Broadcasting Safety Information in Vehicular Networks: Issues and Approaches

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Abstract

A primary goal of intelligent transportation systems is to improve road safety. The ability of vehicles to communicate is a promising way to alleviate traffic accidents by reducing the response time associated with human reaction to nearby drivers. Vehicle mobility patterns caused by varying traffic dynamics and travel behavior lead to considerable complexity in the efficiency and reliability of vehicular communication networks. This causes two major routing issues: the broadcast storm problem and the network disconnection problem. In this article we review broadcast communication in vehicular communication networks and mechanisms to alleviate the broadcast storm problem. Moreover, we introduce vehicular safety applications, discuss network design considerations, and characterize broadcast protocols in vehicular networks.

Every year, millions of traffic accidents occur worldwide, resulting in tens of thousands of casualties and billions of dollars in direct economic costs. For many years now, transportation planners have been pursuing an aggressive agenda to increase road safety through intelligent transportation system (ITS) initiatives. Furthermore, in 2001 the European Transport Policy set out a goal to reduce road fatalities by 50 percent by the year 2010. Similarly, in 2008 the U.S. Department of Transportation’s (DOT’s) Research and Innovative Technology Administration challenged the industry to reduce 90 percent of traffic crashes by 2030. In recent years various stakeholders have come together to address these short-term and long-term challenges, and initiative efforts have been formed such as the U.S. IntelliDrive and European eSafety programs. A novel communication system known as dedicated short-range communication (DSRC) has been proposed within the 5.8–5.9 GHz frequency spectrum allocated for its use. Standard activities for the overall system architecture and communication framework are coordinated by a variety of entities that include the IEEE (IEEE 802.11p, IEEE 1609 working group) in the United States, and the Car 2 Car Communications Consortium (C2C-CC), European Telecommunications Standards Institute (ETSI, TC ITS), and International Organization for Standardization (ISO, TC204/WG16) in Europe and other parts of the world.

To achieve the future road safety vision, time-sensitive, safety-critical applications in vehicular communication networks are necessary. Broadcasting will play an important role in disseminating safety messages to all nearby vehicles such as look-ahead emergency warnings and information about unsafe driving conditions. However, the lack of packet acknowledgment, packet retransmission, and a medium reservation scheme makes it difficult to achieve high broadcast reliability and efficiency in dense vehicular networks due to wireless contention and interferences.

The Routing Problem

The fundamental design consideration for routing protocols is the network environment and whether it is a static or dynamic network. Design in the underlying communication system is complicated by requirements that satisfy multiple constraints which include high reliability, efficiency, and scalability performance measures.

A vehicular ad hoc network (VANET) is a specific type of mobile ad hoc network (MANET) where dynamic routing protocols are necessary. A VANET operates in a self-organized manner without permanent infrastructure and, similar to a MANET, encounters two major routing issues, the broadcast storm problem and the network disconnection problem. The broadcast storm problem occurs when mobile nodes send messages by flooding, causing frequent link layer contention with other nearby broadcasting nodes that result in high packet loss due to collisions. Specifically, this phenomenon happens during multihop relay and message broadcast. Multihop relay occurs in MANETs in wireless mesh configurations and in VANETs when there are no roadside stations nearby. For MANETs, message broadcast occurs during route discovery or route maintenance, such as route request hello messages. For VANETs, this happens in periodic broadcast beacons of vehicle or traffic information. Achieving high communication reliability and efficiency is an essential requirement for safety-based ITS applications. Furthermore, the network disconnection problem for VANETs is more severe than for MANETs due to high mobility caused by fast moving vehicles and the sparse traffic densities during off-peak hours. This disconnection time (on the order of a few seconds to several minutes) makes MANET protocols such as Ad Hoc On Demand Distance Vector unsuitable for VANETs.

Hence, new network designs to improve broadcast reliability in dense networks and routing decisions in sparse networks are necessary. In this article we review existing methods and design considerations for vehicular communication networks. In partic-
ular, our discussion includes application requirements, communication systems, traffic characteristics, and routing protocols. We conclude by summarizing the lessons learned, field experiments, and future challenges of broadcasting in vehicular communication networks. In the literature previous surveys and tutorials on routing protocols for VANETs have been explored by [1–7]. This article is an extension from these related works as it focuses on broadcast methods with an emphasis on the design requirement of high reliability and efficiency for vehicular safety applications by alleviating the broadcast storm problem.

