DV-CAST: A DISTRIBUTED VEHICULAR BROADCAST PROTOCOL FOR VEHICULAR AD HOC NETWORKS

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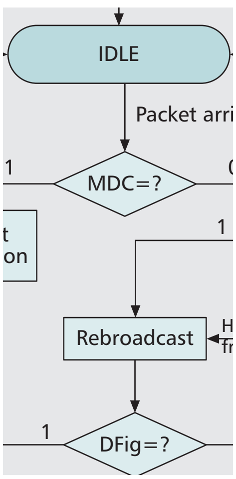

The authors focus on highway scenarios and present the design and implementation of a new distributed vehicular multihop broadcast protocol, which can operate in all traffic regimes, including extreme scenarios.

ABSTRACT

The potential of infrastructureless vehicular ad hoc networks for providing safety and non-safety applications is quite significant. The topology of VANETs in urban, suburban, and rural areas can exhibit fully connected, fully disconnected, or sparsely connected behavior, depending on the time of day or the market penetration rate of wireless communication devices. In this article we focus on highway scenarios, and present the design and implementation of a new distributed vehicular multihop broadcast protocol, that can operate in all traffic regimes, including extreme scenarios such as dense and sparse traffic regimes. DV-CAST is a distributed broadcast protocol that relies only on local topology information for handling broadcast messages in VANETs. It is shown that the performance of the proposed DV-CAST protocol in terms of reliability, efficiency, and scalability is excellent.

INTRODUCTION

Applications developed for vehicular ad hoc networks (VANETs) have very specific and clear goals such as providing intelligent and safe transport systems. Emergency warning for public safety is one application that is highly time-critical and requires an intelligent broadcast mechanism to distribute warning messages. In order to design a broadcast protocol for VANETs, one must consider two major problems:

- *The broadcast storm problem*, which occurs when multiple nodes attempt to transmit at the same time, thereby causing several packet collisions and extra delay at the medium access control (MAC) layer
- *The disconnected network problem*, which occurs when the number of nodes in the area to help disseminate the broadcast message is not sufficient.

Although both problems, especially the broadcast storm problem, are well-known in the mobile ad hoc network (MANET) research community, so far each problem has been treated separately: most of the proposed algorithms were developed to either cope with the broadcast storm problem or handle the disconnected network problem. A good routing protocol targeting safety in VANETs, however, must be able to deal with these two extreme cases in a seamless manner. Hence, the goal of this work is to design a distributed broadcast protocol, that can both mitigate the broadcast storm and maintain network connectivity in disconnected networks.

In this article we present a detailed implementation of the Distributed Vehicular BroadCAST (DV-CAST) protocol. Unlike other existing protocols, which solve either the broadcast storm or disconnected network problem, DV-CAST can handle both problems simultaneously while incurring only a small amount of additional overhead. The proposed protocol utilizes local topology information (i.e., a list of one-hop neighbors) as the main criterion to determine how to handle the rebroadcast of the message.

The remainder of this article is organized as follows. The next two sections present the related work and outline different regimes of interest in VANETs that the designed broadcast protocol should be able to handle. The design overview of DV-CAST is then presented, while the detailed implementation of the protocol is described in the following sections. We then provide the details of the simulation environment and the performance evaluation of the DV-CAST protocol. In the following section certain design issues are highlighted along with a discussion. Finally, we summarize our findings in the final section.

RELATED WORK

There are a number of routing protocols specifically designed to cope with routing in sparsely connected MANETs. Data mules are proposed to function as mobile messengers that collect data from sensors and deliver to a virtual backbone in sensor networks [1]. Epidemic routing relies on mobile nodes to exchange the data they possess whenever they encounter new neighbors [2]. Role-based multicast [3] is proposed to achieve maximum reachability in a sparsely connected or fragmented network by using the *store-carry-forward* mechanism. Single-copy [4] and multi-copy *Spray and Wait* [5] are shown to be efficient alternatives for message delivery. However, most of these studies focus on using ran-

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Our research has identified two extreme regimes of operation in VANET: dense traffic regime and sparse traffic regime. To design a good broadcast routing protocol that is robust enough to operate in any type of vehicular traffic conditions, it is important to understand the characteristics of these two regimes.

dom way point (RWP) model where node mobility has fewer real-world restrictions and may not be appropriate for VANET studies, as typical road topology is much more constrained and has a very well defined structure.

There are a few studies that address similar routing issues in sparsely connected VANETs. For example, [6] focuses on exploring the feasibility of the store-carry-forward concept on a bidirectional highway via extensive simulations. Building on this pioneering work, we have previously developed a comprehensive analytical approach to characterize key routing parameters in intermittently connected or disconnected VANETs by using empirical, analytical, and simulation-based studies [7]. While our work in [7] only focuses on highway networks, some recent studies have looked into a sparsely connected VANET using a Manhattan Grid model [8]. The proposed techniques to disseminate information in such a scenario include disseminating the packet in different directions when passing by the intersections [9]. These approaches, however, either rely on fixed infrastructures to provide network connectivity [10] or use GPS and map information to determine to whom to forward the packet [11]. These 2D Manhattan Grid studies are complementary to the problem of disconnected VANETs in a 1D highway scenario.

To the best of our knowledge, however, there is no prior study that can handle both the disconnected network and broadcast storm problems in a seamless manner via a distributed routing protocol for highway VANET scenarios. Our work fills this gap by designing a fully distributed new VANET broadcast protocol known as DV-CAST. Unlike existing studies, the proposed DV-CAST protocol can suppress the broadcast storm in a dense VANET environment in addition to routing in a sparsely connected VANET. The algorithm relies only on GPS information of the one-hop neighbors and does not require any centralized node or maps.

