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SCALABLE MULTI-HOP DATA DISSEMINATION IN VEHICULAR AD HOC NETWORKS

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Under the Supervision of Dr. Abderrahmane Lakas

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Declaration of Original Work

I, Moumena Abdullah Chaqfeh, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this dissertation entitled "*Scalable Multi-hop Data Dissemination in Vehicular Ad hoc Networks*", hereby, solemnly declare that this dissertation is an original research work that has been done and prepared by me under the supervision of Dr. Abderrahmane Lakas, in the College of Information Technology at UAEU. This work has not been previously formed as the basis for the award of any academic degree, diploma or a similar title at this or any other university. The materials borrowed from other sources and included in my dissertation have been properly cited and acknowledged.

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Abstract

Vehicular Ad hoc Networks (VANETs) aim at improving road safety and travel comfort, by providing self-organizing environments to disseminate traffic data, without requiring fixed infrastructure or centralized administration. Since traffic data is of public interest and usually benefit a group of users rather than a specific individual, it is more appropriate to rely on broadcasting for data dissemination in VANETs. However, broadcasting under dense networks suffers from high percentage of data redundancy that wastes the limited radio channel bandwidth. Moreover, packet collisions may lead to the broadcast storm problem when large number of vehicles in the same vicinity rebroadcast nearly simultaneously. The broadcast storm problem is still challenging in the context of VANET, due to the rapid changes in the network topology, which are difficult to predict and manage. Existing solutions either do not scale well under high density scenarios, or require extra communication overhead to estimate traffic density, so as to manage data dissemination accordingly. In this dissertation, we specifically aim at providing an efficient solution for the broadcast storm problem in VANETs, in order to support different types of applications. A novel approach is developed to provide scalable broadcast without extra communication overhead, by relying on traffic regime estimation using speed data. We theoretically validate the utilization of speed instead of the density to estimate traffic flow. The results of simulating our approach under different density scenarios show its efficiency in providing scalable multi-hop data dissemination for VANETs.

Keywords: Vehicular Ad hoc Networks (VANETs), Data Dissemination, Traffic Density, Traffic Regime, Data Redundancy, Performance Modeling, Speed Adaptive Broadcast.

Title and Abstract (in Arabic)

نشر المعلومات في شبكات المركبات واسعة النطاق ومتعددة النواقل

الملخص

يعتبر النشر الإذاعي (Broadcasting) في شبكات المركبات الطريقة الأنسب لتوزيع المعلومات، وذلك لعدم خصوصية تلك المعلومات وعموم فائدتها للمركبات المشاركة. وعلى الرغم من ذلك، يواجه هذا النوع من النشر ما يعرف بمشكلة عاصفة البث (Broadcast Storm)، والتي تسببها الزيادة في نسبة المعلومات المشاركة، خصوصا في حالات الكثافة العالية عند الازدحام المروري. وفي إطار البحث في هذا المجال، لا تزال الطرق المقترحة تواجه تحديا في التغلب عليها دون الحاجة إلى عبء اتصال إضافي، بحيث تتمكن من تخفيض نسبة الفائض في المعلومات مع المحافظة على تحقيق التغطية المطلوبة.

تهدف هذه الأطروحة أساسا إلى اقتراح طريقة جديدة لنشر المعلومات في شبكات المركبات متعددة النواقل (Multi-hop Vehicular Ad hoc Networks)، حيث تعالج مشكلة عاصفة البث بطريقة فعالة تختلف عن الحلول المقترحة لها، إذ تعاني هذه الحلول من إحدى المشكلتين التاليتين: فهي إما تتطلب عبئا إضافيا من مشاركة المعلومات مع المركبات المجاورة، أو أنها لا تعمل بكفاءة في حالات السعات العالية. تعتمد الطريقة التي طورناها في هذه الأطروحة على كشف مستوى الازدحام المروري بشكل أوتوماتيكي من أجل ملاءمة مختلف الحالات وخصوصا السعات العالية، بالاعتماد على معلومات محلية دون الحاجة إلى عبء اتصال إضافي. وتشير النتائج المنشورة في هذه الأطروحة إلى فاعلية هذه الطريقة، إذ تحقق انخفاضا ملحوظا في نسبة الزيادة في المعلومات مع الحفاظ على تغطية كاملة أو شبه كاملة.

الكلمات المفتاحية: شبكات المركبات، نشر المعلومات، الكثافة المرورية، التدفق المروري، فائض المعلومات، نمذجة الأداء، النشر الإذاعي المعتمد على السرعة.

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Dedication

To my parents, my husband, Saad, and my daughters, Farah and Mona

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List of Abbreviations

VANET	Vehicular Ad hoc Network
WHO	World Health Organization
AAA	American Automobile Association
U.S. DOT	United States Department of Transportation
ITS	Intelligent Transportation Systems
SAB	Speed Adaptive Broadcast
P-SAB	Probabilistic Speed Adaptive Broadcast
S-SAB	Slotted Speed Adaptive Broadcast
G-SAB	Grid Speed Adaptive Broadcast
MANET	Mobile Ad hoc Network
MAC	Medium Access Control
OBU	On-Board Unit
IVE	In-Vehicle Equipments
RSU	Road-Side Unit
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
DSRC	Dedicated Short Range Communication
WAVE	Wireless Access in Vehicular Environment
DOT	Distributed Optimized Timeslot

Chapter 1: Introduction

World Health Organization (WHO) indicates that road traffic crashes annually cause around 1.24 million deaths on the world's roads, and 20 to 50 million non-fatal injuries. Road traffic injuries are the eighth leading cause of death globally, and the leading cause of death for young people. If preventive measures are not taken into serious consideration, road traffic deaths will become the fifth leading cause of death by 2030 [1]. A study from the American Automobile Association (AAA) concluded that car crashes cost the U.S. 300 billion dollar per year [2].

However, the deaths caused by car crashes are in principle avoidable. Studies show that in Western Europe a mere 5 km/h decrease in average vehicle speeds could result in 25% decrease in deaths [3]. Policing speed limits will be notably more efficient using communication technologies. According to the U.S. Department of Transportation (DOT), vehicular communication systems potentially address about 81% of all-vehicle target crashes; 83% of all light-vehicle target crashes; and 72% of all heavy-truck target crashes annually [4].

Beside traffic safety improvements, vehicular networks have several other benefits that can be achieved by processing real time data. Examples include: congestion detection and avoidance, travel-time estimation, speed expectation, route guidance and cooperative driving. These services can save both time and fuel and therefore they have significant economic advantages. The U.S. DOT anticipates that eventually, vehicular networking applications will be an expected feature and a part of our daily driving experience [4].

Vehicular Ad hoc Networks (VANETs) aim at improving road safety and travel comfort, by providing a self-organizing network environment, without requiring a fixed infrastructure or centralized administration. In VANETs, vehicles are enabled to communicate cooperatively for exchanging information about road conditions and travel situations. With the increasing number of vehicles being equipped with communication capabilities; VANETs are expected to be available in the near future. When such vehicular networks are already in place, many of the proposed Intelligent Transportation Systems (ITS) can be supported [5] [6].

Traffic data that will be disseminated through VANETs is of public interest and usually benefits a group of users rather than a specific individual. Therefore, it is more appropriate to rely on broadcasting for data dissemination in the VANET context. However, broadcasting in dense networks suffers from a high percentage of redundant data that wastes the limited radio channel bandwidth. Moreover, packet collisions may lead to broadcast storm problem since a large number of vehicles in the same vicinity may rebroadcast the same data nearly simultaneously. The broadcast storm problem is still challenging in the context of VANET, since rapid changes in the network topology are difficult to predict and manage [7], while data redundancy should be limited.

