

One design issue for vehicle-to-vehicle communications is the impact of an inconsistent multihop throughput available for safety applications. The multi-hop throughput is influenced by factors including

- The network load and topology characteristics
- Characteristics of the shared wireless medium

NETWORK LOAD AND TOPOLOGY

As the number of hops increases, the multihop throughput may decrease dramatically due to protocol overhead and node capabilities. As the number of vehicles increases, the explosion of routing messages reduces the effective throughput. As mobility increases, maintaining routes incurs a higher load on the network since the channel quality changes every millisecond, so routes cannot be based on a single-route message usually sent every second. Safety traffic behavior will influence the network load and increase contention due to its bursty nature (clustered warning arrivals). The power of the antennas, link strength, and operation modes of vehicles will impact the one-hop neighbors. Omnidirectional antennas with a larger radius can reach more vehicles but create more contention, while a smaller radius can result in frequent loss of link connectivity as vehicles move and interference changes. These factors should be considered in LPG sizing and performance engineering.

MAC THROUGHPUT

When multiple vehicles share a channel and have warning packets to transmit (say, for the same road obstacle), packet collisions will occur. The contention interval will reduce throughput since the bandwidth is unused when vehicles go into backoff mode as in 802.11b. Procedures such as request to send/clear to send (RTS/CTS) for every packet and acknowledgments (ACKs) also consume bandwidth. Although enhancements have been proposed to improve single-channel MAC [5–7], design of MAC protocols for LPG that support high throughput in presence of hidden vehicles remains an issue.

Since current 802.11 protocols use radio technologies that are half-duplex, and thus vehicles cannot send and receive messages simultaneously, one approach to improve throughput is to use multichannel MAC for LPG. The maximum throughput per node achievable with multichannel MAC is half of the channel capacity μ as the number of channels $n \to \infty$, while single-channel MAC throughput is on the order of $\mu\sqrt{\kappa}$ where κ is the number of nodes [8]. The dedicated short-range communications (DSRC) draft standard [9] in fact has seven channels, with one control plus six service channels. LPG can be built on DSRC by using the channels and radios of DSRC. LPG in turn can manage VSC performance by controlling group size, group configuration, and the unicasting/multicasting of safety information, and adding multihop communication capability (not considered by DSRC) for efficiency and reliability.

For future work, the grouping approaches proposed in this article will be further developed. Within LPG, efficient and reliable unicasting and multicasting protocols need to be developed, along with multiple-channel MAC protocols to support such routing protocols.

Open Issue: Connection Setup Time

Connection setup time is defined as the time required to connect one vehicle to another vehicle and begin transmission of information. In this article we focus on the latencies at the IP and MAC layers.

IP Latency

Nodes need to be configured with valid IP addresses for communication in a network. This is typically done using dynamic schemes such as DHCP or DRCP/DCDP. If IPv6 is used, permanent unique IP addresses are possible, removing the need for IP configuration in real time.

LPG needs to minimize routing delays, which are impacted by latencies for neighbor discovery, route setup (reactive), or route convergence (proactive). Latency of neighbor discovery (via listening to hellos from neighbors) is proportional to the periodic hello intervals, which are about 1 s for many ad hoc schemes. Appropriate hello intervals should be investigated for LPG. One challenge is to choose a suitable routing strategy for LPG and minimize the latency for route setup or convergence as the case may be when vehicle mobility is high and the available route changes frequently:

- The time for route setup to a destination in unicast routing (e.g., AODV, DSR) [10]
- The time for route setup for multicast spanning tree in multicast routing [11]
- Time to acquire the destination GPS location in position-based forwarding [12]
- Route convergence delay in proactive unicasting/multicasting (e.g., OLSR, CAMP [13])

Cross-layer protocol design for LPG should be adopted to reduce overall latency where contention resolution (at underlying MAC) and unicast/multicast forwarding are jointly considered. For LPG, link-layer implementation of unicasting/multicasting protocols must also be explored.

MAC Latency

For LPG, a multichannel MAC should minimize latencies related to channel selection (vehicles scanning for the best channel to use and avoid hidden node) and channel access. LPG can be built on the seven channels (one control plus six service) of DSRC. For multichannel with a single transceiver, the control channel can be used to resolve medium access and coordinate service channels for transmission. If multiple transceivers are available, an additional functionality is the multitasking-capable MAC and LLC to coordinate multiple channels simultaneously. To date, the DSRC MAC protocol has not been finalized. But with conventional carrier sense multiple access with collision avoidance (CSMA/CA) in 802.11b, when multiple vehicles try to access the channel simultaneously (say, to warn about the same emergency event) they go into contention mode and back off for some random time before trying to attempt to send again. To minimize channel access latency, LPG can help the MAC by controlling the group size, assigning access priorities to vehicles, controlling message direction and range to minimize flooding, and coordinating unicast/multicast forwarding to minimize MAC-layer contentions.