Different Regimes for Broadcasting in VANET

Our previous research has identified two extreme regimes of operation in VANETs: dense traffic and sparse traffic. In order to design a good broadcast routing protocol that is robust enough to operate in any type of vehicular traffic conditions, it is important to understand the characteristics of these two regimes. In the following, we give a brief overview of these regimes based on our previous work [7, 12].

Dense Traffic Regime

This scenario occurs when traffic density is above a certain value such that the considered network is fully connected. Because of the shared wireless medium, blindly broadcasting the packets may lead to frequent contention and collisions. This problem is sometimes referred to as the broadcast storm problem [13]. While multiple solutions exist to alleviate the broadcast storm problem in a typical MANET environment [13–16], only a few solutions exist for resolving this issue in the VANET context [9, 10, 12].

Sparse Traffic Regime

The other extreme scenario, which is very troublesome for conventional routing protocols, is the case where there are very few vehicles on the road. For instance, the traffic density might be so low at certain times of the day (e.g., late night or early morning) that multihop relaying from a source (the car trying to broadcast) to cars coming from behind might not be plausible because the target node might be out of the source's transmission range. To make the situation worse, there might be no cars within the transmission range of the source in the opposite lane either. Under such circumstances, routing and broadcasting becomes a challenging task.

While several routing techniques address the sparsely connected nature of mobile wireless network, (e.g., epidemic routing [2], single-copy [4], multi-copy Spray and Wait [5]), there are only a few studies that considered a VANET topology [9–11].

For both sparse and dense traffic scenarios, all vehicles operating in these two extreme regimes observe the same local topology, which also reflects the real global topology. However, it is possible that both of these two traffic conditions may coexist in the same network; for example, traffic is normally congested at a merging section on the highway, but flows smoothly beyond the merging point. Hence, it is possible that in such cases, not every vehicle sees the same local topology; some may have very few neighbors while some have many neighbors. In this case some vehicles will have to apply the broadcast suppression algorithm while others will have to store-carry-forward the message in order to preserve the network connectivity.

In the following section, we use these fundamental traffic scenarios as our building blocks in designing a new VANET broadcast protocol (DV-CAST).

DV-CAST Design Overview

In this section we present an overview of the DV-CAST protocol. The reported protocol is a new general-purpose vehicular broadcast framework that has unique features:

- It is robust against different types of vehicular traffic conditions.
- It depends *only on the local one-hop neighbor information* observed by each node (car) via the use of periodic hello messages.

Figure 1 illustrates, at a high level, the main concept behind the DV-CAST protocol, which consists of three major components: *neighbor detection*, *broadcast suppression*, and *store-carry-forward mechanisms*. The neighbor detection mechanism estimates the *local topology* by monitoring periodic hello updates received from one-hop neighbors. The local topology is an important piece of information as it is used to assist DV-CAST in determining how the packet should be handled. More specifically, each vehicle has to continuously monitor its local topology in order to determine the relevance of the broadcast message (i.e., whether it is an intended recipient of the message or not) and whether there is any neighbor in the broadcast direction or in the opposite direction. DV-CAST takes one of the two major courses of action according to the status of the vehicle. That is, a vehicle in a well connected neighborhood should immediately apply one of the broadcast suppression algorithms previously described in [12] when it receives the broadcast message, while it should resort to a store-carry-forward mechanism in a sparsely connected neighborhood.

The motivation for using the local topology information in our framework is to minimize the additional network overhead and keep the complexity of the protocol to a minimum. In particular, other safety applications such as blind spot detection also rely on these beaconing messages; therefore, the local connectivity is already a given piece of information, which the routing protocol can utilize. We believe that local topology information is sufficient for proper handling of the broadcast packet.

While the DV-CAST protocol presented in this article mainly targets safety applications, it has the potential to be useful for other non-safety applications, such as traffic information systgems [18] and entertainment applications [19], as well. Further research is needed to explore this potential.

In the following section we present the implementation of DV-CAST in detail.

Key Routing Components

Assumptions

As illustrated in Fig. 1, a key component of DV-CAST is the neighbor detection mechanism, which provides the protocol with local topology information. To simplify the problem, we focus on a highway topology with traffic traveling in two opposite directions. Let us consider a typical scenario where a source vehicle or a roadside unit (RSU) broadcasts a warning message to approaching vehicles. In general, the message would be beneficial to vehicles following the source vehicle or vehicles moving toward the RSU, while the message will most likely be irrelevant to vehicles moving in the opposite direction. Thus, the goal of DV-CAST is to distribute this broadcast message to a certain group of vehicles who will benefit from that warning.

For this work, we assume that the broadcast application can specify the Region of Interest (ROI) or the broadcast region where the intended recipients of the message are located. This ROI information will be tagged along with the routing message and will also be used along with the one-hop neighbor information in order to determine how the message should be handled. In particular, each vehicle should be able to determine the three pieces of information that are the main input parameters to the DV-CAST protocol:

- Destination flag (DFlg), which determines whether a car is the intended recipient of the message
- Message direction connectivity (MDC), which determines whether a car is the last vehicle in the group/cluster (or whether there is any next-hop neighbor moving in the same direction who will be responsible for reforwarding the message)

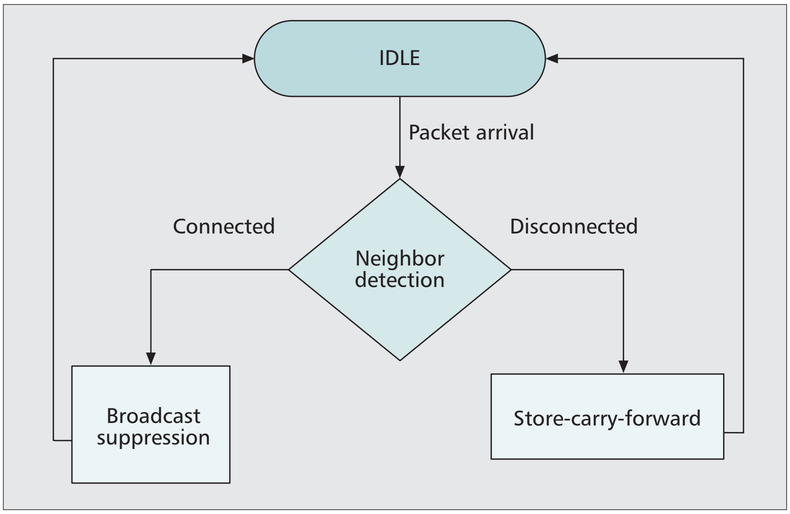

Figure 1. *High-level concept of DV-CAST protocol.*

- Opposite direction connectivity (ODC), which determines whether a car is connected to at least one vehicle in the opposite direction