A common employed solution to deal with such scalability issues is reducing the percentage of redundant data. This is typically done by selecting only some of the vehicles to relay the data as opposed to letting every single vehicle rebroadcast it. A major challenge in existing broadcasting solutions is to reduce data redundancy while maintaining high delivery ratio [8].

Existing solutions either do not scale well under high density scenarios, or require extra overhead for neighborhood management gathered though beaconing to support scalability. Beaconing with a fixed period may have several drawbacks on the networking performance such as: wasted bandwidth, delaying of data packet and increased network congestion [9]. The communication channel may become congested especially under high densities due to the fact that beacons may be sent several times per second. Beaconing alone can generate a high load on the network, and therefore cannot be simply regarded as “background traffic” [10]. It is shown that when all vehicles send 200 bytes beacons every 100 ms (each vehicle sends 10 packets of 200 bytes data every second), channel would be 80% loaded at the range of 300 m [11], and sending 5 packets with the same mentioned settings would cause a channel load of 40%. It is true that beacons will be part of VANET safety management, but it is important not to increase packet size to include the required neighbor knowledge, since larger packets would certainly decrease the limited available bandwidth.

In this dissertation, we propose and evaluate three variants of a speed adaptive broadcasting approach that aims at improving scalability in data dissemination, in order to offer broadcast mitigation for VANETs. We solely rely on simple data detected locally without considering neighborhood management. We beat the challenge of achieving low broadcasting overhead while maintaining high delivery ratio. We propose the Probabilistic Speed Adaptive Broadcast (P-SAB) which is a probabilistic-based protocol for multi-hop VANET broadcasting. To improve the broadcasting delay and overhead, we propose the Slotted Speed Adaptive Broadcast (S-SAB), which relies on the delay-based broadcasting scheme. To further limit the broadcasting overhead, we propose an improved delay via the Grid SAB (G-SAB). Our broadcasting protocols effectively detect traffic regime based on traffic flow theory fundamentals [12] via speed data, without direct density information, using the negative correlation between the speed and the density proven in traffic flow theory [13]. In the reminder of this introductory chapter, we provide a motivation section 1.1, problem statement in section 1.2, research objective and contributions in sections 1.3 and 1.4 respectively. In section 1.5, we describe the organization of this dissertation.

1.1 Motivation

Targeting the broadcast storm as a research problem was not a result of literature review in the case of this dissertation, but due to a low performance experienced during a simulation of a congestion reduction application, as part of previous research effort to develop a Vehicle to Vehicle (V2V) communication protocol [14]. While the performance of communication protocols developed for VANET requires evaluation under high density scenarios, many existing simulations fail to address such scalability requirement. Monitoring slow simulations leads to a careful literature review to investigate the actual problem, which is found not to have a perfect solution yet.

Unlike traffic safety systems where data are proactively disseminated, in travel comfort applications similar to what we have proposed in our previous work [14] [15], traffic data are sent on demand. However, broadcasting is commonly required in both cases of applications. In the case of traffic safety, broadcasting usually achieves the goals of data dissemination; while in travel comfort applications, broadcasting is commonly part of the routing process. Therefore, addressing the broadcast storm problem can serve both types of applications whenever broadcasting is initiated, especially under high density scenarios.

While the broadcast storm problem is defined in Mobile Ad hoc Networks (MANETs), the VANETs context poses multiple challenges for existing mitigation strategies and solutions, basically because of the mobility feature that characterizes these environments. Those reasons have prompted this dissertation to address scalability in VANETs, in order to provide an efficient broadcast mitigation approach that can serve many types of traffic safety and travel comfort applications.

1.2 Problem Statement

Broadcasting forms the basis of all communication types in ad hoc networks [16]. In VANET context, Data dissemination requires the notion of broadcast to spread traffic data. Flooding is the simplest style of broadcasting, where the originating vehicle broadcasts a data packet to all its one-hop neighbors. In multi-hop dissemination, all receiving neighbors would rebroadcast the packet to their one-hop neighbors, and so on. Simple broadcast may easily lead to broadcast storm problem in high density networks, when many vehicles in the same vicinity broadcast simultaneously, thereby causing high data traffic, network congestion, packet collisions, service disruption and extra delay at the medium access control (MAC) layer [17]. Therefore, plain flooding does not scale with dense networks, due to the excessive dissemination of the same data, which wastes the limited available channel bandwidth.

The impact of the broadcast storm problem is quantified in [18]. Figure 1-1 illustrates the broadcast storm problem in plain flooding. In the figure, node A initiates a broadcast and data is received by nodes B and C. B and C rebroadcast the data if they had not broadcasted it before. Therefore, after receiving the data, D will rebroadcast if there is no collision. Flooding is extremely costly and may easily lead to the following [16]:

- Redundant rebroadcasts; that occurs when a node decides to rebroadcast data to its neighbors; however, they have already received the same data. In figure 1-1, since node A is within the transmission range of B and C, it will receive two redundant copies of the data from B and C, which is the same case with nodes B and C, as they receive the message from node D and also from each other.
- Packet collisions; which result in packet loss or corrupted messages. If nodes B and C broadcast at approximately the same time, there is a possibility of a packet collision at node D.

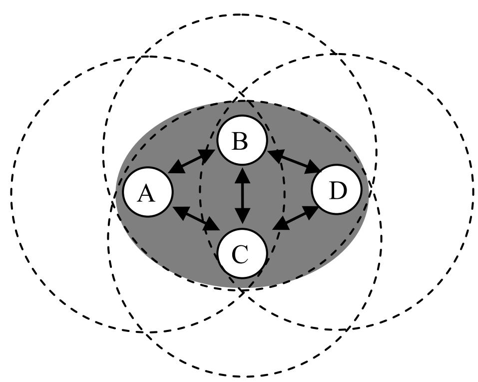


Figure 1-1: The Broadcast Storm Problem

1.3 Research Objective

The main objective of this dissertation is to develop and evaluate an efficient broadcast mitigation approach for scalable data dissemination, in order to support different VANET applications. By efficiency we specifically aim at achieving low broadcasting overhead, basically be reducing data redundancy, while maintaining high delivery ratio.

To achieve its main objective, our research has the following three basic questions:

- *Question1: Can a broadcast mitigation approach achieve low overhead while maintaining high ratio of data delivery?*
- *Question 2: What traffic parameters to utilize in order to provide scalable broadcast in VANET?*
- *Question 3: How to evaluate the performance of data dissemination in the VANET context?*

1.4 Research Contribution

The contribution of this dissertation is four folds:

- First, we provide a comparative study of existing performance modeling approaches for data dissemination in VANETs in a form of a comprehensive review.
- Second, we design a novel approach for broadcast mitigation in VANETs that overcomes the limitations of existing approaches.
- Third, we prove the efficiency of delay-based Speed Adaptive Broadcast in terms of scalability and reliability under high density scenarios.
- Forth, to our best knowledge, we are the first to succeed in adapting broadcast in VANET to traffic regime without extra communication overhead.

1.5 Dissertation Organization

This dissertation is organized as follows: in the second chapter, we provide a summarized background on VANETs, from the perspectives of characteristics, technology, applications and current projects worldwide. The third chapter introduces data dissemination challenges, models and performance evaluation methods in the VANET context. In the forth chapter, we provide a review on existing data dissemination optimization approaches, by addressing the broadcast storm problem, not only in safety-oriented applications, but also for the benefit of convenience-oriented applications. We describe our data dissemination approach with three variations in the fifth chapter. Later in the sixth chapter, we evaluate the performance of our proposed approach via simulation results. The last chapter provides concluding comments and suggestions for further work.

