Reliable Neighborcast

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***Abstract*—In this paper, we introduce a new communications paradigm, namely, reliable neighborcast, and present a reliable neighborcast protocol (RNP) that operates as an overlay on the existing reliable broadcast protocols. The protocol is intended for vehicle-to-vehicle communications networks that communicate the speed, position, and state of nearby vehicles to coordinate or control their operation. The implementation of RNP that we describe operates on top of overlapping groups that use the mobile reliable broadcast protocol and provides the guarantees and characteristics of that protocol to each neighborhood. The efficiency of the overlays—defined as the fraction of the received messages that apply to a neighborhood—widely varies. We present an efficient overlay for 1-D networks, which is implemented in many highway applications. The characteristics of mobility are considered, and techniques are presented to eliminate delays as vehicles change neighborhoods and to move the underlying broadcast groups with the general flow of traffic.**

***Index Terms*—Broadcast, multicast, neighborcast, vehicle control.**

I. Introduction

NEIGHBORCAST is a new communications paradigm for applications that exchange information on speed, position, and state between vehicles. Each vehicle communicates with a set of nearby vehicles—called its neighborhood. The neighborhoods for nearby vehicles overlap, but may be different, as shown in Fig. 1. The communications group for each of the vehicle's neighbors is different from its own group, so the neighbors communicate with different vehicles than the first vehicle, and the neighbor's neighbors communicate with different vehicles than the neighbor. Neighborcast is substantially different from conventional broadcast or multicast, which contains communications within single group.

The communications environment for vehicle-to-vehicle applications is extremely demanding. Communications is over wireless links that have much less bandwidth and much higher error rates than wired networks. The bandwidth constraints and the nature of radio transmission lead us to use broadcast rather than point-to-point links between neighbors. The error rates mandate efficient message recovery procedures. Finally,

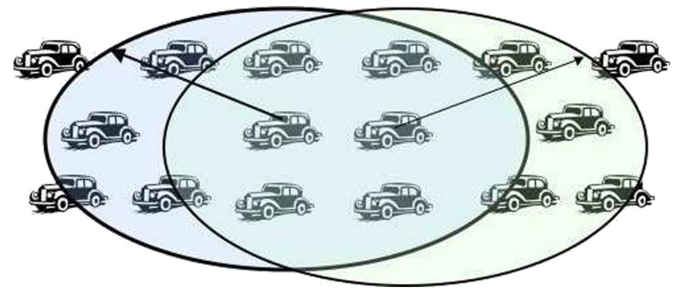

Fig. 1. Neighborcast.

the vehicles in the applications continuously move with respect to one another and change the neighborhoods.

A reliable neighborcast protocol (RNP) provides guarantees such as message delivery, sequencing, and delay. In this paper, we construct RNP as an overlay on multiple overlapping reliable broadcast protocols. The efficacy of the overlay is determined by the fraction of the received messages that are new messages in a participant's neighborhood. In Section III-A, an efficiency measure is defined, which is decreased by receiving broadcast messages that are outside the neighborhood and receiving duplicate messages from the overlapping groups.

RNP can be constructed on top of any reliable broadcast protocol. In this paper, we construct RNP on top of the mobile reliable broadcast protocol (M-RBP) [1], [2]. M-RBP provides reliable delivery and consistent message sequencing between all members of a broadcast group. It is efficient in terms of the number of control messages required per broadcast message. Unlike earlier reliable broadcast protocols, M-RBP has a dynamically changing broadcast group, which makes it well suited to mobile applications. A brief description of M-RBP is provided in Section II.

In Section III, we show how to construct efficient overlays that we can pass guarantees from the underlying broadcast groups to each of the neighborhoods. In the mobile environment, the membership in the broadcast groups and the neighborhoods continuously change because vehicles move with respect to one another. In Section III-B, we show how to configure the overlap so that vehicles do not experience delay when they enter a neighborhood, although they experience delays when changing broadcast groups. A self-organizing protocol that moves broadcast groups with the general flow of vehicles and manages changes in the number and size of the broadcast groups is described in Section III-C.

A. Applications

Vehicle-to-vehicle applications can provide warnings of impending danger to the operator, can control external devices such as traffic signals, or can directly control the operation of

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a vehicle. There is a reluctance by drivers to give up control of their vehicles, but considering the acceptance of antilock brakes and the willingness to let technology parallel park our cars, automatic control will be accepted as its value is demonstrated.

Many applications can be implemented with sensors and no communications. However, applications can almost always be improved by also using information from sensors in nearby vehicles. The applications can be further improved by providing information that cannot yet be detected by sensors. For instance, communications can provide a warning when a driver steps on the brakes, before the car slows down. In addition, when vehicles are controlled, communications can be used to negotiate an operation such as a lane change, and vehicles can be prevented from stopping more quickly than a larger heavier vehicle behind them.

The guarantees provided by communications protocols and the message delay determine the type of operations a vehicle can perform, and how well the applications perform. For instance, when there is a high probability that a message is not received, warning lights may be useful, but the messages are less useful for control. Message delay determines how well a vehicle can be controlled. For instance, the current Federal Aviation Administration (FAA) and European aviation agency communications standard VDL Mode 4 [3] can only read data from an airplane every 5 s in a reasonably congested airspace such as the airspace around Heathrow airport. Because of this delay, the separation between planes must be greater than the distance a plane can travel in 5 s.

Most current applications apply to automobiles and trucks on roadways [4]. The three main problems that are being investigated are the four-way stop problem, the lane change problem, and the convoying problem.

The four-way stop problem [4]–[6] controls traffic signals. The objective is to reduce commuting time and to improve fuel efficiency by reducing the time that vehicles spend stopped at intersections. Sensors are currently used to detect cars waiting at an intersection to control the traffic light. The first application of communications will provide information about cars that are approaching the traffic light so that the light can be better scheduled. The long-term objective is to control the operation of cars so that they approach an intersection in tightly packed groups, with space between the groups, so that it is not necessary for any cars to actually stop at the intersections.

In Europe and Japan, systems are being used to warn cars when changing lanes is dangerous [7], [8]. Eventually, communications will make it possible for cars to negotiate lane changes. When a car signals a lane change, the cars in the adjacent lane will make space for the car to safely enter the lane and inform the car when it is safe.

Distributed techniques are being applied to groups of vehicles that are traveling in close proximity to one another on a highway. In the literature, this application is referred to as platooning, convoying, or automatic cruise control [8]–[14]. The braking and accelerating of trucks in a convoy is controlled to prevent vehicles with different stopping distances from colliding. This technique is analogous to an antilock brake system that is distributed among all nearby vehicles. It has been shown that convoying on highways can significantly reduce accidents [9]. Convoying also decreases the time that vehicles spend on a highway, thus reducing fuel consumption and increasing the capacity of highways during peak hours.