Open Issue: Network Configuration

While current networking technologies require a priori configuration, vehicle networks may lack the infrastructure for this. With infrastructure, address assignment via DHCP or destination resolution via DNS can be done with servers in the infrastructure. Without such infrastructure, vehicles need to cooperate to manage configuration information. Configuration issues include:

- Node configuration parameters: In vehicle networks, for dynamic ID configuration such as IP addressing we need to consider how addresses and address pools are defined and allocated. We need to consider how to deal with LPG merges and partitions as well as releasing addresses for vehicles no longer in the domain.
- Server access: Vehicles will need to know where information is located, whether within their group or externally. A discovery and selection process may be needed within LPG to determine which vehicles will act as servers.
- Destination discovery: Vehicles need a mechanism to establish end-to-end connection with a specific destination, and be able to determine who the destination node is and how to reach it.

Related Work

In the United States the FCC in 1999 assigned a 75 MHz bandwidth band in the 5.9 GHz frequency band for DSRC dedicated for ITS applications. In 2002 the American Society for Testing and Materials (ASTM) issued a DSRC standards draft (ASTM 2213-03) focused on layers 1 and 2 [9]. The DSRC draft was based on IEEE 802.11a and designated seven 10 MHz channels (one control plus six service channels) in the 5.9 GHz band. In 2003 IEEE activity changed the name from DSRC to WAVE, and the standardization effort is underway within IEEE 802.11. In the United States DSRC protocol specification has so far focused on vehicle-with-infrastructure communications; consideration of vehicle-to-vehicle communications is underway. While the DSRC PHY and link layers will use the 802.11a protocols, the DSRC MAC protocol is still open. Also, DSRC does not consider multihop communications. Our LPG architecture is complementary to DSRC. LPG can be built on DSRC by using its channels and radios, and LPG in turn can manage VSC performance by controlling group size, group configuration, access priorities, and transmission direction and range to minimize flooding, coordination of unicasting/multicasting forwarding to minimize MAC collisions, and enabling multihop communication.

A recent simulation study [14] on DSRC links showed the one-hop packet latency at the MAC layer (on a single channel using CSMA/CA without RTS/CTS/ACK) to be below 100 ms under random arrivals for the packet generation rates used in the simulations, but only about 60 percent of packets were successfully received (i.e., about 40 percent of neighbors never received the warning messages). These results reinforce the need for LPG architecture for timely delivery and sustained multihop throughput under bursty cluster arrivals.

A mobile P2P approach to traffic environment was proposed in [15] for traffic information distribution among application peers, and basic rule-based mechanisms were defined for selection of the peer space by application peers. This work is complementary to our LPG architecture; logical peer space for application peers may be formed on top of several LPGs that provide VSC capability.

To assess the state-of-the-art commercial capabilities, we conducted extensive roadway experiments using 802.11b-like products (no DSRC product is available yet) and multihop routing protocols. Both 802.11b and 802.11a use the same MAC protocol with different radios. From our results (Table 2), 802.11b offered the best throughput and latency, but had no multihop routing. Product A used an AODV-like protocol (with proactive/reactive components), and offered the best latency (~2 s) among products with multihop routing. Products B and C used AODV and TBRPF routing protocols, respectively. All products suffered rapid deterioration of multihop throughput (from the one-hop throughput shown), and the maximum hop number was 4. The LPG concept was motivated in part by the experimental results to organize neighboring vehicles for efficiency and reliability.

	Throughput (kb/s)	Max distance (m)	Connection time (s)	Max number of hops
802.11b	3900	500	> 0.1	1
Product A	1400	500	~ 2	4
Product B	370	1600	< 5	3
Product C	2900	350	> 30	> 3

Table 2. *Benchmarking commercial ad hoc technologies.*

Conclusions

We have identified key open issues that will impact the near-instantaneous dissemination of safety information in vehicle-to-vehicle communications. To meet the stringent VSC requirements, current ad hoc networking approaches for MAC, routing, and configuration need to be enhanced to support the 100 ms latency bound and sustained multihop throughput for reliability.

While there are still many issues to be resolved, we have proposed the local peer group (LPG) architecture to organize neighboring vehicles as a first step toward providing near-instantaneous safety communications. Two LPG alternatives, stationary and dynamic, are proposed to take advantage of roadway characteristics and support efficient dissemination of safety information. For future work, the grouping approaches proposed in this article will be further developed. Within LPG, efficient and reliable unicasting and multicasting protocols need to be developed, along with multichannel MAC protocols to support such routing protocols.

Acknowledgments

The authors would like to thank Jasmine Chennikara-Varghese, John Lee, Marcus Pang, Chiao-Wai Lee, Toshiro Hikita, Onur Altintas, and the anonymous reviewers for helpful comments that improved the presentation of this article.

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