Chapter 2: Vehicular Ad Hoc Networks

Vehicular Ad hoc networks (VANETs) are self-organizing networks that offer timely information through wireless communications among vehicles on the road, without fixed infrastructure or centralized administration. VANETs have the potential to improve traffic safety and increase travel efficiency and driver comfort. Figure 2-1 illustrates a sample VANET, where each vehicle can directly communicate with the vehicles within its transmission radio range. Vehicles are assumed to be equipped with On Board Units (OBUs) or In-Vehicle Equipments (IVEs) to enable the required communication among vehicles, or between the vehicles and Road Side Units (RSUs), which are communication devices that provide different services to vehicles on the road.

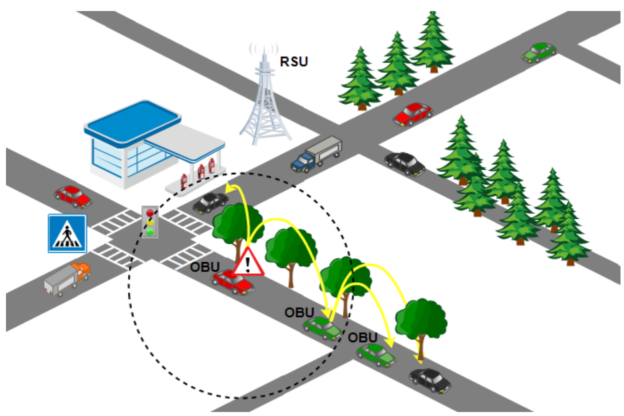


Figure 2-1: VANET Example

Here we describe the two basic components of VANET architecture, OBUs and RSUs [19]:

- **OBUs:** An OBU is a wave device mounted on vehicle for exchanging information with other OBUs or RSUs. It consists of a processor and other resources which include a read/write memory for data storage and retrieval, a user interface to visualize communication, and a network device based on IEEE 802.11p radio technology. The OBU basically aims at providing wireless access, ad hoc and geographical routing, network congestion control, reliable message transfer and data security.
- **RSUs:** RSUs are wave devices usually fixed along the road side or in dedicated locations such as road junctions or gas stations. The RSU is equipped with a network device for Dedicated Short Range Communication (DSRC) based on IEEE 802.11p technology. It can also be equipped with other network devices for providing communication with the infrastructural network. The main function of an RSU is to extend the communication range of the ad hoc network by re-distributing data to other OBUs and/or RSUs in order to forward it further. The RSU can also connect vehicles to the Internet or the infrastructural network.

From these two definitions, two communication modes can be distinguished in VANET environment:

- **Vehicle to Vehicle (V2V):** where vehicles communicate with other vehicles through their OBUs forming a mobile ad hoc network, in a fully distributed manner with decentralized coordination. Vehicles can directly communicate with neighboring vehicles if there is a direct wireless connection available. In other words, if they lie within its transmission radio range, forming a single-hop V2V communication. Multi-hop V2V can serve communication beyond the transmission range of individual vehicles using data dissemination techniques and/or routing protocols.

- **Vehicle to Infrastructure (V2I):** where vehicles communicate with an RSU in order to achieve two major benefits: first, to increase the communication range by sending, receiving and forwarding data from one vehicle to another. Second, to benefit from the ability of the RSU to process some kinds of applications. It is worth noting that V2V and V2I are sometimes combined together as V2X communication.

In the remaining of this chapter, we provide an overview of VANET characteristics (section 2.1), technology (section 2.2), applications (section 2.3) and current projects (section 2.4).

2.1 VANET Characteristics

There are a set of characteristics that make VANETs a specific type of Mobile Ad hoc Networks (MANETs). Some characteristics represent advantages over MANETs, and some others pose challenges. Characteristics of the former type are [19]:

- Constrained mobility; since vehicles are constrained by road topology and layout, in addition to the requirements to obey road signs and traffic light, and to respond to other vehicles on the road.
- No power constraints: since power provision is not challenging in VANET like other MANETs, because vehicles are can continuously provide power to their OBUs through long-life batteries.
- High computational ability: because vehicles can be equipped with sensors and different types of resources (such as processors, memories and GPS) that enable

them to reliably obtain wireless communication and accurately acquire information about their location, speed and direction.

On the other hand, challenging characteristics can be summarized in the following key points:

- Application requirements: VANET allows traffic safety and travel comfort applications, in addition to infotainment. Each of those application categories has different requirements in terms of coverage, delay and communication modes.
- Variable Network density: since traffic regime reflects the density of the vehicular network, which is dense in traffic jam and sparsely connected in free-flow traffic.
- Large scale networks; which are expected in dense areas such as city centers and highways. Under high densities, scalability issues arise and data redundancy should be limited.
- Rapid changes in the network topology; due to the high mobility feature that characterizes VANETs. The life time of the link between vehicles is affected by the communication range and the direction of the vehicles. An increased range and a same-direction communication cause longer living links, while smaller ranges and opposite-direction communication lead to very short living links.

2.2 VANET Technology

Characteristics of vehicular networks have directed efforts to establish new communication standards, which are essential to promote interoperability between equipment developed by distinct groups and countries. Standards simplify product development and enable the users to compare competing products. Through the use of standards, the requirements of interconnectivity and interoperability can be guaranteed, and the emergence of new products can be verified to enable the rapid implementation of new technologies. There are many standards that relate to wireless access in vehicular environments [20]:

2.2.1 Dedicated Short Range Communication (DSRC)

DSRC [21] [22] is a short-range to medium-range communications service that was developed to support V2V and V2R communications. Such communications cover a wide range of applications. DSRC is aimed at providing high data transfers and low communication delay in small communication zones. In 1999, the United States Federal Communications Commission (FCC) allocated 75 MHz of spectrum at 5.9 MHz to be used by DSRC. In 2003, The American Society for Testing and Materials (ASTM) approved the ASTM-DSRC standard, which was based on the IEEE 802.11a physical layer and 802.11 MAC layer. In February 2004, the report issued by the FCC established service and licensing rules that govern the use of the DSRC band. DSRC is free but licensed spectrum, which is organized into 7 channels, each channel is 10 MHz wide. Two channels are reserved for special purposes and one channel is restricted for safety communications. Remaining channels are service channels which can be used for either safety or non-safety applications.

2.2.2 Wireless Access in Vehicular Environment (WAVE)

Traditional IEEE 802.11 Media Access Control (MAC) operations suffer from significant overheads when used in vehicular scenarios. To address the challenging requirements in VANETs, the DSRC effort migrated to the IEEE 802.11 standard which renamed the DSRC to IEEE 802.11p. Efforts on the standardization of additional layers include the IEEE 1609 family of standards that specify multichannel operation, networking services, resource manager and security services [23]. The combination of IEEE 802.11p and the IEEE 1609 protocol suite is denoted as Wireless Access in Vehicular Environments (WAVE). In contrast to the regional standards of DSRC, by incorporating DSRC into IEEE 802.11, WAVE will become a standard that can be universally adopted across the world. Since IEEE 802.11p is limited by the scope of IEEE 802.11 which strictly works at the media access control (MAC) and physical layers, the operational functions and complexity related to DSRC are handled by the upper layers of the IEEE 1609 set of standards, which define how applications that utilize WAVE will function in a VANET. More specifically, IEEE P1609.1 defines management activities, while IEEE P1609.2 defines security protocols, and IEEE P1609.3 defines networking protocols. The IEEE 1609.4 protocol resides above 802.11p to support the operation of higher layers without dealing with the physical channel access parameters. It is worth noting that WAVE defines the two types of devices we described earlier: OBUs and RSUs [20].