The techniques that are proposed to control automobiles are also being used to coordinate the operation of robots on a factory floor [15]. The same techniques can well be equally applied to air traffic, to safely space airplanes in holding patterns, and to landing fields, to prevent runway incursions. Likewise, the techniques can be applied to trains to maintain safe-stopping distances and to coordinate a larger number of smaller commuter trains. The advantage of applying the techniques to trains and planes is that communication is regulated, and access to the infrastructure is restricted. Automotive applications must consider the effect of nonparticipating vehicles, nonvehicular traffic, and pedestrians.

The techniques that are used to improve safety and conserve fuel also increase the volume of traffic that can use a highway during rush hour [9]. This reduces the need to invest in new highways. Likewise, applying the techniques to trains and planes will increase the volume of traffic that can be supported by our current infrastructure and reduce the need for additional investments.

The applications establish the requirements on RNP. In [4] and [5], the need for new communications protocols was shown. In [16], the need for peer-to-peer communications, rather than just sensors, roadside communications networks, or cellular communications systems to support these applications, was cited. In [4], the need for broadcast protocols to conserve bandwidth and the need for a protocol to control group membership were cited. In [17]–[19], the effect of message loss on the ability to control a vehicle was analyzed and the need for message recovery mechanisms was supported. Tsugawa *et al.* [10] analyzes the effect of delay on platooning mechanisms, and Yang [20] analyzes the effect of delay on collision warning.

B. Related Work on Intervehicle Communication Protocols

Numerous medium access control (MAC) protocols have been considered for use in intervehicle communication. In [21], the authors analyze the performance of the standard IEEE 802.11 with user datagram protocol and transmission control protocol in a vehicle platooning application. In [20], [22], and [23], the IEEE 802.11 contention resolution protocol is modified to give precedence to emergency messages. In [24], a dedicated short-range communications is evaluated, which uses a 5.9-GHz MAC/physical layer with carrier sense multiple access/collision detection and orthogonal frequency division multiplexing. In [25]–[27], the authors reduce contention by mapping the spatial location of a vehicle to channel resources in time-division multiple access, frequency-division multiple access, and code-division multiple access (CDMA). Borgonovo *et al.* [28] introduce a fully distributed reservation-based time slot MAC scheme for vehicular *ad hoc* networks. Reference [29] shows a proposal from Toyota that uses multiple channels and power control to reduce contention. Khaled *et al.* [30] describe a power control scheme that adjusts the transmit power dependent on driving conditions. RNP and M-RBP are application-level protocols that can operate on any

MAC layer and can take advantage of any of the techniques described in these papers.

Broadcast protocols that rely on MAC layer services have also been developed to communicate application-specific information and/or provide additional capabilities. The FAA and European aviation agencies have backed the single-hop automatic dependent surveillance-broadcast protocol, in which an aircraft transmits position and velocity packets at 1–2 Hz on a 1-Mb/s random access channel [31]. Matsuda *et al.* [32] describes a multihop broadcast flooding relay protocol that filters forwarded packets based on delay, relative distance, and other metrics on slotted Aloha. In [33] and [34], the authors describe token-based protocols that only permit sources to transmit when they receive the token, so there are no collisions at the MAC layer. However, communication can be delayed if token transmission is delayed. Reference [35] provides a reliable broadcast through a source sequence number and receiver negative acknowledgement mechanism.

A number of networking approaches have been proposed for automotive communications systems that use relaying nodes that are installed along roadways. In [36], vehicles are organized into clusters and communicate with a relay box that acts as a gateway between clusters. The relay box operates as a cluster coordinator and guarantees that all of the vehicles in a cluster receive the messages in the same order. In [37], the vehicles use the IEEE 802.11 to communicate with the relay boxes, and in [38], the vehicles use Aloha to reach the nearest relay box and are then assigned a fixed time slot. These proposals require a considerable investment in infrastructure before they can be deployed.

The concepts of moving groups and neighborhoods are entering the literature on vehicle-to-vehicle communications systems. In [39], quasi-static and moving "application clusters" are discussed, and a cluster controller is defined to ensure consistent data delivery to all cluster members. In [40], vehicle "peer spaces" are formed using either a moving cluster or peer-centered architecture. Reference [41] is a broadcast flooding protocol that uses Global Positioning System techniques to determine nodes used to forward messages to a specific moving geographical zone, which is the neighborhood. In [42], the road is divided into nonoverlapping broadcast cells that move with the vehicles. One vehicle serves as a base station in each cell and is responsible for relaying messages to neighboring cells.

II. M-RBP

RNP can operate on top of any reliable broadcast protocol and can provide the guarantees of that protocol to neighborhoods. M-RBP provides a set of guarantees that is useful in vehicle applications, and has characteristics that are needed in mobile networks. In this paper, we describe the operation of RNP as an overlay on M-RBP. The operation of M-RBP is described here, but a more complete description is found in [1] and [2].

M-RBP is the most recent of a family of reliable broadcast protocols, including RBP [43] and timed reliable multicast protocol (T-RMP) [44]. These protocols are peer-to-peer protocols that operate on top of any MAC layer or wireless interface. In a highway application, with short transmission distances, automobiles may use the inexpensive IEEE 802.11 devices; in an aircraft application, longer distance transmissions are required that may use CDMA to share the channel, and in a subway, multihop forwarding is needed to transfer a signal around bends in a tunnel. The RBP family of protocols may be used on top of any of these transmission layers.

M-RBP guarantees the delivery of all of the source messages to all of the receivers, places the source messages in the same sequence at each receiver, and informs the receivers when all of the other receivers have the message. It provides the guarantees with as little as one acknowledgment per source message, independent of the number of receivers, by a receiver token passing mechanism that was first used in RBP. It also provides delay guarantees by using a timed token passing mechanism first described for T-RMP. There are two levels of delay guarantees as follows: one happens in a very short time and the other happens in a longer time. In a very short time, approximately equal to twice the time needed to recover a single message, M-RBP guarantees that all of the receivers that are still in the broadcast group have received a source message. In a longer time, proportional to the number of receivers in the broadcast group, M-RBP provides a list of the receivers that were in the group and have the message. The tradeoff between delay and delivery guarantees makes M-RBP useful for a wide range of applications.