Although additional information such as a neighbor's local topology might also help to improve the performance of the protocol, obtaining such information also implies an increase in network overhead. Hence, we claim that these three flags provide the necessary knowledge about the local topology information, which is sufficient for DV-CAST to determine how to handle the broadcast packets and achieve acceptable performance.

Local Topology Updates via Periodic Hello

In order to determine the value for the flags described earlier, each vehicle must have the most up-to-date local topology information (i.e., who is in its one-hop neighborhood and where each neighbor is located relative to its current position). To achieve this, each vehicle is required to periodically broadcast its GPS information `<latitude, longitude, heading>`, which can easily be done by adding an extra field in the hello packet and data packet headers. In the current protocol design, the hello broadcast frequency is set to 1 Hz, and the hello packet content is kept at a minimum. Note that the periodic hello beaconing is also a requirement in many other VANET safety applications. Hence, DV-CAST can also work with existing VANET applications without any change required.

Neighbor Detection Mechanism

Perhaps the most essential module in DV-CAST is the neighbor detection mechanism, as the routing action taken by the protocol depends mainly on the *local connectivity information*. Upon receiving the hello or data packet from the neighbor, each vehicle has to compare its GPS information against the neighbor's GPS information and determine whether the neighbor is moving in the same direction or in the opposite direction. In addition, neighbors moving in the same direction must also be further categorized into leading vehicle or following

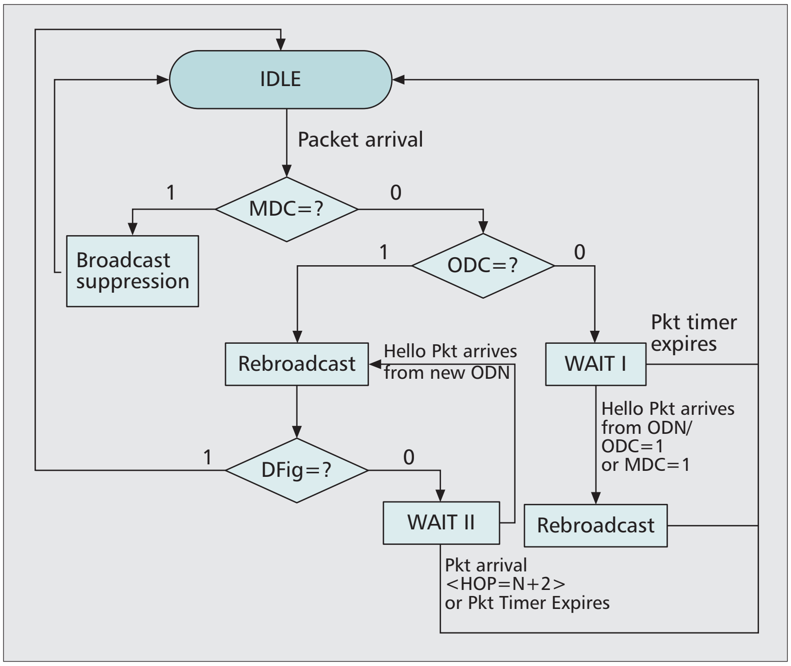

Figure 2. *Decision tree for DV-CAST protocol (ODN; opposite direction neighbor).*

vehicle. For this purpose, DV-CAST maintains three separate neighbor tables, `NB_FRONT`, `NB_BACK`, and `NB_OPPOSITE`, which contains the list of neighbors who are leading, following, or moving in the opposite direction, respectively. Each table is a priority queue, in which up to a MAX_{NB} number of neighbors are ordered according to the time of the neighbors' most recent GPS updates.

These neighbor tables along with the information from the broadcast packet header can be used to determine the three *binary flags* described earlier. Hence, MAX_{NB} does not need to be a large value since DV-CAST makes its decision based on these binary flags only. We set MAX_{NB} to 5 in our implementation.

Broadcast Suppression

A mobile node performs a broadcast suppression when it is in a dense traffic regime with at least one neighbor in the broadcast direction. In [12] we explore how serious the broadcast storm is in VANETs using a case study for a four-lane highway scenario and propose three lightweight broadcast techniques (i.e., weighted p-persistence, slotted 1-persistence, and slotted p-persistence), which can provide 100 percent reachability in a well connected network and up to approximately 70 percent reduction in the broadcast redundancy and packet loss ratio in a well connected vehicular network. The proposed schemes are distributed and rely on GPS information, but do not require any other prior knowledge about network topology. In this article we propose to use the weighted p-persistence scheme introduced in [12] in the final design of the protocol to handle the broadcast storm problem.

Store-Carry-Forward

In a sparse network we propose to cope with such an extreme situation via the so-called store-carry-forward mechanism [3]. Our previous results show that depending on the sparsity of vehicles or the market penetration rate of cars using dedicated short range communication (DSRC) technology [17], the network delay incurred in delivering messages between disconnected vehicles via the store-carry-forward mechanism can vary from a few seconds to several minutes. This suggests that a new ad hoc routing protocol will be needed as conventional ad hoc routing protocols such as Dynamic Source Routing (DSR) or Ad Hoc On-Demand Distance Vector Routing (AODV) will not work with such long re-healing times. This article addresses the detailed implementation of the distributed store-carry-forward mechanism, while [3] introduces only the concept of the mechanism.