2.3 VANET Applications

VANET research has been driven mainly to support the demand for providing networking services for the development of miscellaneous applications. From a user benefit perspective, these applications can be classified into three basic categories: safety-oriented, convenience-oriented and commercial-oriented. In the context of this dissertation, and similar to many other research, we are interested in the first two categories. Commercial-oriented applications provide drivers with various types of communication services such as web access and multimedia streaming, with the objective of improving productivity, entertainment and satisfaction, which is out of the scope of this research. Candidate criteria to characterize and classify VANET applications can be found in [24]. In the following, we provide an overview of safety-oriented and convenience-oriented applications in VANET environment.

2.3.1 Safety-oriented Applications

In safety applications, the state of nearby vehicles and the road condition is monitored by exchanging messages among vehicles, so as to assist drivers in handling upcoming events or expect a potential danger, either by taking the appropriate action automatically (such as automatic braking), or by providing advisory or warning information as configured by the driver.

Safety applications have strict latency constrains, but limited geographical coverage requirements. With the assistance of vehicular communication systems, traffic safety applications like collision avoidance and hazardous condition warning can be developed, which can considerably lower the accident rates [16]. In the following list, we specify safety applications of interest in the context of this dissertation [24]:

- Stopped or Slow Vehicle Advisor (SVA): where a slow or stopped vehicle broadcasts a warning message to approaching vehicles to notify the drivers of the slow/stopped vehicle.
- Post Crash Notification (PCN): a vehicle involved in a road crash broadcasts a warning message to approaching vehicles to plan their routes, until the crash site is cleared.
- Road Hazard Condition Notification (RHCN): a vehicle that detects hazardous road condition warns the vehicles in the affected region.

- Cooperative Collision Warning (CCW): a vehicle monitors status messages sent from its neighboring vehicles to warn the driver of potential collisions.
- Cooperative Violation Warning (CVW): a roadside unit actively broadcasts signal related information to approaching vehicles, such that the drivers are warned of potential signal violations.

2.3.2 Convenience-oriented Applications

Convenience-oriented applications are travel comfort applications, known as delay-tolerant systems with more relaxed time constraints, but are expected to require data transmission spanning relatively faraway distances. Those applications can significantly improve our everyday lives, by making the delivery of announcements and advertisements possible. Examples include: sale information or remaining stocks at a department store, the available parking slots at a parking place, the meeting schedule at a conference room, and the estimated bus arrival time at a bus stop. Only clients around the access point can directly receive the information, since the broadcast range is limited. However, this information may be received by drivers and passengers who are far away. For example, a driver may want to query some department stores to decide where to go. A passenger on a bus may query several bus stops to choose the best next stop for bus transfer. Such queries may be issued tens of kilometers away from the broadcast site. Within a VANET, the requester can send the query to the broadcast site and may tolerate the expected delay as long as the reply eventually returns [16]. The following is a list of convenience-oriented applications of interest [24]:

- Congested Road Notification (CRN): a vehicle detects road congestion and broadcasts the information to other vehicles, such that their drivers can utilize the information for trip planning.
- Traffic Status Notification (TSN): a vehicle requests information about the traffic flow status of a faraway road, and receives a reply through the ad hoc network.
- Parking Availability Notification (PAN): A requesting vehicle broadcasts a message to the parking site through the ad hoc network and receives a respond about the available parking slots.
- Parking Spot Locator (PSL): a vehicle entering a parking area requests the parking roadside unit about the location of available parking spaces and receives a reply from the unit.

2.4 Vehicular Networking Projects

This section presents examples of vehicular networking projects in the U.S, Canada, Europe and Japan. These projects mainly aim at improving traffic safety, increasing travel efficiency and reducing the environmental impact of transportation. According to the U.S Department of Transportation, Safety has the highest priority in the Emerging, state-of-the-art technologies and systems. In 2009, there were 5.5 million crashes, around 34,000 fatalities, and 2.2 million injuries on U.S. roads as the result of vehicle crashes. According to DOT, combined V2V and V2I systems potentially address about 81% of all-vehicle target crashes; 83% of all light-vehicle target crashes; and 72% of all heavy-truck target crashes annually [4].

Since 2002, the U.S. DOT has been engaged in research with automotive manufacturers on V2V crash avoidance systems that use high-speed wireless communications and vehicle-positioning technology. In 2006, the U.S. DOT joined together with a partnership of automotive manufacturers, Crash Avoidance Metrics Partnership (CAMP), to develop and test prototype V2V safety applications. CAMP includes Ford, General Motors, Honda, Hyundai-Kai, Volkswagen, Mercedes-Benz, and Toyota. The Connected Vehicle Safety Pilot [4] project is a major source of robust data. It is a real-world research that aims at testing V2V and V2I safety technologies, applications, and systems using everyday drivers. The effort will test performance, evaluate human factors and usability, and collect empirical data to present an accurate understanding of the potential safety benefits of these technologies.

In addition to safety, vehicular networking in the U.S aims at improving transportation in the areas of mobility and environment. Minimizing driver distraction is a major factor in the design of all vehicular networking applications, whether the application is for safety, mobility, or the environment. According to the U.S. DOT, nearly 5,500 people in the United States were killed and almost half a million were injured in accidents related to distract driving in 2009. 18% of those fatal accidents involved the use of a cell phone [4]. To provide improvements to mobility and accessibility, Dynamic mobility applications project [4] introduces innovative methods for operating existing transportation systems, based on the availability of new data sources and communications methods. It seeks to identify, develop, and deploy applications that leverage the full potential of connected vehicles to enhance current operational practices and transform future surface transportation systems management.

Traffic congestion is an $87.2 billion annual drain on the U.S. economy, with 4.2 billion hours and 2.8 billion gallons of fuel spent sitting in traffic [4]. Connected vehicles can support transportation management systems for maximized efficiency and minimized congestion, by providing transportation agencies with real-time traffic and parking data. It also has the potential to enable travelers to change their route based on the road network conditions, to avoid traffic jams. On the other hand, connected vehicle environmental applications can support and facilitate green transportation choices, by generating and utilizing environmentally relevant real-time transportation data, in order to reduce the environmental impacts of transportation.

Real-Time Information Synthesis (AERIS) [4] project aims to generate, capture, and analyze data to create information that helps system users and operators make green transportation choices. For instance, travelers may decide to avoid congested routes or take alternate routes or public transit, in order to make their trip more fuel-efficient. Data generated from connected vehicle systems can also provide operators with detailed, real-time information on vehicle location, speed, and other operating conditions. This information can be used to improve system operation. The AERIS project intends to assess how the suite of V2V and V2I connectivity and communications options may contribute to air quality improvements and reductions in pollutants. The program will investigate a handful of applications to determine whether they provide significant environmental benefits.

In Canada, The vision of DIVA project [81] (Developing Next Generation Intelligent Vehicular Networks and Applications) is to see developed and deployed distributed, robust, secure and fault-tolerant communication solutions, for enabling intelligent vehicular network systems. These systems basically aim at reducing the environmental impact of transportation, while providing drivers and passengers with convenience applications such as location-aware services, local news, multimedia streaming alert messages on highways and city streets. The expected outcomes of this network research will include solid understanding of intelligent vehicular network service and application requirements, in addition to design of an integrated framework for heterogeneous VANETs, considering robust and secure infrastructure. Moreover, DIVA would provide a suite of efficient vehicular communication protocols and test-beds to foster Canadian research in large-scale VANETs.