Design Considerations

Safety Applications

Specific ITS applications govern the performance requirements in vehicular communication networks. During phase one DSRC experiments, several road safety scenarios based on cooperative intersection collision avoidance systems were tested. These scenarios included traffic signal violation warnings, stop sign alerts, and left turn signal assistance. According to the U.S. Vehicle Safety Communications Consortium, a comprehensive list of more than 75 application scenarios for intelligent vehicle safety applications enabled by DSRC have been identified [8]. Table 1 describes a list of safety applications, and their corresponding communication and traffic parameters. In particular, safety applications at intersection roads (infrastructure-to-vehicle) and message exchange among vehicles (vehicle-to-vehicle) have the most promising safety benefits in the near and mid-term future.

Message transmit mode can be triggered periodically or event-driven. In the periodic case, preventive safety messages are disseminated to keep drivers informed with details such as forward and opposing vehicle speed, acceleration, and deceleration values. On the other hand, event-driven messages are delivered occasionally as in the case of a sudden hard braking vehicle from other nearby vehicles or emergency vehicles such as ambulances. Moreover, many applications that send event-driven messages are relevant for farther vehicles, allowing upstream vehicles to undertake early countermeasures to prevent severe catastrophes such as chain-reaction accidents.

In Table 1 the latency for safety requirements are approximate values proposed previously by several sources that include previous research papers, automotive practitioner recommendations, and consortium reports. In addition, preliminary evaluation in field tests indicate the typical delay requirement for many safety applications is between 100 and 500 ms, a lower bound value compared with human reaction time. The delay factor for safety applications is important, and the IEEE 802.11p specification has set a minimum allowable latency of 100 ms for periodic message broadcast. In general, near real-time information is essential as even non-safety traffic-based applications require delay latencies in the range of several seconds to a few minutes for many ITS applications to be useful. The maximum communication range depends on usefulness of the safety information to nearby vehicles for both upstream and downstream traffic in the same direction for highways, as well as opposing directions on arterial roads and local streets. In situations where the maximum communication range does not reach the intended distance, multihop communication is a useful mechanism.

Communication

In communication networks packet delivery can be unicast, multicast, or broadcast. The behavior of multicast and broadcast systems are different, as the former sends a message to multiple destinations based on specific group attributes, while the latter sends a message to all recipients within its coverage area. In vehicular communication networks, for example, a group of taxi or courier vehicles in a metropolitan city may only relay messages among their fleets. However, an ambulance siren alert must notify all nearby vehicles to pull over rapidly and safely. In recent years other forms of network delivery have been proposed that include geocast and anycast. In particular, for vehicular networks geocast, which is based on geographic routing, has been studied extensively by taking a form of greedy forwarding in relaying information to the destination such as most forward within range (MFR) or nearest with forward progress.

Different from other wireless networks, packets in vehicular networks are mostly autonomous and have specific temporal and spatial relevance. Furthermore, the assumptions may include knowledge of digital road layouts, location coordinates (GPS), and in some cases the location of the destination node. Performance metrics that are important include message delivery ratio, packet reception rates, packet error rates, and end-to-end transmission delay. A comprehensive classification of different automotive applications in DSRC and detailed performance measures for VANETs is reviewed in [9].

Traffic

The mobility patterns of communication nodes in VANETs are significantly different from those in conventional wireless networks. Vehicles' space-time trajectories are restricted by paved roadways and drivers' choices of origins, destinations, departure times, and routes. The positions of vehicles are not independent on a road due to car following or lane changing rules. Densities of vehicles can vary dramatically along a communication path due to driving behaviors and restrictions caused by network geometry.

Previous studies have shown that the topological properties and mobility models can have dramatic impact on network protocol performance. Two popular mobility models for vehicular communication that generate movements at the microscopic level include SUMO and VanetMobiSim, incorporating aspects of the car following model developed by Stefan Krauss and the TSIS-CORSIM traffic simulator. An in-depth survey and taxonomy of mobility models for VANEts is described in [10].