In the following section we describe in detail the implementation of DV-CAST, which consists of these key routing components.

Routing Rules

Figure 2 illustrates the detailed implementation of DV-CAST. In order to handle the broadcast message properly, we propose that each vehicle follow two basic routing rules:

- If DFlg is set to 1, the vehicle should ignore any duplicate broadcast or follow the diagram in Fig. 2 if the message is received for the first time.
- If DFlg is set to 0, the vehicle is a relay node and should follow the routing diagram shown in Fig. 2. This is because in a very sparse network environment, a certain relay vehicle may have to help store-carry-forward the same message more than once.

Depending on the level of local connectivity the vehicle experiences, we propose three different courses of action the vehicle should follow in order to properly handle the broadcast packet.

Case I: Well Connected Neighborhood

A vehicle is said to be in a well connected neighborhood if it has at least one neighbor in the message forwarding direction (MDC = 1). As illustrated in Fig. 2, upon receiving the broadcast message, a vehicle in this regime should apply one of the broadcast suppression techniques previously presented in [12]. For example, if the slotted 1-persistence scheme is employed, each vehicle in this neighborhood will use the relative distance information calculated by using the source's information available in the packet header to determine the necessary backoff time, which is typically less than 100 ms. If the vehicle does not hear any rebroadcast of the same packet during this backoff period, it should rebroadcast the packet when this backoff timer expires. However, if it overhears the rebroadcast from its neighbor, it should cancel the pending rebroadcast and go back to the IDLE state. Observe that information regarding neighboring vehicles in the opposite direction is not relevant in this case. In particular, vehicles that are in a well connected neighborhood assume that they are operating in a dense traffic regime, regardless of the actual global traffic condition. That is, a vehicle whose MDC flag is 1 will behave as if it

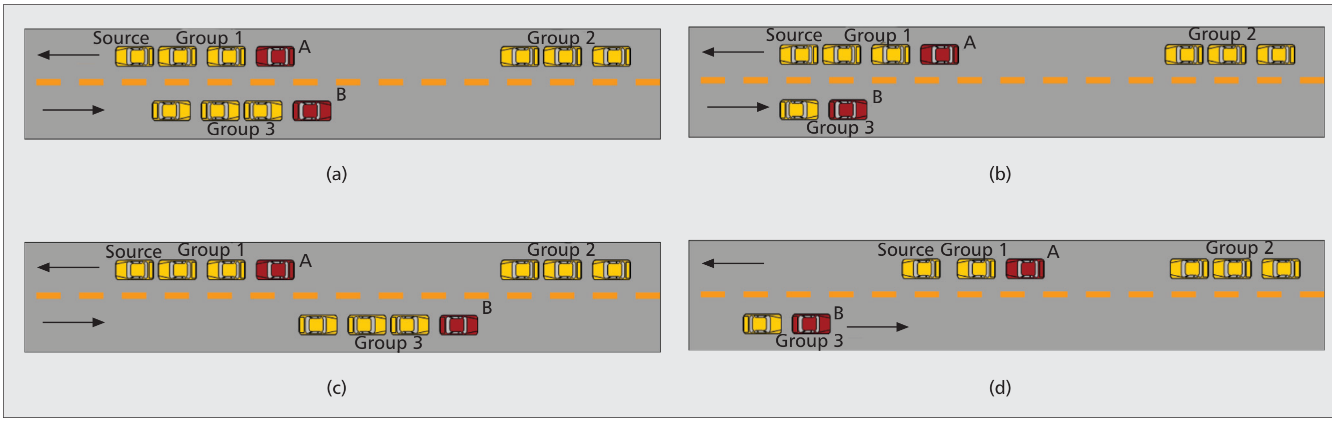

Figure 3. *The three different scenarios: a) Scenario 1: A's flag is <MDC = 1, ODC = 1, DFlg = 1>; b) Scenario 2.1: A's flag is <MDC = 0, ODC = 1, DFlg = 1>; c) Scenario 2.2: A's flag is <MDC = 0, ODC = 1, DFlg = 1>; d) Scenario 3: A's flag is <MDC = 0, ODC = 0, DFlg = 1>.*

is in a dense traffic regime, and it will apply the broadcast suppression algorithm regardless of the global traffic condition, which may be dense or sparse. It is expected that all vehicles will be in a well connected neighborhood during rush hours, while only a fraction of vehicles will be in a well connected neighborhood under normal or light traffic conditions.

According to Fig. 3a, each vehicle in Group 1, except for *A* which is the last vehicle in the group/cluster (MDC = 0), upon receiving the broadcast message from *S*, will have the following flags `<MDC = 1, ODC = 1/0, DFlg = 1>` (ODC can either be 1 or 0). Vehicles in group 3 except for *B* will also have similar flags, `<MDC = 1, ODC = 1/0, DFlg = 0>`. Each vehicle from both groups except for *A* and *B* will apply the broadcast suppression algorithm presented in [12].

Case II: Sparsely Connected Neighborhood

A vehicle is operating in a sparse traffic regime if it is the last node in a cluster. Furthermore, a vehicle in this regime is said to be in a sparsely connected neighborhood if there is at least one neighbor in the opposite direction as in the case of vehicles *A* and *B* in Fig. 3b and 3c. The parameters for these vehicles should be set to `<MDC = 0, ODC = 1, DFlg = 0/1>`. Upon receiving the broadcast message, these vehicles can immediately rebroadcast. However, if the vehicle is moving in the same direction as the source, as in the case of vehicle *A* whose DFlg is set to 1, it can go back to an IDLE state after the rebroadcast. On the other hand, a vehicle whose DFlg is 0, as in the case of vehicle *B*, has to make a transition to the WAIT II state where it waits until the packet timer expires or it can rebroadcast the packet back in the original message forwarding direction. Similar to the previous case, vehicles in a sparsely connected neighborhood assume that they are operating in a sparse traffic regime regardless of the actual global traffic condition.