In Europe, Car 2 Car Communication Consortium aims to develop an open European standard for ITS. It provides an associated validation process and realistic deployment strategies and business models to speed-up the market penetration roadmap for the deployment of V2V and V2I systems [82]. A significant set of projects related to Car 2 Car Communication Consortium have been completed, while another set of projects are currently ongoing. As an example of completed projects we select to provide an overview of SAFESPOT project, while we select AdaptIVe project as an example of ongoing projects in Europe.

The technologies developed in SAFESPOT [83] (Smart Vehicles on Smart Roads) project have been verified in test beds located in six European countries, i.e., France, Germany, Italy, Netherlands, Spain and Sweden. SAFESPOT applications were demonstrated in the Cooperative Mobility Showcase (2010), which was one of the world's largest demonstrations of V2V and V2I communication technologies and applications. Demonstration area was divided into four parts: Safety Distance Warning

& Lane Change, Frontal Collision Warning & Head-on Collision Warning, Accident at Intersection & Obstructed View at Intersection, and Wrong Way Driver Detection & Hazard & Incident Warning.

AdaptIVe [84] (Automated Driving Applications & Technologies for Intelligent Vehicles) is an ongoing research project co-funded by the European Commission. It started its work in January 2014. The objective is to develop and test new functionalities for vehicles offering partially automated and highly automated driving. Necessary cooperative interaction between the driver and automated systems shall be enabled by advanced sensors, cooperative vehicle technologies and adaptive strategies.

In Japan, Smartway [25] project supports V2I communication at 5.8 GHz. Its driver warning system was successfully demonstrated in field trials on public roads in 2004 and 2005, while its OBU was publicly presented in 2006. During the same year, Smartway driver information and warning service became operational. Frequency bands that will be used for V2V, V2I and for radar communication were defined in ITS-Safety [25] project. In 2008 and 2009 verification testing on public roads has been accomplished. In addition to traffic safety, Advanced Safety Vehicle (AVS) [25] is a program that focuses on efficiency applications supported by V2V and V2I communication. The demonstration project results took place on a test track in October 2005.

Chapter 3: Data Dissemination in VANETs

Data dissemination refers to data transportation from a source vehicle to other vehicles in the network. In VANETs, data can be disseminated periodically or on demand in a push-based or pull-based manner. In this research, we assume push-based event-driven multi-hop data dissemination, in order to support different types of applications. We choose to rely on event-driven dissemination to send data on demand, instead of the periodic broadcast that wastes the limited available channel bandwidth. This way, we provide scalable communication to serve both: safety-oriented and convenience-oriented applications. In addition, we specifically target multi-hop instead of single-hop data dissemination, trying to provide the maximum propagation distance to serve convenience-oriented applications.

VANET environment poses multiple challenges on data dissemination basically due to the high mobility feature that characterizes it from other types of Mobile Ad hoc Networks (MANETs). Such challenging issues are reviewed in section 3.1. In section 3.2, we review existing data dissemination models with examples. After that, we provide a comparative study of existing mathematical modeling approaches in section 3.3.

3.1 Challenges of Data Dissemination in VANETs

VANET applications impose diverse requirements on the supporting technologies. This diversity leads to a number of challenges [20]. In this section, we particularly focus on the main research issues and challenges of data dissemination in vehicular environments, which are: limitations of the technology, scalability, connectivity, modeling, security and privacy. In the context of this research, we select to address technology limitations, scalability and modeling.

3.1.1 Limitations of the Communication Technology

IEEE 802.11p standard inherits limitations exist in other amendments of the 802.11 family of standards. Challenges arise when relying on broadcasting for data dissemination, which is the predominant communication paradigm in VANETs. The unreliability of broadcasting is due to the lack of acknowledgment in the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism [26]. Another technical limitation is due to the lack of a congestion control mechanism. Periodic one-hop beacon messages can alone lead to the exhaustion of the wireless channel capacity in dense networks [10]. Those messages are referred to as Basic Safety Messages (BSMs) in the U.S., and Cooperative Awareness Messages (CAMs) in Europe.

3.1.2 Scalability

The limitation of the VANET technology poses scalability challenges under high density scenarios. The excessive number of redundant messages can lead to broadcast storm problem, which will be overviewed in the next chapter. Data dissemination methods in the VANET context have to address the scalability challenge, basically by proposing broadcast storm mitigation strategies that can effectively reduce data redundancy and utilize the limited available channel bandwidth.

3.1.3 Connectivity

Connectivity is considered to be an important issue in VANET. The high mobility and rapid changes of the topology lead to a frequent network fragmentations in sparsely connected environments. The life time of a communication link should be as long as possible, a task that can be accomplished by increasing the transmission power. Nevertheless, that may lead to throughput degradation [19].

3.1.4 Modeling and Simulation

There is no standard methodology for performance evaluation of data dissemination in VANET. Dissemination techniques are commonly verified via simulations, and are rarely analyzed by utilizing mathematical modeling. This is mainly due to the major challenge of providing sufficient level of details to the model to ensure realistic traffic scenarios and driving behavior. Mathematical modeling will be further explored later in this chapter. A survey on modeling and simulation of wireless mobile ad hoc networks can be found in [85].

The cost and complexity of implementing VANET data dissemination schemes and applications in large test-bed systems forces such an implementation to be within a simulation environment [27]. Three major challenges can be addressed in the context of VANET simulation. First, the credibility and feasibility of simulation systems require reliable and standardized simulation parameters so that verification techniques can be applied. Second, mobility models should address sufficient levels of complexity to simulate realistic traffic scenarios and realistic driving behavior [28]. Third, the scalability of simulation represents a huge challenge in this context. Specifically, it is currently impossible to simulate the full-stack of very large networks [29].

3.1.5 Security and Privacy

In safety-oriented applications, integrating security mechanisms is highly necessary within VANETs [30]. Warning systems will not be accepted by customers if trust, security and reliability are not provided. The introduction of trust by providing trustworthy applications is considered as the most crucial security issue within a VANET [27]. However, integrating security schemes will increase the delay of message arrival. Keeping a reasonable balance between the security and privacy is one of the major challenges in the context of vehicular environments. Specifically, the receipt of trustworthy information from its source is important for the receiver. However, this trusted information can violate the privacy requirements of the sender [31].

3.2 Data Dissemination Models

The majority of data dissemination techniques designed for VANETs follow one of a three basic models: push-based, pull-based or hybrid. In the push-based model, data is usually disseminated proactively using periodic broadcast, while in the pull-based model; it is disseminated only on-demand.

Push model is generally preferred for safety-oriented applications, such as collision warning systems and emergency dissemination systems. In contrast, the pull model techniques often target convenience-oriented applications known as delay-tolerant systems such as arrival time estimation or congestion detection. By combining both models together, a hybrid model can support different types of information and dissemination applications in VANETs.

3.2.1 The Push Model

Push model is generally preferred for safety-oriented applications, such as collision warning systems, emergency message dissemination systems and information systems specified for hazardous road conditions like ice, water or snow. Nevertheless, other approaches also exist to support other types of applications such as arrival time estimation, speed expectation and congestion detection. In this section, a representative example is provided for each of those applications.