The predecessor protocols are quasi-stationary, i.e., they operate on a fixed group of receivers. When the group changes, the protocol stops, forms a new group, and distributes a token list to the group members. M-RBP continues to operate when the underlying receiver group changes by using an aggressive token passing strategy that does not require receiving a token before using it. Inconsistencies that occur because of this strategy are resolved by a distributed voting procedure. The voting procedure also identifies and removes receivers that have left the group. Receivers enter the group by sending a message to the group and waiting until the vote to accept that message is complete.

M-RBP uses a token ring of receivers, as shown in Fig. 2. The m receivers take turns as the acknowledging site by passing a token every Δ_T second. When a receiver passes the token, it transmits a control message with a unique sequence number. The control message contains an acknowledgment for all received source messages that have not been previously acknowledged. The source messages have a unique identifier. The sequence number assigned to the source message is the composition of the control message sequence number and its position in the control message list. All receivers recover missing control messages. When the receivers recover the missing control messages, they place the source messages in the same order.

In M-RBP, a receiver assumes the token at its scheduled time, whether it receives the control message from the previous token site. When a token site does not recover a missing control message before transmitting its own control message, it may acknowledge source messages that were previously acknowledged, and source messages may receive several sequence numbers. When multiple control messages sequence

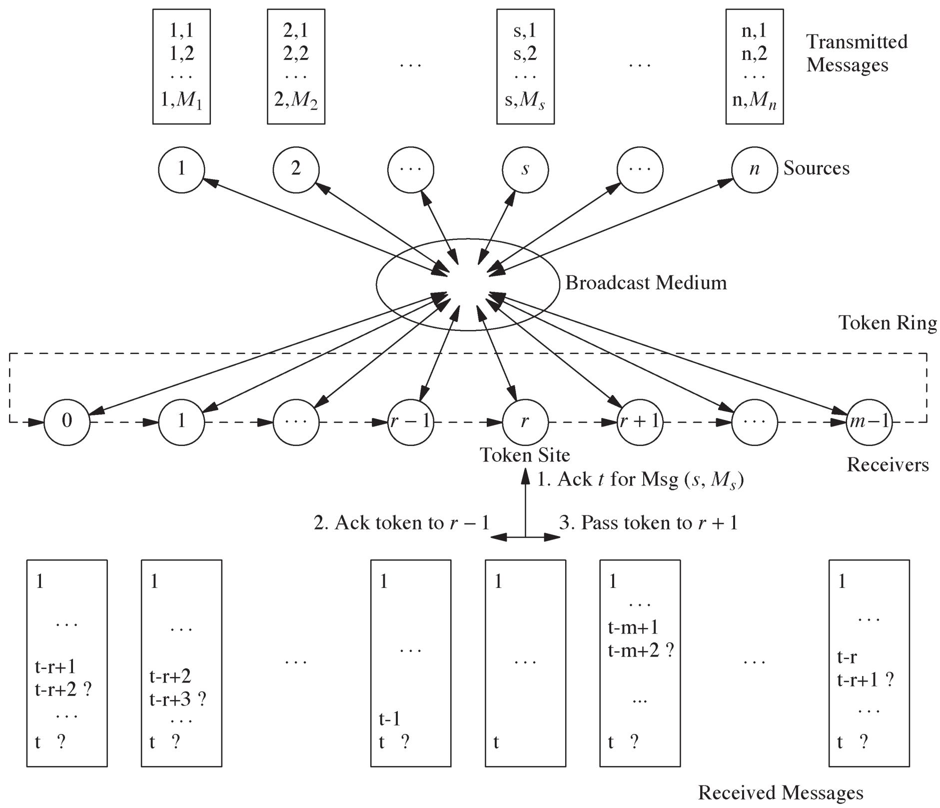

Fig. 2. M-RBP.

the same message, the lower-numbered sequence number takes precedence at each receiver, and unique sequencing is preserved.

Aggressive token passing, rather than waiting to receive a token, allows M-RBP to continue to operate when receivers leave the group. The receivers use a distributed voting procedure to determine when a receiver that was scheduled to send the control message has left the group. When the vote is complete, if a majority of receivers vote that a receiver failed to transmit a control message, all of the receivers remove that receiver from the token list, and the protocol continues to operate.

The e^{th} control message is scheduled to be transmitted at time t_e, and the other receivers begin a recovery process if they do not receive the message within the maximum propagation time. The maximum allowed recovery time for the control message is $T_A = (n_{\max} + 1/2)T_R$, where T_R is the time between recovery attempts, and $n_{\max}$ is the maximum number of recovery attempts before giving up. The control messages that are transferred after $t_e + T_A$ include a vote on whether the control message at t_e was transmitted. If there are m receivers in the group, at $t_e + 2T_A + m\Delta_T$, then all of the receivers have voted, and the control messages with the votes have been recovered by all of the receivers that can recover the control messages. The vote is then tallied at each of the receivers. A similar vote is started for the messages acknowledged by the e^{th} control message to decide which messages are included in the final sequence. That vote is started at time $t_e + (2n_{\max} + 1/2)T_R$, which is the maximum time to recover the acknowledged messages after recovering the acknowledgment.

When the vote for the e^{th} control message is tallied, we have the following:

1) $A(e)$ receivers that have received the e^{th} control message;
2) $B(e)$ receivers that have not received the e^{th} control message;
3) $C(e)$ receivers that have left the group and have not voted.

$C(e) = m_e - (A(e) + B(e))$, where m_e is the number of receivers in the group when the vote starts. If $A(e) < m_e/2$, then the receiver that was scheduled to transmit the control message is voted out of the group, and it is not counted in m_e in future votes.

Each receiver may not receive all of the votes. At receiver r_j, $A_j(e) \le A(e)$, and $B_j(e) \le B(e)$. We require r_j to make the correct decision or leave the group itself. At r_j, the following are considered.

- If $A_j(e) \ge m_e/2$, then $A(e) \ge m_e/2$, and r_j leaves the receiver that transmitted the e^{th} control message in the group.
- If $B_j(e) > m_e/2$, then $B(e) > m_e/2$, $A(e) < m_e/2$, and r_j removes the receiver that transmitted e^{th} control message from the group.
- If $B_j(e) \le m_e/2$ and $A_j(e) < m_e/2$, then r_j is uncertain whether $A(e) < m_e/2$ and leaves the group itself.
- If $A_j(e) \ge m_e/2$, but r_j has not recovered the e^{th} control message, then r_j leaves the group.