In order to get a better understanding of how to handle the broadcast packet in this case, below we use the two scenarios shown in Fig. 3b and 3c as an example.

Scenario 2.1 — *A* and *B* are neighbors, and may receive the broadcast from *S* at the same or different times. Since *A* is aware of the presence of *B*, it will simply rebroadcast and make a transition to the IDLE state. On the other hand, the status of *B* will be `<MDC = 0, ODC = 1, DFlg = 0>`, so it will have to immediately rebroadcast since it cannot distinguish whether it is in scenario 2.1 or 2.2. After the rebroadcast, it transits to the WAIT-II state and holds on to the message until it detects a new neighbor vehicle in the opposite direction or the packet timer expires. The packet expiration time is a very important parameter for a relay node whose DFlg is set to 0, as it is the maximum time a relay node has to hold on to the message. The value used for this parameter depends on many factors, such as the maximum time the relay node is willing to store the packet, the message lifetime, or the expected time the vehicle remains in the region of interest. Hence, the packet expiration time is typically on the order of several seconds to a few minutes.

After the rebroadcast, if *B* comes into contact with vehicles in Group 2, *B* will rebroadcast and go into the WAIT II state again. This time, however, *B* will have to wait for an implicit acknowledgment that this is the rebroadcast of the message with greater hop count and go into the IDLE state.[1] However, if the gap between group 1 and group 2 is very large, *B* will likely be out of the broadcast region (ROI) and drop the packet before it reaches group 2.

Scenario 2.2 — Vehicles *A* and *B* would behave in the same way as in scenario 2.1. That is, they will rebroadcast and go into the WAIT II state. Since group 3 is connected to both group 1 & 2, both *A* and *B* will hear a rebroadcast with greater hop count and will make a transition into the IDLE state.

Case III: Totally Disconnected Neighborhood

A vehicle operating in a sparse traffic regime is said to be in a totally disconnected neighborhood if it has no neighbor in the message forwarding direction and is not connected to anybody in the opposite direction (i.e., MDC = ODC = 0). In this case the disconnected vehicle, vehicle *A* in Fig. 3d, should hold on to the broad-

[1] Note that although the protocol can force B *to go into the IDLE state immediately after it has rebroadcast to vehicles in group 2 by keeping extra routing parameters such as the number of rebroadcasts, we propose to use only three routing parameters (MDC, ODC, and DFlg) so the number of states are optimized for three parameters.*

MDC	ODC	DFlg	Scenario	Actions taken by DV-CAST Protocol
1	0/1	1	Well connected	Broadcast suppression
1	0/1	0	Well connected	Help relay the packet by doing broadcast suppression
0	1	1	Sparsely connected	Rebroadcast and assume that the ODN will help relay or rebroadcast
0	1	0	Sparsely connected	Rebroadcast, and help carry and forward the packet to the first new neighbor in the opposite direction or in the message direction encountered
0	0	0/1	Totally disconnected	Wait and forward the packet to the first neighbor in the opposite direction or in the message direction encountered

Table 1. *Summary of DV-CAST operations.*

cast message until it can delegate the broadcast responsibility to a vehicle in the opposite direction or to a more suitable vehicle moving in the same direction, but no longer than the packet expiration time.

According to Fig. 3d, *A* is disconnected from group 3 and group 2. The flags should be set to `<MDC = 0, ODC = 0, DFlg = 1>`. For this scenario, *A* will have to go to the WAIT I state and wait for the hello packet from vehicles in group 3 or a vehicle in group 2 who may have caught up with group 1 while *A* is in the WAIT I state. Once *B* moves into *A*'s range, the ODC flag of *A* will be changed to 1, and *A* will immediately rebroadcast. Vehicle *B*, according to Fig. 3d, may or may not have heard the broadcast message when it receives the rebroadcast from *A*. However, since DFlg of *B* is 0, it will always help to relay the message. Therefore, when *B* receives the broadcast message from *A* it will have the following flags; `<MDC = 0, ODC = 1, DFlg = 0>`. This is the same setting as in scenario 2.1.

Note that it is likely that vehicles in a dense traffic regime will only be in a well connected neighborhood, and every vehicle will have to use the broadcast suppression mechanism. On the other hand, most vehicles in a sparse traffic regime will be in either a sparsely connected or totally disconnected neighborhoods, so they will have to resort to the store-carry-forward mechanism. Table 1 presents the summary of actions taken by DV-CAST.

Network Performance and Analysis

In this section we present the network performance of the novel DV-CAST protocol under various traffic conditions (i.e., heavy vehicle traffic condition, representing a well connected network, and a light vehicle traffic condition, which corresponds to the disconnected network case) previously discussed in [7]. The protocol is implemented on an ns-2 (version 2.29.1) platform and tested against a realistic highway mobility pattern with a Ricean fading propagation model with *K* factor equal to 1 and the 802.11a MAC protocol.

Test Scenarios

Due to the limited capability of the NS-2 simulation platform, which cannot simulate an open system, we have resorted to the use of a circular highway, which allows one to mimic an open system, where vehicles can leave or enter the considered road section at any point in time using a closed circular highway system with a fixed number of vehicles. Hence, the network topology considered in this study is a four-lane circular highway with a radius *R*, where two lanes of traffic are moving clockwise and two are moving counter-clockwise. To mimic an open system, we focus only on a certain section of the highway: the ROI. More specifically, vehicles leaving the ROI drop any network activities, while vehicles re-entering the ROI are treated as new vehicles. At the beginning of the simulation, initial placement of vehicles follows an exponential distribution, which is derived from the real traffic pattern observed on I-80 [7]. Each vehicle first moves along the highway at a random speed uniformly chosen from $[V_{\min}, V_{\max}]$, where the minimum vehicle speed ($V_{\min}$) and maximum speed ($V_{\max}$) considered in the simulations are 24 m/s and 30 m/s, respectively. Afterward, each vehicle gradually updates its speed at every second using the following equation:

$$V_t = k \times V_{t-1}, \qquad (1)$$

where the factor $k \in [0.8 - 1.2]$.