3.2.1.1 Safety Messaging System

In [32], the push model is studied in the context of the "Traffic View" vehicular data dissemination system. The study differentiates between the vehicle's own data and the stored data about other vehicles. Three propagation models were compared: same-direction, opposite-direction and bi-direction. In the same-direction model shown in figure 3-1(A), a vehicle periodically broadcasts both its own data in addition to its stored data in a single packet, which is propagated "backward" by vehicles moving in the same direction. While in the opposite-direction model shown in figure 3-1(B), vehicles in the same direction only broadcast their own generated data, which are aggregated and propagated backwards by vehicles moving in the opposite direction. These two models are combined together in the bi-direction model, in which generated and stored data are propagated backwards by vehicles moving in the same direction, and only stored data is propagated by vehicles moving in the opposite direction. Such a simple approach poses a great dissemination overhead since all the vehicles in the desired direction participate in broadcasting.

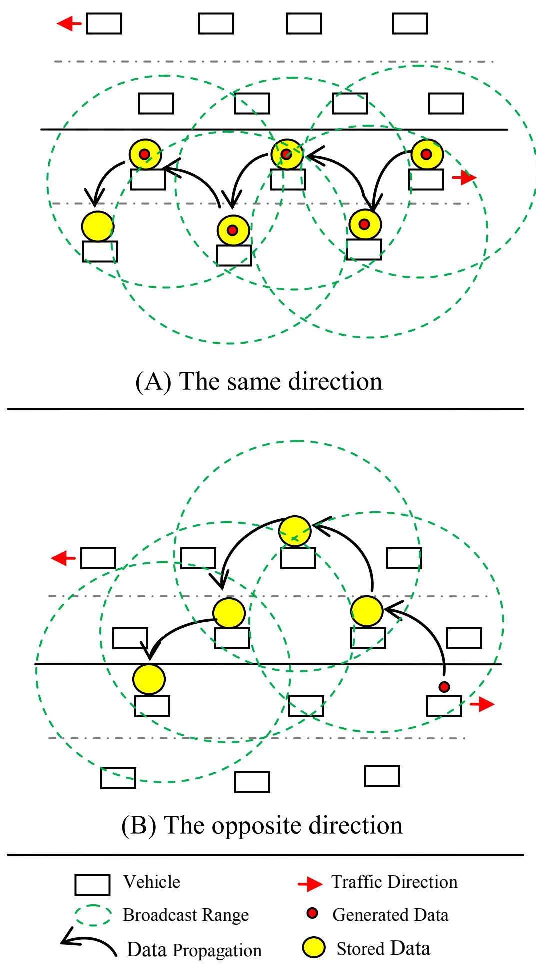


Figure 3-1: Dissemination Models in Traffic View

3.2.1.2 Hazardous road condition warning

In [33], two dissemination protocols for VANETs are proposed in the context of the Life WArning System (LIWAS) research project, which is a traffic warning system that aims at providing drivers with information about hazardous road conditions such as ice, water and snow.

The first protocol is called the “Zone Flooding” protocol shown in Figure 3-2(A). This protocol proposes three different optimization techniques to limit the forwarding of packets. The first is “hop-count”, which aims at ensuring the maximum number of hops before discarding a packet. The second technique is “sequence-list”, which ensures that a certain packet can be forwarded only once. The “zone flooding” concept is also introduced to further limit the dissemination of packets. The second protocol is called the “Zone Diffusion” protocol shown in Figure 3-2(B), which is a data- centric protocol that is based on data aggregation. This protocol assumes that every node maintains an environment representation (ER) for the surrounding environment. ER is updated whenever data is received from sensors, and data are periodically broadcasted to neighbors.

Simulation results proved that these two protocols are robust to changes in network mobility and density. However, the three simple techniques utilized for dissemination optimization are not sufficient to mitigate broadcasting overhead under high densities.

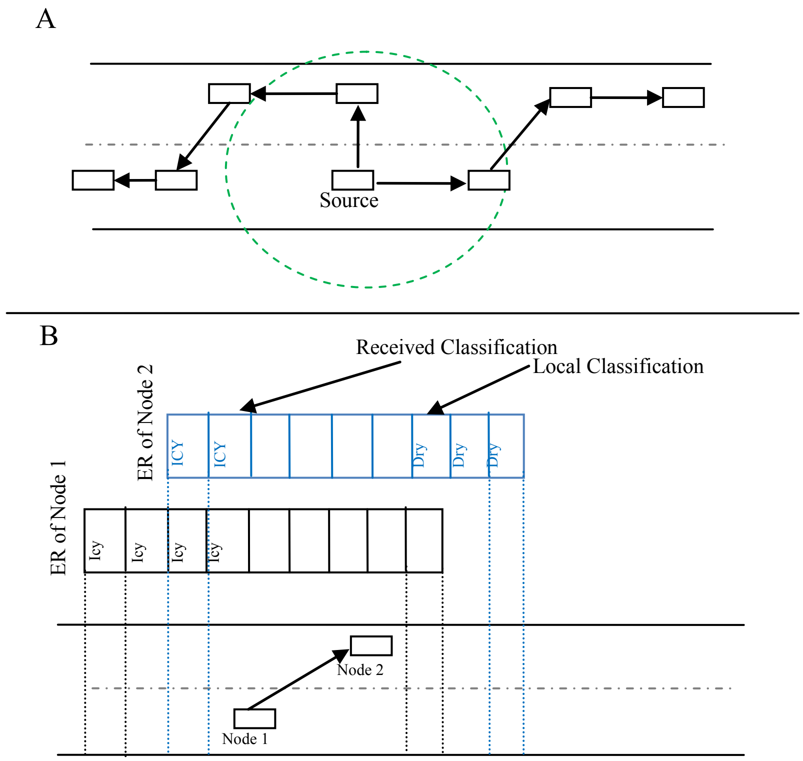


Figure 3-2: (A) Zone-Flooding Protocol (B) Zone Diffusion Protocol

3.2.1.3 Arrival Time Estimation

An example of estimating arrival time to vehicles' destinations is proposed in [34], where the road map is divided into areas in which vehicles can measure the time required to pass through each area. A sufficient number of vehicles is required in each area in order to keep accurate traffic information statistics continuously. Each vehicle periodically broadcasts area passage time to share with neighboring vehicles. When the number of area passage records reaches a predetermined threshold, the vehicles average area passage time by creating statistics data. The proposed approach is evaluated with realistic traffic flows on realistic road system and proved to achieve the traffic information sharing at a practical level. Broadcasting is not optimized in this approach, and the network could be easily flooded with data under high densities.

3.2.1.4 Speed expectations

Speed expectations example approach is proposed in [35] where vehicles are enabled to build their own local traffic maps of speeds experienced on visited roads, and share them with other vehicles. This allows a vehicle to build a map of expected speeds even on non-visited roads, which indicates traffic congestion through the network. This approach was applied on a simple Manhattan grid network map, and data is exchanged only on areas of unexpected traffic; by using a distributed clustering algorithm that does not require constant network connectivity. This approach performs well in sparsely connected dynamic network, but it is not evaluated in large-scale scenarios.

3.2.1.5 Congestion Detection

In [36], an example of congestion detection is presented based on disseminating and propagating traffic data using Received Message Dependent Protocol (RMDP). Most of the vehicles can acquire the head of traffic jam in a short time using RMDP. A simple communication approach is considered, in which a vehicle broadcasts its own information to its surrounding vehicles that are traveling on the opposite lane. As shown in figure 3-3, the proposed approach can be presented as follows: Assume that a moving vehicle A disseminates its locally stored information to vehicle B moving on the opposite direction lane. B moves forward and re-disseminates A’s information to a vehicle C moving in the same direction as A, such that C can determine the head of traffic jam and may decide to change its route. From this simple illustration, it can be concluded that RMDP has a limited scope since it focuses on the congestion of the road directly ahead.