One token round later, the receivers know which receivers have received the e^{th} control message and have remained in the group. If more than half of the receivers leave the group on a particular token passing round, then the group dissolves and is

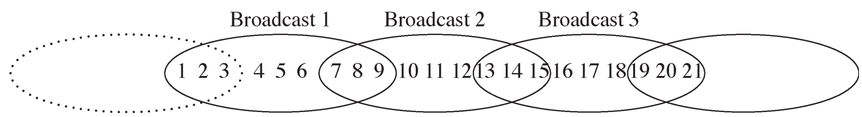

Fig. 3. Overlapping broadcast groups, with evenly spaced vehicles, in a 1-D network.

reformed by individual receivers joining a group with nearby receivers.

III. RNP Overlay on M-RBP Groups

In this section, we operate RNP as an overlay on top of the overlapping M-RBP groups. An underlying M-RBP group includes all of the vehicles in an area, and the area covered by M-RBP group covers all or part of the neighborhoods of the vehicles in the area. A separate RNP operates in each vehicle and joins the messages from each of the M-RBP groups that cover its location. To provide the M-RBP guarantees to the neighborhood, as described in Section III-D, each member of a vehicle's neighborhood must be in at least one of the M-RBP groups that cover the vehicle's location. One-dimensional overlays that are adequate for highways are described in Section III-A, and the 2-D and 3-D extensions that are needed for airports and airspaces are described in Section III-E.

As vehicles move, they can enter and leave neighborhoods and can change the M-RBP groups. In M-RBP, it takes more than a token rotation time to add a new vehicle to the group. The overlap of the M-RBP groups is selected so that the time that it takes to enter and delete vehicles from the M-RBP groups does not cause any delay when entering or removing vehicles from the neighborhoods in RNP, as described in Section III-B.

The frequency with which vehicles enter and leave the M-RBP groups is reduced by having the groups move with the vehicles on a highway. However, the vehicles move with respect to one another and the groups change. A self-organizing algorithm that organizes groups around the vehicles is described in Section III-C.

A. Architecture of 1-D Underlying Groups

A highway can be modeled as a 1-D network of vehicles that move with respect to one another. Depending on the application, the separate lanes on a highway may be modeled as parallel 1-D networks or as a single 1-D network.

The underlying broadcast protocols are arranged in overlapping groups that span a region in the network. A vehicle transmits and receives messages in all of the broadcast groups that cover its location. The size and overlap of the M-RBP groups is selected so that all of a vehicle's neighbors are in at least one of the M-RBP groups that cover the vehicle's location. This allows a vehicle to communicate with its neighbors without forwarding messages between broadcast groups.

Consider the simple example in Fig. 3. In this example, we show a 1-D system with three M-RBP groups and 21 evenly spaced vehicles. A vehicle's neighborhood is the vehicles three in front and three behind the vehicle. For instance, vehicle 10's neighbors are vehicles 7, 8, and 9 and 11 to 13. Broadcast group 1 includes vehicles 1 to 9, group 2 includes vehicles 7 to 15, and group 3 includes vehicles 13 to 21. Vehicles 1, 2, 3, 7, 8, 9, 13, 14, 19, 20, and 21 each transmit all of their messages in two broadcast groups and receive all of the messages from both groups. The other vehicles only transmit and receive in a single broadcast group. With this overlap, every vehicle belongs to at least one broadcast group with each of its neighbors. For instance, vehicle 5 has all of its neighbors, which are vehicles 2 to 4 and 6 to 8 in group 1, whereas vehicle 8 has its neighbors 5, 6, 7, and 9 in group 1 and its neighbors 7, 9, 10, and 11 in group 2. Note that its neighbors 7 and 9 are in both broadcast groups.

From the example, it is clear that there are many arrangements of broadcast groups that satisfy the constraints on neighborhoods. On one extreme, there can be a single broadcast group that covers the entire highway. The disadvantages with this configuration are the following: 1) Many of the guarantees are not provided until the token has cycled through all of the vehicles; 2) vehicles that participate in the group must receive or recover many messages which are not used; 3) powerful transmitters are required to have single-hop transmissions over the entire highway; and 4) there are a very large number of sources sharing the channel. The broadcast groups should be small.

At another extreme, each vehicle can have a broadcast group that covers its neighborhood. When a vehicle has N_n neighbors, it belongs to $N_n + 1$ broadcast groups. The disadvantage with this configuration is that each source message must be acknowledged in $N_n + 1$ separate groups, and the sequences in the different groups must be coordinated. Messages should be transmitted in a small number of broadcast groups.

To quantify the differences between the configurations, we define the overlay efficiency η_{ov} as the number of new messages received from neighbors over the total number of messages received. Assuming that each vehicle transmits about the same number of messages, $\eta_{\text{ov}} = \text{Average}_v[(N_n(v)/\sum_{v\in B_i}(N_{B_i} - 1))]$, where v is a vehicle, B_i are the broadcast groups that cover v, and N_{B_i} is the number of vehicles in B_i. In a configuration with a single broadcast group, the number of vehicles on the highway is $N_H \gg N_n$, and $\eta_{\text{ov}} = (N_n/N_H) \to 0$. In the configuration with one broadcast group per vehicle, each vehicle receives messages, many of which are duplicates, from N_n vehicles in $N_n + 1$ broadcast groups, $\eta_{\text{ov}} = (N_n/N_n(N_n + 1)) = (1/N_n + 1)$. In the example in Fig. 3, with one broadcast group per vehicle, $N_n = 6$, and $\eta_{\text{ov}} = 0.14$. In the configuration in the example $N_B = 9$, one third of the vehicles belong to one group, and two thirds of the vehicles belong to two groups: $\eta_{\text{ov}} = (1/3)(6/8) + (2/3)(6/16) = 0.5$. If the group size in the figure is reduced to 6, with the same overlap, then the efficiency increases to 0.6.