Furthermore, vehicle movements can be complicated by other factors such as traffic signals and stop signs in arterial roads and ramp meters on highways. Traffic simulators such as TransModeler and Paramics that incorporate traffic flow theory and traffic control systems can provide greater realism in vehicle trajectories. Another approach to formulating the topological properties and mobility model involves using realistic vehicular traces to account for other variables. Some research work has adopted this method, using mobility trace data from SUVnet (taxi traces via GPS) and BTL/NG-SIM (vehicle traces via loop detectors).

Overview of Broadcasting Protocols in Vehicular Networks

In this section we present a classification of broadcast protocols based on methods to reduce the broadcast storm problem for vehicular communication networks. Table 2 illustrates the historical taxonomy of broadcast communication with a qualitative comparison of the communication methods, traffic characteristics, network simulation environment, and mobility model used in the protocol design and evaluation. In certain cases the literature on broadcast protocol did not specify the simulation environment, road topology, and mobility models used in their evaluation. For these situations, we omit their discussion and leave the table field entries blank.
Communication Characteristics

In the MANET literature several suppression schemes have been proposed to improve the overall reliability of the shared communication channel. These schemes include probabilistic-based, counter-based, distance-based, and location-based methods. These schemes have been adopted in broadcasting for vehicular communication networks along with new methods such as cluster-based and traffic-based methods. In location- and position-based methods, messages are broadcast based on the geographic area of the transmitting and receiving vehicle locations. In distance and hop-based methods, messages are broadcasted considering the geometrical distances and hop count from the transmitting node. Cluster-based methods improve communication reliability by broadcasting messages over a geographical area.
methods broadcast messages to vehicle groups, for example, to a platoon of vehicles with common paths. In probabilistic-based methods, messages are broadcast with a given probability $p$, and in many cases this probability is based on the protocol’s backoff timer. For traffic-based methods, information on traffic dynamics such as vehicle speed are incorporated into the message broadcast decision. The predominant network simulator used is the state-of-the-art open source ns-2 simulator. A variety of mobility models are used for simulating vehicle movements in highway and arterial roads.

<table>
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<tr>
<th>Broadcast protocols</th>
<th>Communication characteristics</th>
<th>Traffic characteristics</th>
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<td>TrafficView, 2004</td>
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<td>MDDV, 2004</td>
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<td>ODAM, 2004</td>
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<td>OAPB/DB, 2005</td>
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<td>AMB, 2006</td>
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Table 2. Classification of broadcast protocols in vehicular networks.

**Urban Multihop Broadcast (UMB) and Ad Hoc and Multihop Broadcast (AMB)** — In these techniques, preference on a broadcast relay and suppression scheme is utilized based on road location or vehicle position. To reduce the multihop messaging, UMB and AMB elect vehicles farthest away (MFR) from the information source as relay nodes. This location metric is computed based on the black-burst method, which lets receivers send black-burst signals proportional to their location from the source. Furthermore, the AMB protocol is an enhancement to UMB that does not require repeaters (infrastructureless) when vehicles may not be in the intersection to retransmit a message by nominating the node closest to the intersection position as the relay node for broadcasting instead.

**Smart Broadcast (SB), Position-Based Adaptive Broadcast (PAB), and Distributed Vehicular Broadcast (DV-Cast)** — SB and PAB use a dynamic backoff timer for medium access control (MAC) contention window adjustment to improve the efficiency of packet transmissions. SB’s backoff timer scheme is based on the sender and receiver node distance, while PAB determines the backoff timer based on vehicle position and vehicle speed. DV-CAST uses local one-hop neighbor topology to make routing decisions. The protocol adjusts the backoff timer based on the local traffic density, and computes forward and opposing direction connectivity with periodic heartbeat messages. Moreover, DV-CAST is adaptive to the totally disconnected network and can temporarily wait-and-hold a packet until the vehicle hears heartbeat messages from other vehicles.

**Multihop Vehicular Broadcast (MHVB)** — MHVB adjusts the packet transmission interval with a position-based method. The two proposed schemes for packet retransmissions in MHVB include the location between sender and receiver, and...
the traffic congestion level, which is determined by a multitude of threshold values that include number of nearby vehicles, number of vehicles in forward and opposing directions, and vehicle speed. A subsequent improvement for MHVB was later published that includes more efficient angular coverage from sender to receiver and introduces a dynamic scheduling algorithm that prioritizes received packets.