We consider five traffic densities with 432, 864, 1188, 1728, and 2995 vehicles per hour (vph), which corresponds to the average road-level intervehicle spacing (E[S]) of 210 m, 125 m, 90 m, 63 m, and 37 m, respectively; or to the probability of being in a sparsely connected neighborhood (P_d) of 36 percent, 13 percent, 6 percent, 1 percent, and 0 percent, respectively [7]. These network densities cover a range from low (normal or night time) to high vehicular traffic density (rush hour). The ROI is set to be approximately 5 km, measured from the accident scene and extending 5 km in length along the highway, and is located at the first quadrant of the highway, as shown in Fig. 4. Assume that an accident occurs at the upper part of the circular highway, so the fixed RSU or the crashed vehicle is put in place to periodically broadcast the traffic alert message to the approaching vehicles. As previously discussed in [7], traffic with a certain percentage of market penetration can be characterized by the same traffic model with different densities. Therefore, we assume that all vehicles are equipped with wireless communication devices.

We collected statistics of 1000 broadcast packets from each scenario and compared with the benchmark performance, which is the controlled broadcast protocol without the store-carry-forward mechanism [12]. The suppression technique used in the current implementation of DV-CAST is slotted 1-persistence with three time slots. Note that the controlled broadcast results obtained in this article should be similar to results obtained from other broadcast suppression mechanisms [13–16] as none of them has a feature to solve the disconnected network problem. On the other hand, most protocols developed for delay-tolerant networks (DTNs) rely on infrastructure or maps and are developed mainly for urban environments; hence, we cannot compare our results to their results as the underlying assumptions about network topology and vehicle knowledge are different.

Performance Metrics

DV-CAST is designed to achieve robustness against extreme traffic conditions; hence, the three main performance metrics of interest are *reliability*, *efficiency*, and *scalability*. To test whether the protocol is reliable, efficient, and scalable, we use the following quantitative measurements, respectively:

- **Broadcast success rate**: Percentage of time the protocol can successfully deliver the packet to the nodes in the target region (reliability)
- **Network reachability**: Maximum packet penetration distance measured as a function of time (efficiency)
- **Network overhead**: Number of duplicate packets received at the network layer (scalability)

DV-CAST Performance Results

Broadcast Success Rate

For the scenario considered with approximately 5 km ROI, the packet is said to be successfully delivered if the maximum packet delivery distance reached is 5 km or the packet reaches all the vehicles in the ROI. Obviously, as the network density increases, the success rate also increases. In particular, as the network density increases from 432 to 1728 vph, the observed success rates corresponding to each network density are 53.3 percent, 78.8 percent, 89.5 percent, and 95.5 percent, as shown in Fig. 5a. As the network density increases to 2995 vph, which also corresponds to the well connected case, the success rate is 100 percent. In contrast, without the store-carry-forward feature introduced by DV-CAST, the success rate will be less than 20 percent in a sparsely connected case. While we expect DV-CAST to achieve a 100 percent success rate, we observe that not all the broadcast packets reach the end of the ROI zone at low network densities. This is due to the fact that either the disconnected relay nodes move out of the ROI before encountering a new relay node, or there is simply nobody within the transmission range of the RSU at the time of the broadcast.

Network Reachability

Figure 5b shows the average packet penetration distance as a function of time (i.e., how fast the DV-CAST can deliver a packet). The faster the packet delivery, the more efficient the protocol. In particular, the protocol is said to be efficient if it can deliver the message to the target destination within an acceptable time, which is specified by the application. Ideally, it is expected that as time increases, the packet penetration distance increases up to the end of the ROI. However, if there is nobody within the transmission range of the RSU at the time of the broadcast, or the disconnected node moves out of the ROI before encountering a relay node, the penetration distance observed in such scenarios even long after the initial broadcast time will not reach the end of ROI (5000 m). Despite this discrepancy, DV-CAST offers a much better network reachability than controlled broadcast or blind flooding.