In general, vehicles and broadcast groups are not evenly spaced, a vehicle's neighborhood may extend further in one direction than another, and each of the groups and neighborhoods

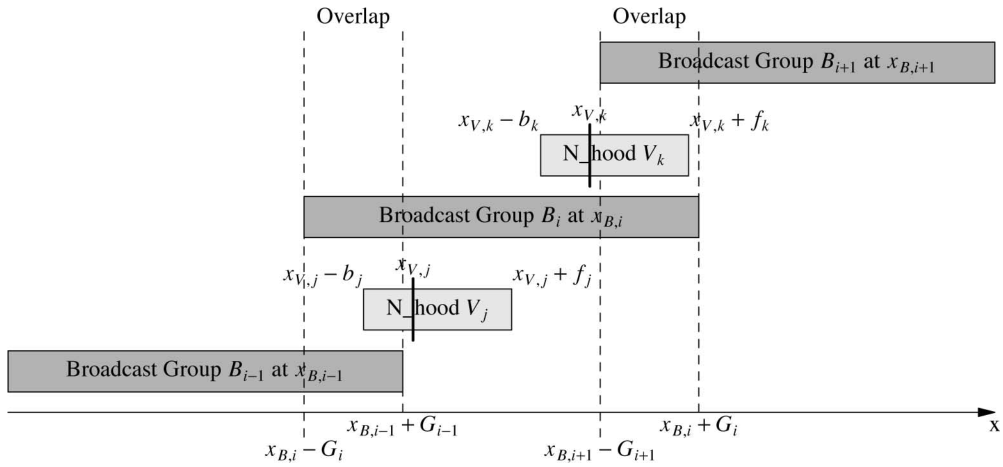

Fig. 4. General 1-D network.

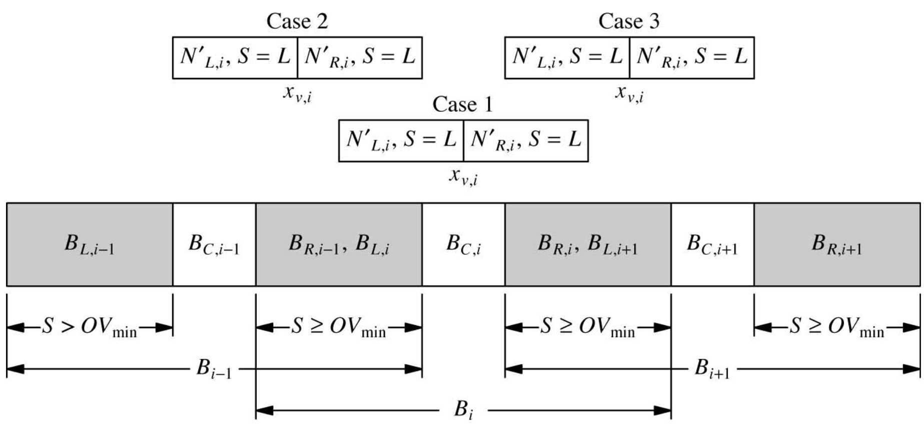

Fig. 5. Neighborhood and group partitions.

may have a different size, as shown in Fig. 4. In the remainder of this section, we show how to pick the group overlaps so that vehicles participate in at most two broadcast groups and can communicate with all of their neighbors without forwarding between groups.

Each vehicle participates in at most two groups when the maximum distance from the center to the edge of a group is less than the minimum distance between the centers of groups.

Broadcast group B_i is centered at location $x_{B,i}$ and includes all of the vehicles at distance G_i from $x_{B,i}$, $B_i = [x_{B,i} - G_i, x_{B,i} + G_i]$. Without loss of generality, $x_{B,1} < x_{B,2} < x_{B,3} < \cdots$. The separation between the centers of two adjacent groups is $S_i = (x_{B,i+1} - x_{B,i})$.

As long as B_{i-1} and B_{i+1} do not overlap for any i, at most, two broadcast groups cover any location. These two groups do not overlap when $x_{B,i-1} + G_{i-1} < x_{B,i+1} - G_{i+1}$, which can be rewritten as $G_{i-1} + G_{i+1} < S_{i-1} + S_i$, and holds for all i when $G_{\max} < S_{\min}$. In the remainder of this section, $G_{\max} < S_{\min}$, so that none of the vehicles are in more than two broadcast groups.

Any vehicle can communicate with all of its neighbors without forwarding between groups when the smallest overlap between groups is greater than the greatest distance between a vehicle and its neighbor.

Vehicle V_j is located at $x_{V,j}$. The vehicle's neighborhood includes all of the vehicles up to distance b_j behind it and distance f_j in front of it, $N_j = [x_{V,j} - b_j, x_{V,j} + f_j]$. The overlap between adjacent groups is $\mathrm{OV}_i = (x_{B,i} + G_i) - (x_{B,i+1} - G_{i+1})$. We show that a vehicle can reach all of its neighbors as long as $\mathrm{OV}_{\min} > L$, where $L = \max_j(b_j, f_j)$ is the greatest distance from a vehicle to its neighbor.

Define a larger symmetric neighborhood $N'_j = [x_{V,j} - L, x_{V,j} + L]$. If V_j can reach any vehicle in N'_j, then V_j can reach any vehicle in N_j.

N'_j can be viewed as a left-hand and a right-hand neighborhood, where the left-hand neighborhood is $N'_{L,j} = [x_{V,j} - L, x_{V,j}]$ and the right-hand neighborhood is $N'_{R,j} = [x_{V,j}, x_{V,j} + L]$. The size of $N'_{L,j}$ and $N'_{R,j}$ is L (Fig. 5).

When $G_{\max} < S_{\min}$, at most two broadcast groups cover any region, and any B_i can be broken into three distinct parts as follows:

1) a left-hand part $B_{L,i}$ that overlaps B_{i-1};
2) a central part $B_{C,i}$ that does not overlap with any other groups;
3) a right-hand part $B_{R,i}$ that overlaps B_{i+1},

as shown in Fig. 5. The size of $B_{L,i}$ and $B_{R,i}$ is $\geq \mathrm{OV}_{\min}$.

For a vehicle, $x_{V,j} \in B_i$.

1) When $x_{V,j} \in B_{C,i}$, the vehicle is in the center of the group.
   a) All right-hand neighbors can be reached in B_i because the distance from $x_{V,j}$ to the right-hand edge of $N'_{R,j}$

is L and the distance from $x_{V,j}$ to the right-hand edge of B_i is greater than the size of $B_{R,i}$ which is $\geq \text{OV}_{\min} > L$.

b) All left-hand neighbors can be reached in B_i because the distance from $x_{V,j}$ to the left-hand edge of $N'_{L,j}$ is L, and the distance from $x_{V,j}$ to the left-hand edge of B_i is greater than the size of $B_{L,i}$, which is $\geq \text{OV}_{\min} > L$.

2) When $x_{V,j} \in B_{L,i}$, the vehicle is in the overlap with B_{i-1}.

a) All right-hand neighbors can be reached in B_i because the distance from $x_{V,j}$ to the right-hand edge of $N'_{R,j}$ is L, and the distance from $x_{V,j}$ to the right-hand edge of B_i is greater than the size of $B_{R,i}$, which is $\geq \text{OV}_{\min} > L$.

b) All left-hand neighbors can be reached in B_{i-1} because the distance from $x_{V,j}$ to the left-hand edge of $N'_{R,j}$ is L, and the distance from $x_{V,j}$ to the left-hand edge of B_{i-1} is greater than the size of $B_{L,i}$, which is $\geq \text{OV}_{\min} > L$.