**Mobility-Centric Data Dissemination Algorithm for Vehicular Networks (MDDV)** — MDDV is a geo-cast protocol that defines the destination region and trajectory-based routing based on travel directions to deliver packets to the region. The MDDV protocol runs a localized broadcast routing algorithm to continuously forward messages to the head node in the cluster pack and moves closer to the intended destination. Results from MDDV indicate that the routing protocol performance depends on the market penetration rate of vehicle-to-vehicle communication and road traffic density, which is affected by the time of day with its realistic movement traces.

**Fast Broadcast (FB) and Cut-Through Rebroadcasting (CTR)** — FB is a distance-based protocol that minimizes forwarding hops when transmitting messages and contains two components: the estimation and broadcast phases. In the estimation phase, the protocol adjusts the transmission range using heartbeat messages to detect backward nodes. In the broadcast phase, it gives higher priority to vehicles that are farther away from the source node to forward the broadcast message. CTR also gives higher priority to rebroadcast alarm messages to farther vehicles within transmission range but operating in a multichannel environment.

**Distributed Fair Transmit Power Assignment for Vehicular Ad Hoc Network (D-FPAV)** — D-FPAV describes a scheme that provides fairness in broadcasting heartbeat messages by dynamically adjusting every node's transmission power based on distance to other neighboring nodes. The method enables all nodes to share the channel capacity fairly. Although power control and adjustment is well explored in wireless networks, D-FPAV is unique as it investigates the problem in the context of broadcasting in vehicular networks by using realistic movement traces obtained from DaimlerChrysler on a German highway.

**Dynamic Backbone-Assisted MAC (DBA-MAC)** — DBA-MAC is a cluster-based broadcast for message propagation based on cross-layer intersection in the MAC. For a group of interconnected vehicles, higher-priority nodes within the cluster are considered backbone members and are able to broadcast messages. The process of choosing backbone nodes within the cluster occurs periodically by selecting nodes that are farther apart to minimize hop count.

**Receipt Estimation Alarm Routing (REAR)** — In the REAR protocol, nodes that relay broadcast messages are selected based on estimated message delivery ratio. This is computed based on the received signal strength and packet reception rates for packets that nodes receive, and this information is exchanged with neighboring nodes using heartbeat broadcast messages. Hence, nodes with higher message delivery ratios are more likely candidates to flood messages in the network while the other nodes are kept silent to alleviate wireless contention conflict.

**TrafficView** — The TrafficView protocol is a part of the broader e-Road project with the goal of building a scalable and reliable infrastructure for intervehicular communication systems. In TrafficView, the message data contain information on a list of vehicle IDs and the vehicle’s own position and speed, as well as broadcast duration time. TrafficView conserves bandwidth and deals with flow control of broadcast messages by aggregating multiple data packets based on relative vehicle distance and message timestamp. For example, two vehicles on the same highway lane traveling at similar speeds are likely to have similar vehicle positions and vehicle trajectories. Hence, when updated information on vehicle positions is available, vehicle speeds may not be necessary, which reduces packet size and results in lower packet transmission delay (less air time).

**Time Reservation-Based Relay Node Selection (TRRS) and Routing Protocol for Emergency Applications in Car-to-Car Networks Using Trajectories (REACT)** — TRRS proposes a method where nodes in the communication range choose their waiting time based on a specified time window. The time window is determined by a distance that is inversely proportional to the previous relay node and reservation ratio of the time window. A node with higher reservation ratio will have received duplicate broadcast messages and incurred longer time window waiting duration in the next transmission round. REACT gives more influence on the forwarding trajectory and angle, and integrates the position-based information with the time-division multiple access 802.11 MAC.

**Optimized Dissemination of Alarm Message (ODAM) and Optimized Adaptive Probabilistic Broadcast and Deterministic Broadcast (OAPB/DB)** — ODAM has a “defertime” to broadcast messages, computed based on the inverse proportional distance between receiver and source node. For ODAM, broadcast messages can only occur within the risk zone region, determined with a dynamic multicast group based on vehicles’ proximity to the incident site. OAPB/DB uses an adaptive approach to rebroadcast emergency warning messages near the incident zone. Nodes rebroadcast messages probabilistically within the region based on the delivery ratio, which is computed based on local traffic density information.