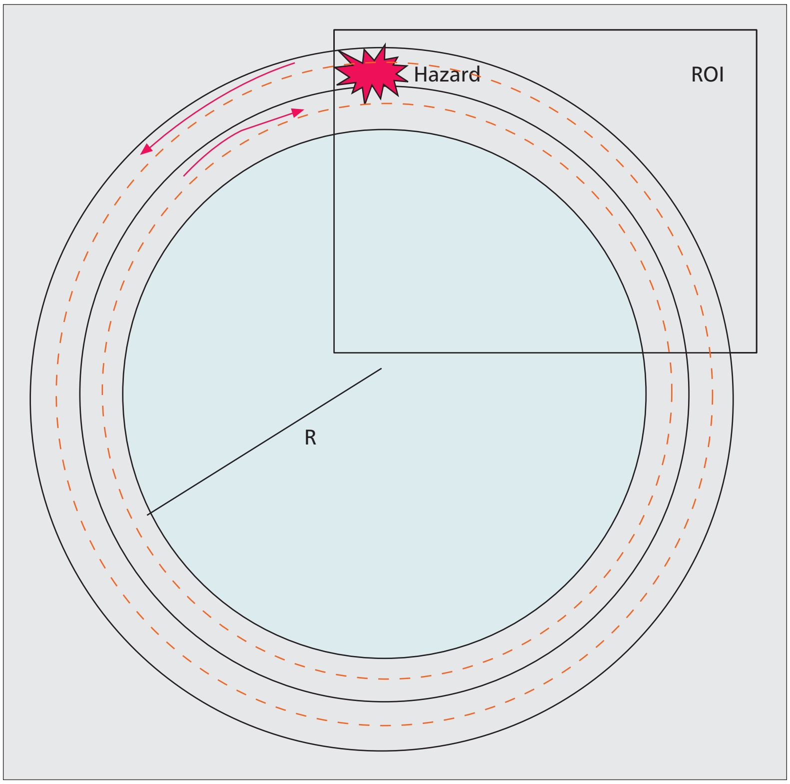

Figure 4. *Circular highway scenario used for simulations.*

Network Overhead

Figure 5c shows the average network overhead for a single broadcast as observed by each node. The network overhead seems to scale very well, especially in heavy traffic conditions where a broadcast storm is likely to occur. In particular, the amount of overhead is about three times less than that of the blind flooding (1-persistence) case. Observe that as the traffic density increases beyond 2000 vph, DV-CAST behaves similar to the controlled broadcast protocol. For the intermediate cases, each node observes only a few additional overhead packets as DV-CAST relies on these extra overhead packets to maintain network connectivity. Despite the small amount of extra overhead introduced by DV-CAST in order to maintain network connectivity and achieve better success rate and reachability, the DV-

CAST protocol appears to be very scalable, especially in a dense traffic scenario.

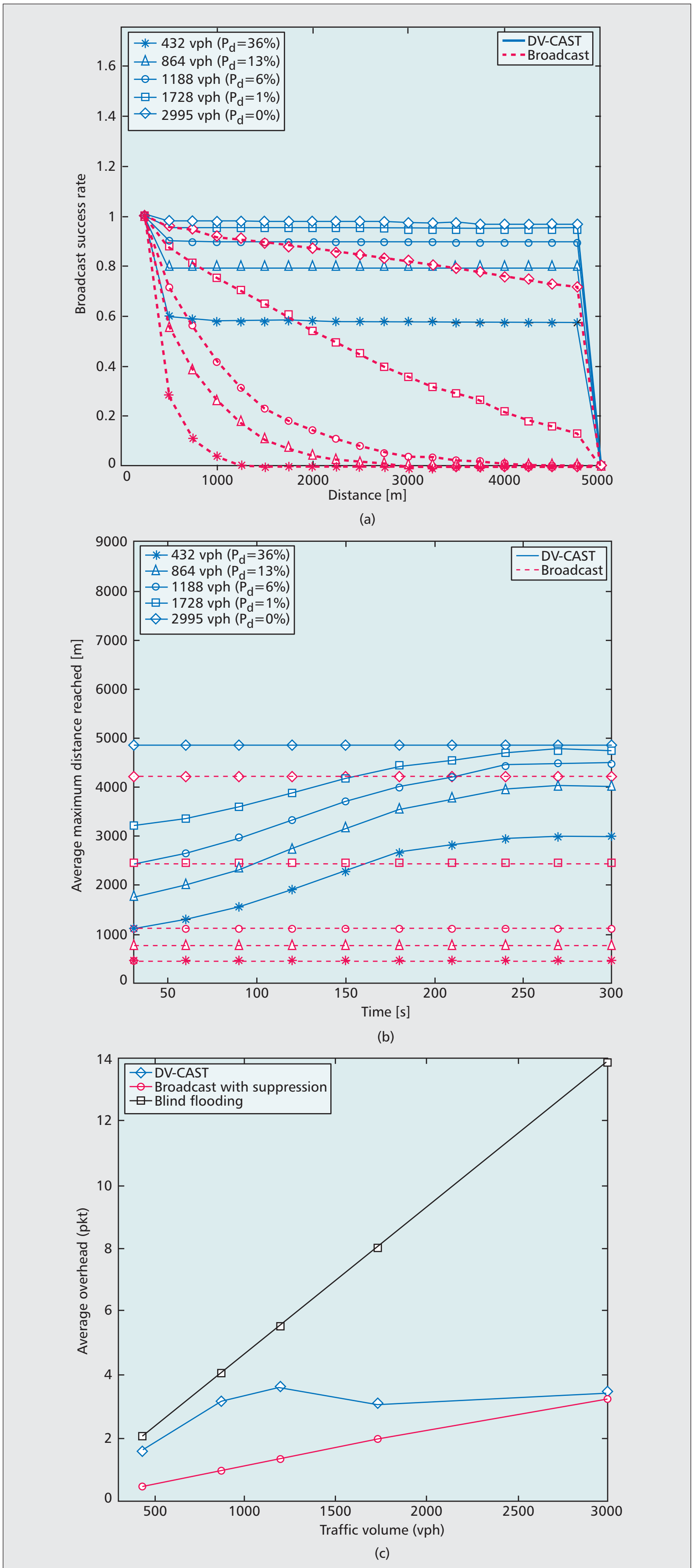

Figure 5. *DV-CAST performance at various traffic densities: a) broadcast success rate; b) network reachability; c) average network overhead.*

Design Issues and Discussion

DV-CAST has many design parameters that need to be tuned appropriately in order to optimize the performance. Due to limited space, we briefly discuss the impact of each parameter in this section.

Hello Update Frequency

Intuitively, if each vehicle periodically updates its location at a high frequency, the wireless channel may become congested; consequently, this leads to long MAC delay and high packet loss rate. For a typical VANET environment, where topology does not change much in a millisecond or even a second, the majority of hello updates received may be useless. On the other hand, if the hello frequency is too small, the local topology information provided by the neighbor detection mechanism may not be accurate, subsequently causing the protocol to fail. For example, a mobile node may choose to do broadcast suppression instead of store-carry-forward the message, which would then lead to low network reachability.