3) When $x_{V,j} \in B_{R,i}$, we have the following.

a) All right-hand neighbors can be reached in B_{i+1}, as in step 2a.

b) All left-hand neighbors can be reached in B_i, as in step 2b.

The smallest overlap is $\text{OV} = L + \varepsilon$, with this overlap, the smallest size group is $2G = 2 * \text{OV} + \varepsilon = 2L + \varepsilon$. With the smallest group size and smallest overlap, every vehicle is in two groups. When $f_i = b_i = L$, the neighborhood size equals the group size, and $\eta_{\text{ov}} = 0.5$.

B. Extending the Overlap to Avoid Delay When Entering a Neighborhood

We keep the broadcast groups small, for efficiency. However, if a neighborhood ends near the edge of a broadcast group, then a vehicle that enters an area must first join the broadcast group before joining the neighborhood. Therefore, there is a delay before the vehicle can join the neighborhood. M-RBP continuously modifies the broadcast group, but it takes time to enter a new participant in the group. The new member transmits a message asking to join the group and must wait until the message is acknowledged and voted into the group. If we make the group size larger than the minimum and use the extra coverage to increase the overlap, then we can include mobile vehicles in M-RBP group before they can join a neighborhood. In this way, a vehicle is never delayed when it enters a neighborhood.

For example, let the overlap $\text{OV} = L + C$. In Fig. 6, the overlap consists of regions 1, 2, and 3. Regions 1 and 3 are C long, and region 2 is $L - C$ long. Vehicle A enters broadcast group B_i when it enters region 1. However, all of its neighbors are in broadcast group B_{i-1} until it enters region 2, since the size of regions $2 + 3$ is L. Once vehicle A enters region 2, some of its neighbors may only be in group B_i, and it must be included in that group to communicate with those neighbors. Vehicle A has the time it takes to cover distance C to join B_i. Similarly, when vehicle A' enters region 3, it has the time it takes to enter region 2 before some of its neighbors may only be in B_{i-1}.

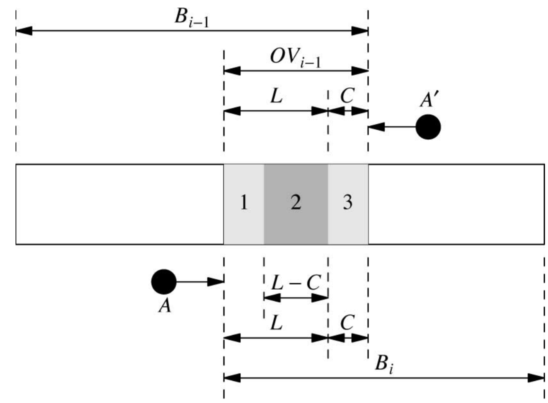

Fig. 6. Vehicles change broadcast groups when the overlap is extended by C.

The size of C depends on the time it takes to enter a vehicle into a broadcast group and the time it takes for a vehicle to cross a region of size C. For instance, assume that it takes at most 5 s to enter vehicles into a broadcast group. If the broadcast groups are stationary and the vehicles are moving at 50 mi/h, then the vehicles can travel about 75 ft in 5 s. Therefore, C is 75 ft. However, if the broadcast groups are moving with the average speed of the vehicles instead of being stationary and vehicles travel within 5 mi/h of the average speed, then the value of C is about 7.5 ft, which is only $(1/10)^{\text{th}}$ the value for stationary groups.

The region C decreases the efficiency η_{ov} by increasing the size of the broadcast groups, whereas the size of the neighborhood remains the same. The decrease in efficiency is greater for stationary groups than for moving groups. Therefore, it is advantageous to have the groups move with the vehicles.

C. Managing Moving Broadcast Groups

In a highway application, stationary groups can be located at fixed intervals with respect to mileage markers. Locating and spacing moving groups is more challenging than locating stationary groups. We require a self-organizing procedure that moves the groups at the average speed of the vehicles, changes the size and center of the groups as vehicles move relative to one another, adjusts the size of adjacent groups toward the desired value, and adds and deletes broadcast groups when necessary. In this section, we describe a procedure that uses the characteristics of M-RBP to manage moving groups.

1) Functions Performed by the Vehicles: The vehicles in a broadcast group are responsible for moving the center of the group as the vehicles move, expanding the size of a group to cover vehicles that move at different speeds, splitting groups that become too large, joining groups that become too small, and starting new groups when necessary. The rules for changing the broadcast group are independently executed at each vehicle. The vehicle reports its suggested change to the group when it transmits its token, and the change does not take place until the token is voted into the list by the M-RBP voting procedure. The vehicle may also send a source message to the group if it must issue a change when it does not have the token. A source message, which is transmitted by a vehicle in the overlap, is used to merge two adjacent groups and simultaneously notify the members of both groups. The source message must also go through the M-RBP voting procedure before the change takes effect.

Each time a vehicle transfers the token, it broadcasts its current location to all of the members of its broadcast group. We assume that a vehicle in B_i knows the current center $x_{B,i}$ and span G_i of the broadcast group, the last reported locations of each vehicle in B_i, and the transmission time of the token that reported the location. Furthermore, a vehicle in the overlap OV_i between B_i and B_{i+1} has the information on both groups.

When a vehicle transmits a token at time t_e, it uses its local information to change the size or center of its broadcast group. The change does not take effect until the vote is tallied at $t_v = t_e + 2T_A + m_e\Delta_T$. To compensate for this delay and possibly outdated information on vehicle locations, the vehicle uses the predicted position of the vehicles at the time the change will take effect, assuming that the vehicles travel at a constant speed. For instance, if the last two times that vehicle V_i transfers the token in B_i is t_1 and t_2, and reports its locations as x_1 and x_2, and vehicle V_j uses the location of V_i to cause a change that will take effect at time t_v, then the location that V_j uses for V_i is $x_{v,i} = x_2 + (x_2 - x_1)(t_v - t_2)/(t_2 - t_1)$. By using the last three reports from V_i, V_j could also estimate V_i's acceleration and make a more accurate estimates of its position.

Vehicles adjust a group's position and size to maintain a target overlap between adjacent groups and a target group size. The target overlap is $\mathrm{OV}_T = L + C + \Delta$, where we have the following.