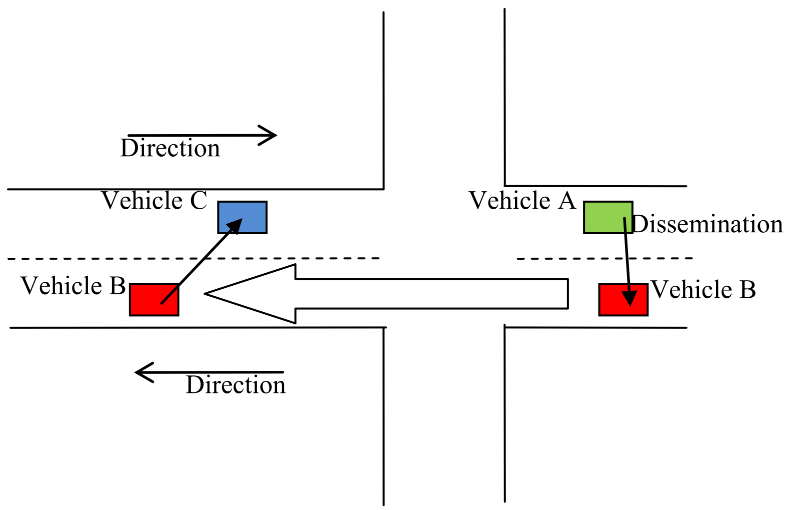


Figure 3-3: RMDP Communication

3.2.2 The Pull Model

The pull model techniques often follow the request-response paradigm for data dissemination. Compared to the push-based model, pull model often requires less overhead, with latency tolerance. In pull-based approach, the requester usually sends a query to the broadcast site, and gets a reply message from there. In such applications, users can tolerate more delays as long as a response eventually returns. Pull-based techniques often target convenience-oriented applications such as service discovery and delay-tolerant systems.

3.2.2.1 Service Discovery

Address Based Service Resolution Protocol (ABSRP) [37] integrates a pull-based technique to discover services in VANETs. When a vehicle needs a service, it creates a service request with the specification of the type of service and the desired service area, and then transmits it to the nearest roadside unit, as shown in figure 3-4. The receiving roadside unit checks if it has proactively learned about the service provider. If it is aware of the service provider's IP address, it forwards the service request to the target service provider. Otherwise, it broadcasts the service request destined to the target service provider over the backbone network.

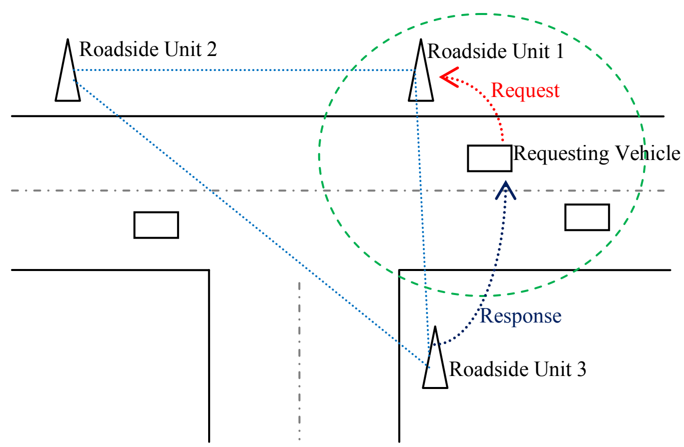


Figure 3-4: ABSRP Information Dissemination Model

In the case of figure 3-4, the request received by roadside unit 1 is broadcasted to the two nearby units. After receiving the request, the target service provider creates a service response and transmits it to the originating vehicle. A roadside unit can transmit a service request to the target service provider over the vehicular network or backbone network. In the former case, broadcasting can rapidly flood a congested vehicular network with data, since no optimization is proposed in ABSRP.

3.2.2.2 Delay-tolerant systems

Vehicle-Assisted Data Delivery (VADD) is another pull-based approach for data dissemination in VANETs [7]. When a vehicle issues a request to a certain fixed site, VADD proposes techniques to efficiently route the packet to that site and receive the reply within a reasonable delay. Involved nodes carry the packet when routes do not exist and forward it to the new receiver that moves into its vicinity.

As shown in Figure 3-5, vehicle A has a packet to forward to a certain destination. Optimal direction for this packet is assumed to be north. Two contacts are available for the packet carrier: B moving south and C moving north. Thus, A has two choices for selecting the next hop for the packet. Both choices aim at forwarding the packet north. B may be selected because it is geographically closer towards the north and provides better possibility to exploit the wireless communication (e.g. B can immediately pass the packet to D, but C cannot). C may also be selected because it is moving in the packet forwarding direction. These two choices lead to two different forwarding protocols: Location First Probe (L-VADD) and Direction First Probe (D-VADD).

VADD makes use of the predictable mobility in a VANET, which is limited by traffic pattern and road layout. Extensive experiments were designed for performance evaluation. Results show that the VADD outperforms existing solutions in terms of data packet delay, packet-delivery ratio, and protocol overhead. Nevertheless, VADD is designed specifically for applications in sparsely connected networks, and did not resolve communication issues under high-densities.

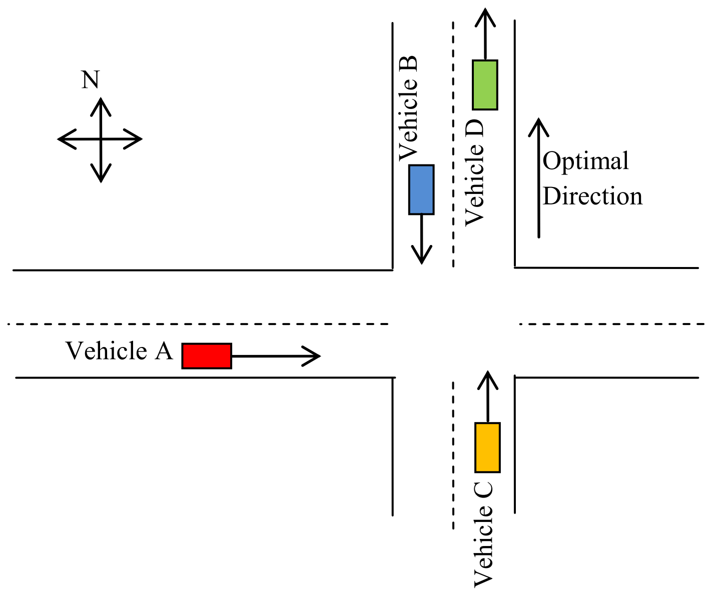


Figure 3-5: VADD in the Intersection Mode

3.2.3 The Hybrid Model

Along with the push and pull models we presented, there are few schemes that combine both models in order to support different types of applications within a VANET environment. Information transfer protocol for vehicular computing "VITP" [38] supports the establishment of distributed service infrastructure over VANETs, by specifying the syntax and the semantic of messages between vehicles. VITP uses both of the data dissemination models. For safety messages such as alerts about emergencies or hazardous traffic conditions, a push-based technique is used, while a pull-based technique is proposed to retrieve information by location-sensitive queries issued by vehicles on demand.