**Lessons Learned, Field Experiments, and Future Challenges**

**Lessons Learned**

An overview of broadcast protocols in vehicular communication networks has been introduced. Specifically, these protocols address the broadcast storm problem by reducing packet redundancy, wireless contention, and collisions in the network. Although numerous design methods have been proposed, each protocol has its limitations and assumptions that may cause certain issues. For instance, the concept of node selection for multihop relay based on node distance (MFR), although reducing the total number of traveling hops, inures a reliability trade-off with lower packet reception rates due to the loss in radio power from longer propagation distances. Also, several broadcast protocols to modify the MAC with different priority schemes have been proposed. However, such schemes may result in “unfairness” in the overall system where certain nodes have more packet transmission rounds than others. Yet another shortcoming for some methods is the assumption that GPS is readily available to provide location position to neighboring vehicles. Hence, the feasibility of these vehicular communication network applications will depend largely on the technology adoption and market penetration rates of vehicles equipped with capabilities, GPS devices, or both.
Field Experiments

In the past few years field trials have been conducted to fine-tune the DSRC specification. Initial results indicate packet error rates (PERs) can be highly affected by urban canyons, caused by radio signal degradation due to multipath fading [11]. The vehicle height profile can also significantly impact the transmission range for DSRC. Initial road test experiments indicate 20 percent PER with about 150 messages/s, and complexity is better for smaller (300 bytes) rather than longer (1200 bytes) messages since longer packet length consumes more air time. The phase one stage provides a strong proof of concept for DSRC. However, VANETs still have many issues to address, including external factors such as road terrain conditions, vehicle types, and environmental factors.

Future Challenges

There remain many open issues and future challenges to solve. The field of vehicular networks has not only fostered academic research interest, but has motivated experts to publish books to share knowledge, most recently in 2009 [12–15] and 2010 [16, 17]. In the lower layers of the communication stack, novel channel access methods, priority access with IEEE 802.11e, dynamic contention window and power adjustment and multi-radio interfaces are just some of the techniques that can improve vehicular communication by optimizing the wireless channel load. This can be thought of as a scalability problem and characterized by the “communication density” metric for vehicular communications [18]. An empirical analysis using 802.11 wireless interfaces in the ORBIT emulation testbed provides some insights on the complexity of broadcasting in dense vehicular networks [19]. However, the communication parameters and how these contribute to the overall system reliability and efficiency are not yet well understood and need further analysis. Moreover, the design of vehicular communication networks needs to be integrated with the safety and traffic-based application requirements. For example, the communication system can dynamically consider the latency requirement in Table 1 and fine-tune its MAC contention window size to the desirable performance measures (e.g., highest delivery ratio, minimum delay).

Initially, the requirements will be for vehicular safety applications. Multihop broadcasting is useful to provide an early countermeasure to prevent catastrophes such as chain-reaction accidents for nearby and following vehicles in the upstream. Subsequent enhancements will include real-time traffic information and environmental applications that reduce emissions in vehicle platoons by stabilizing traffic on the road through adaptive cruise control. In other cases ITS traffic applications may tolerate small delay and allow messages to be queued at intermediate relay points prior to sending information to the intended destination when the network is sparse. In such cases a delay-tolerant geocast protocol that sends messages on demand based on time factors when near other vehicles or a traffic collection roadside station is more appropriate. Finally, security in VANETs remains a rich research area with many problems that need to be addressed including vehicle anonymity, message integrity, and authentication, traceability, and revocation of malicious attackers.

Conclusion

In this article we classify and survey broadcast protocols for vehicular communication networks. Vehicular networks have many safety-based applications where reliability is of utmost importance. Reducing message flooding serves as a fundamental method to alleviate the broadcast storm problem and increase the reliability and efficiency of disseminating safety messages to other vehicles. Future research for network engineers and researchers should incorporate traffic characteristics and application requirements into the communication system design. Traffic flow dynamics, along with improvements in the communication stack, will be important in designing reliable, efficient, and scalable broadcast methods for vehicular communication networks.

References


Biographies

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