— L is the overlap to guarantee that a vehicle can communicate with all of its neighbors.
— C is the additional overlap to allow vehicles to enter an underlying broadcast group before entering a neighborhood.
— Δ is an additional overlap to prevent vehicles near the boundary of a group from rapidly moving in and out of the group as the boundary moves.

A vehicle does not start to join a new group until it is Δ past the boundary. The additional overlap provides hysteresis and stops vehicles from rapidly joining and leaving groups with small changes in the group boundaries. The target broadcast group size has $G = \mathrm{OV}_T + \eta$.

2) Starting New Broadcast Groups: Vehicles start new broadcast groups whenever they are in a region without broadcast groups and when they are near the boundary of a single broadcast group. When a vehicle is not covered by any broadcast groups, it starts a broadcast group with its location as the center, and $G = \mathrm{OV}_T + \eta$. The vehicle periodically transmits a token, with the location and span of the group, as an invitation for other vehicles to join the group. When a vehicle is covered by only one broadcast group and it is within OV_T of an edge of the group it starts a second broadcast group that overlaps the first group by OV_T, with itself in the overlap.

3) Moving the Broadcast Groups With the Vehicles: All of the vehicles in a group move the group every time they pass the token. When a group moves, its size may change. If the size becomes large enough to encompass two target group sizes with a target overlap, then the group is split in two. If a group size decreases to the point where locations are covered by more than two groups, then two of the overlapping groups that were adjacent are joined.

To move a broadcast group, a vehicle in B_i with the token determines $x_{V,\min} \in B_i$ and $x_{V,\max} \in B_i$, the smallest and largest predicted positions for vehicles when the vote on the token message is tallied. The vehicles use these positions and the current edges of the groups to determine the new span of the group, from $x_{\min}$ to $x_{\max}$. The calculation that a vehicle performs depends on whether the vehicle has information about an adjacent group.

1) If the vehicle is not in the overlap with B_{i-1} or B_{i+1}, then it calculates $x_{\min} = \min[x_{V,\min}, x_{B,i} - G_i]$ and $x_{\max} = \max[x_{V,\max}, x_{B,i} + G_i]$.
— All of the vehicles remain in the group.
— The left-hand edge of the group can only move to the left, increasing the overlap with B_{i-1}.
— The right-hand edge of the group can only move to the right, increasing the overlap with B_{i+1}.
— The group size can only increase.

2) If the vehicle is in the overlap with B_{i-1}, then it calculates $x_{\min} = \min[x_{V,\min}, x_{B,i-1} + G_{i-1} - \mathrm{OV}_T]$ and $x_{\max} = \max[x_{V,\max}, x_{B,i} + G_i]$.
— All of the vehicles remain in the group.
— The left-hand edge of the group can move to the left or the right. It moves to the right when all of the vehicles in the group vacate part of the overlap, and the target overlap can be maintained.
— The right-hand edge of the group can only move to the right, increasing the overlap with B_{i+1}.
— The group size can increase or decrease.

3) If the vehicle is in the overlap with B_{i+1}, then it calculates $x_{\min} = \min[x_{V,\min}, x_{B,i} - G_i]$ and $x_{\max} = \max[x_{V,\max}, x_{B,i+1} - G_{i+1} + \mathrm{OV}_T]$.
— All of the vehicles remain in the group.
— The left-hand edge of the group can only move to the left, increasing the overlap with B_{i-1}.
— The right-hand edge of the group can move to the right or left. It moves to the left when all of the vehicles in the group vacate part of the overlap, and the target overlap can be maintained.
— The group size can increase or decrease.

The vehicle calculates $x'_{B,i} = (x_{\max} + x_{\min}/2)$ and $G'_i = \max_i[G_i, (x_{\max} - x_{\min}/2)]$. These values are included in the acknowledgment message.

4) Splitting Groups: All of the vehicles can determine when a group is large enough to be split into two groups. If $2G'_i > 3\mathrm{OV}_T + 4\eta$, then the group can be split into two groups with $G_i^{\mathrm{new}} > \mathrm{OV}_T + \eta$ and an overlap between the groups of OV_T. The centers of the groups are at $x_{i,1}^{\mathrm{new}} = x'_i - ((G'_i - \mathrm{OV}_T/2)/2)$ and $x_{i,2}^{\mathrm{new}} = x'_i + ((G'_i - \mathrm{OV}_T/2)/2)$. The span of the new groups are $G_{i,1}^{\mathrm{new}} = G_{1,2}^{\mathrm{new}} = ((G'_i + \mathrm{OV}_T/2)/2)$. When a broadcast group is split, the change will not take effect until the vote on the token that instructs the split is tallied.

At that time, all of the vehicles in the group know that it will be split.

5) Joining Two Adjacent Groups: Vehicles in the overlap between two broadcast groups B_i and B_{i+1} are responsible for joining groups when the edge of one group covers the center of another group. This condition can result in more than two groups covering a position. As long as the edge of a group cannot cover the center of an adjacent group, three groups cannot cover the same position. When $x_{B,i+1} - G_{i+1} \leq x_{B,i}$ or $x_{B,i} + G_i \geq x_{B,i+1}$, the center of one group is covered by the edge of the other. The groups are joined with the center at $((x_i - G_i) + (x_i + 1 + G_{i+1})/2)$, and $G = ((x_{i+1} + G_{i+1}) - (x_i - G_i)/2)$, so that the new group covers the area of the two groups.

The vehicle in the overlap simultaneously transmits a source message in both groups with instructions not to use the new groups until a time when the vehicle believes that the vote on the source messages in both groups will be complete. If the new group is larger than the maximum size target group because one group was much larger than the other, then it will be divided into two equal size groups by the first token in the new group.

D. Transferring Guarantees Through RNP

The RNP overlay processes the messages from one or more broadcast groups and passes those messages to the application. The broadcast groups include messages that are from vehicles that are not in this vehicle's neighborhood, these messages are filtered out. Some messages are received from more than one of the broadcast groups, the duplicate messages are removed. Finally, when two messages appear in more than one broadcast group, the messages may be in a different order in the two groups. This may happen when the first message is retransmitted in one of the groups.

Complete sequencing over the entire network is an unnecessary burden, since no vehicles receive most of the messages. We define partial sequencing as two messages having the same order at any vehicles that must receive both. We are currently investigating several techniques to convert different orders in two broadcast groups into the same sequence.

One technique first synchronizes the numbers of the acknowledgments so that acknowledgments in different groups that occur at approximately the same time have the same sequence number. When a source message is acknowledged by different acknowledgment numbers in different groups, the source sends a new broadcast message to move the original message to the earlier sequence number. The possibility of moving a message increases the time until a message can be dependably sequenced.