We have simulated the scenarios with hello frequencies of 0.2 Hz, 1 Hz, and 4 Hz. Surprisingly, regardless of the update frequency, DV-CAST behaves similarly in terms of these three different measurements. This could be partly due to the fact that topology as seen by each vehicle does not change rapidly over time, especially when considering vehicles moving in the same direction. This is because the maximum relative velocity of vehicles moving in the same direction considered in our model is only 6 m/s. Therefore, the hello update does not have to be as frequent as the current setting of 1 Hz in the considered scenario since the local topology does not change much during the two consecutive hello updates.

GPS Drift

The accuracy of GPS is also another important factor that may cause the neighbor detection mechanism to fail. This problem is more severe than using a low hello update frequency because a mobile node can completely fail to estimate the local topology if the neighbor vehicles report incorrect GPS information. GPS drift is an inevitable problem for several reasons:

- Different GPS receivers, especially from different vendors, may have different performance.
- Bad GPS reception due to obstruction is a common problem, which could also lead to GPS drift
- Performance of the GPS antenna could deteriorate over time.

We have investigated GPS drift on ns-2 by adding some random skewed factors to the GPS update function so that the reported GPS location is 0–25 m away from the correct position in any direction. The impact of GPS drift on the broadcast success rate, network reachability, and network overhead in a sparsely connected network with 1188 vph is shown in Fig. 6. Our results show that the performance in all three metrics remains relatively unchanged in a sparse network, but slightly deteriorates when the traffic volume exceeds 1000 vph. However, the results are still much better than the blind flooding or controlled broadcast results.

Conclusion

In this article we present the performance in terms of reliability, efficiency, and scalability of the DV-CAST protocol on highways under multiple traffic conditions. Since the protocol is designed to address how to deal with extreme conditions such as heavy traffic during rush hours, very light traffic during certain hours of the day (e.g., midnight to 4 a.m. in the morning), and low market penetration rate of cars using DSRC technology, the simulation results show that the DV-CAST performs well in every aspect considered and is robust against various extreme traffic conditions. For future work, it would be interesting to see how much of the underlying design principles of DV-CAST would also be applicable to urban areas. At a high level, it seems clear that large cities might have a very different and much richer topology (e.g., Manhattan Street type of topologies) than highways. In this sense, one could consider DV-CAST as an instance (or a subset) of designing a distributed vehicular broadcasting protocol that would work anywhere (urban, suburban, and rural areas). Our current research efforts are focused on extending vehicular broadcasting to urban areas.

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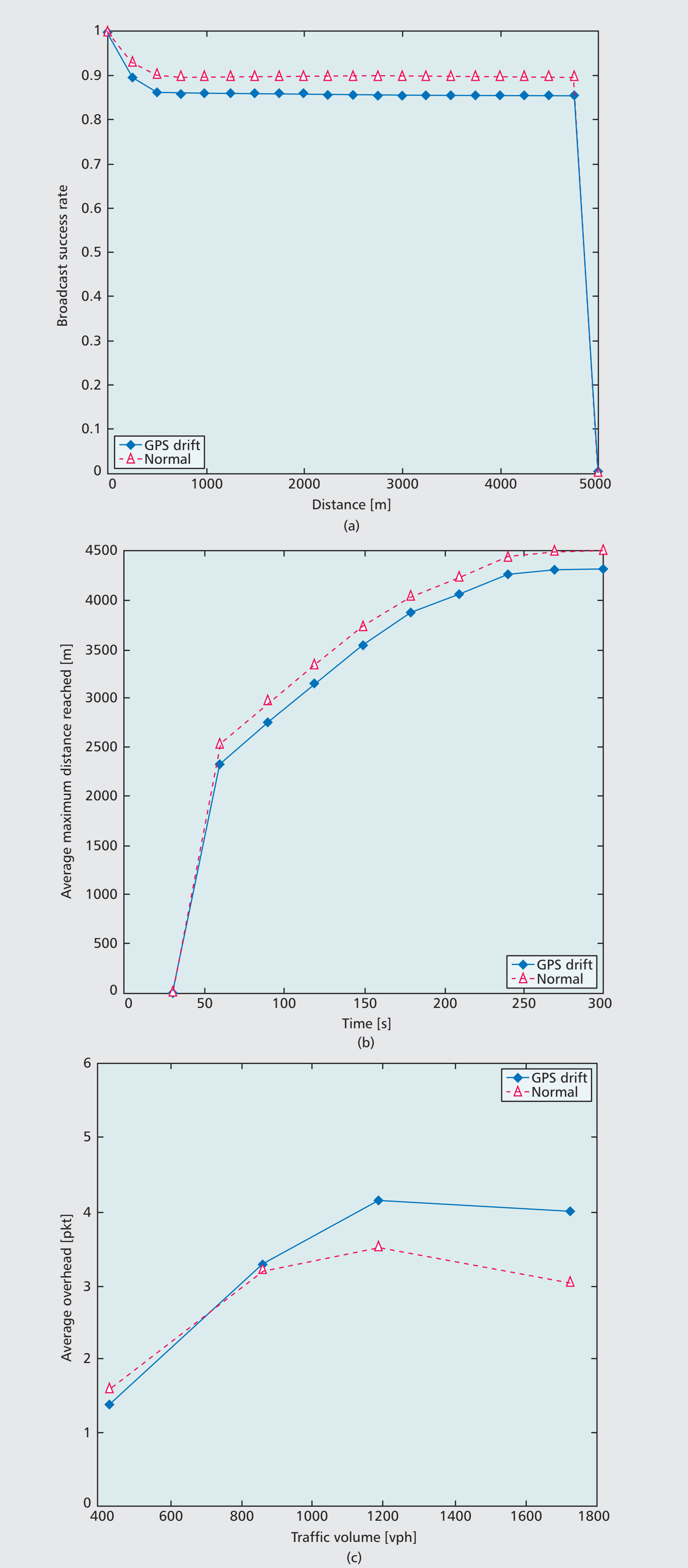

Figure 6. *Impact of GPS drift on: a) broadcast success rate; b) network reachability; c) network overhead.*

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