E. Two- and Three-Dimensional Overlapping Broadcast Groups

Section III-A derives the overlap for a 1-D network. A 1-D network may be applied to single tracks on a railroad or the lanes on a highway. Intersections of roads, switches on a railroad, and the surface of an airport require a 2-D network, and control of an airspace requires a 3-D network. The overlaps

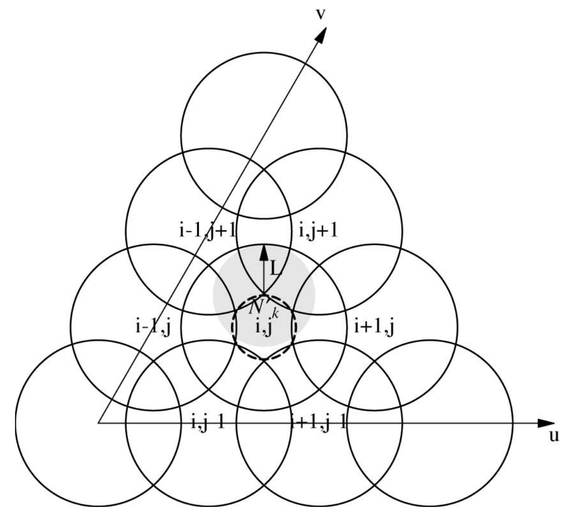

Fig. 7. Two-dimensional reliable neighborcast and the underlying broadcast groups.

of 2-D groups are overlapping circles, and the overlaps for 3-D groups are overlapping spheres. In a 2-D network, a vehicle may need to belong to as many as three underlying broadcast groups to communicate with all of its neighbors. In addition, in a 3-D network, a vehicle may need to belong to as many as four underlying broadcast groups to communicate with all of its neighbors.

When vehicles can randomly move through a 2-D or 3-D area, the underlying broadcast groups must be stationary. We can use groups that move with the vehicles by restricting the motion so that all vehicles in an area travel in the same direction. Airplanes in a 3-D airspace travel in the same direction at different elevations.

In a 2-D application, the neighborhood N_i may have irregular shapes, but it must contain the vehicle V_i at location (x_i, y_i). Similar to the symmetric neighborhood in the 1-D example, we can define a neighborhood N'_i that is a circle with radius L that is the maximum distance from V_i to the edge of N_i for all i. If we can communicate with any vehicle in N'_i, then we can communicate with any vehicle in N_i because $N_i \subset N'_i$.

In Fig. 7, the centers of equal size underlying broadcast groups are equally spaced along the (u, v) axis. The (u, v) axis are at a 60° angle with respect to one another and are commonly used to space base stations in a cellular network on an unobstructed plane [45]. The broadcast groups are the solid circles with radius r. The centers of the broadcast groups are located s apart. When $r < \sqrt{3}s$ at most three broadcast groups cover a location.

The shaded circle is the symmetric neighborhood N'_k with radius L, for vehicle V_k. If we draw a dashed circle with radius $y = r - L$, when the center of the neighborhood is within the dashed circle, then all of the neighbors of V_k can be reached in broadcast group (i, j). When V_k is outside the dashed circle but within $B_{i,j}$, some of the neighbors are outside $B_{i,j}$, and V_k must also be in the other broadcast group to communicate with those neighbors.

When the dashed circle includes the cusp of the circles that intersects in $B_{i,j}$, any V_k that is outside the dashed circle is in multiple broadcast groups and can communicate with any vehicle in N'_k in one or more of the broadcast groups that cover its location. The dashed circles include the cusps when $y \geq (s/2)\sqrt{3} - \sqrt{r^2 - (s/2)^2}$. Since $y = L - r$, we have the constraints on L, r, and s that guarantee communications within a neighborhood. If $L' < L$ defines the symmetric neighborhood, then $C = L - L'$ is the distance that a vehicle can traverse before it must join a new broadcast group.

In three dimensions, the transmission regions are equally spaced spheres. The symmetric neighborhood N' is a sphere with radius L equal to the distance to the furthest vehicle that is considered a neighbor. We have the same construction with an inner sphere whose radius is large enough to include the cusp of spheres that intersects within a transmission radius. The cusp is formed by three spheres, and there may be four broadcast groups covering a vehicle's position.

IV. Conclusion

We have described a new paradigm for vehicle-to-vehicle communications, which is called neighborcast. In neighborcast, a vehicle communicates with all nearby vehicles, which is the vehicle's neighborhood. Each vehicle's neighborhood is distinct from, and overlaps with, that of its neighbors. Communication is not contained in a well-defined group of vehicles, as in broadcast and multicast, but is spread over a large area.

Reliable neighborcast guarantees that messages are delivered to all of the vehicle's neighbors. We have shown how to implement RNP as an overlay on overlapping reliable broadcast protocols such as the M-RBP. Selecting the overlay has a strong effect on the efficiency, which is the fraction of the received messages that are from neighbors. In 1-D systems, which describe many applications, simple overlay configurations that use a single broadcast group or a single broadcast group for each vehicle are extremely inefficient. The efficiency of the single broadcast group approaches zero in a highway application. We show that small broadcast groups, which are comparable in size to the neighborhoods, with the overlap limited to two broadcast groups per vehicle, can have an efficiency of about 0.5.

Mobility is the defining characteristic of intervehicle applications. Vehicles continuously change neighborhoods. We show that we can bring vehicles into new neighborhoods and preserve the delivery guarantees without any delay by slightly increasing the overlap of the underlying broadcast groups. The rate at which vehicles change underlying broadcast groups decreases when broadcast groups move with the vehicles. We present a distributed algorithm that is executed by each vehicle, which moves the groups, adds new groups when needed, merges and splits the groups as vehicles move with respect to one another, and preserves the overlay characteristics that are needed to guarantee communications. This algorithm is being simulated to verify that it works and to determine the efficiency of the overlays. The results will be presented in the sequel.

This paper focuses on 1-D networks, which are adequate for many automobile applications. The architecture to extend the results to 2-D and 3-D networks is presented. Higher dimensional networks are needed for airports and airspaces.

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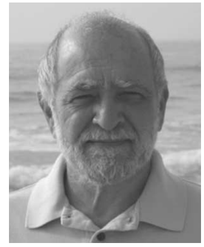

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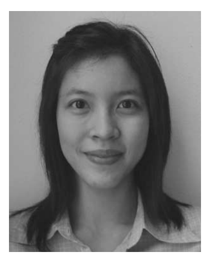

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