The push-based technique proposed by VITP disseminates alert messages among vehicles moving into the affected area. Whenever a vehicle detects such a condition, it generates an alert message and transmits it via the underlying VANET. The generated push message is transported to its target location area using geographic routing. Once arrived, the push message is broadcasted to all vehicles within the target location area. On the other hand, the usage of pull-based technique to disseminate messages is issued on demand in a context of service provision scenario, such as estimating the traffic-flow condition in a target location. When a vehicle initiates such a request, it submits that request to the target area, assuming that there is a connection from the requesting vehicle to that area through the VANET (as shown in figure 3-6). The propagation of such a request is done through intermediate nodes using geographic routing, in a way that is similar to transporting a push message. The semantic of the query determines the way to treat it once it arrives to the target location area, where vehicles construct a virtual ad hoc server (VAHS) to provide a reply message. As figure 3-6 shows, the request message propagates through the virtual server until a certain return condition is satisfied. The vehicle that detects such a return condition immediately creates a reply message, and posts it towards the source area, where the requesting vehicle is located.

Simulation results have proven the feasibility of VITP in VANET environment. However, there is a high drop rate for queries, which grows substantially with increasing query distances, and with decreasing vehicle densities, and therefore, optimization techniques are required to enhance the performance of VITP.

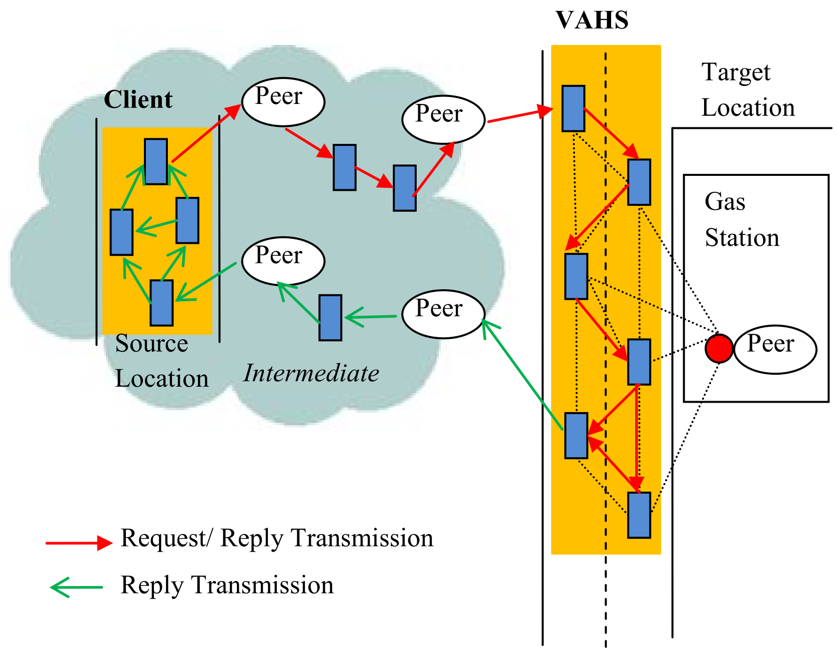


Figure 3-6: VITP Communication

3.3 Performance Evaluation of Data Dissemination in VANETs

There is no standard methodology for performance evaluation of VANET data dissemination. Existing approaches are commonly verified via simulations, and few are analyzed using a mathematical model. This is mainly due to the major challenge of providing sufficient level of details to ensure realistic traffic scenarios and driving behavior. In fact, three different models are to be considered: the road layout model, the mobility of vehicles [28] (or traffic flow model), and data dissemination model. In this section, we review and compare recent studies on mathematical modeling of data dissemination in VANETs (section 3.3.1), and then we provide an overview of simulation-based evaluation (section 3.3.2).

3.3.1 Mathematical Modeling

Here we review existing mathematical modeling approaches for data dissemination in the VANET context. We provide mathematical analysis for push-based model first, and then for pull-based model.

3.3.1.1 Modeling Push-based Data Dissemination

Based on a careful literature review, we have found three modeling approaches: Time-Probabilistic, Modeling with Priority and Warning Delivery Modeling.

Time-Probabilistic Analysis

In [39], the authors consider two algorithms to transfer warning messages in VANET. They have developed analytical models to obtain time-probabilistic characteristics of these algorithms. A linear network topology is assumed as shown in figure 3-7. At a broadcast transmission from a node *i* of the network, its message is received by all the vehicles within its transmission range *r* with probability *p*. If two nodes transmit simultaneously in the vicinity of a recipient node *j*, the transmissions interfere at node *j*.

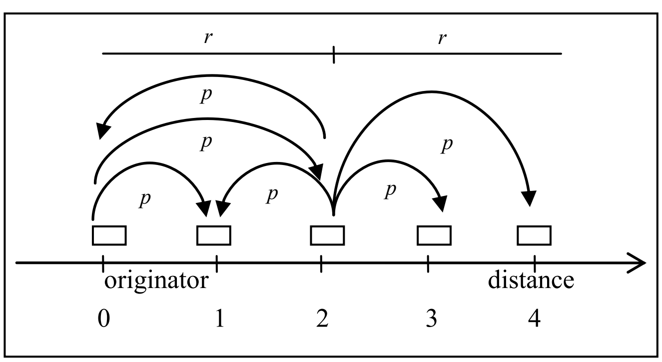


Figure 3-7: Time Probabilistic Analysis

For each algorithm A, $G_A(t,d)$ is the probability of the event in which a node located at distance d from the message originator receives the warning message at the *t-th* step of the system operation. The primary performance metric of A is the mean dissemination delay, which is given by

$$D_A(d) = \sum_{t=0}^{\infty} t G_A(t,d) \tag{1}$$

Considering such a simple model significantly simplifies the task of comparing different algorithms, which is an advantage. However, only limited set of algorithms can be modeled with such simplicity. In addition, the delay metric is not sufficient for performance evaluation.

Modeling with Priority

In [40], the analysis uses two priority classes of traffic, assuming that safety messages have higher priority compared to the other network traffic. One-dimensional VANET modeling in a highway with length R meters and each node has constant transmission range d. Nodes are dispersed in the highway according to a Poisson process with rate φ. Low-priority messages are assumed to arrive according to a Poisson process with rate λ_0. Message transmission time is exponentially distributed with rate μ. Two concurrent transmissions interfere with each other whenever the distance between the transmitting nodes is less than $2d$. If the distance is less than d, the interference is referred to as internal interference. Otherwise, it is referred to as external interference. Figure 3-8 illustrates the two types of interference.

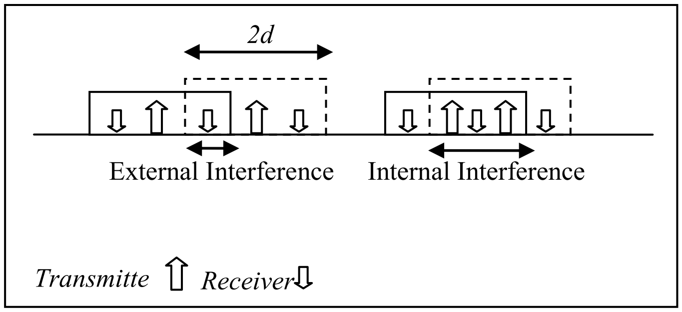


Figure 3-8: Modeling with Priority

First, the probability of interference between two nodes is derived. Then, a birth-death process analysis is used to derive the probability distribution of lower priority messages, which are concurrently transmitted at the steady-state, and also to derive the percentage of destination node population which is affected by the interference, and thus cannot receive the message correctly. Finally, the performance of high-priority traffic is studied in the presence of low-priority traffic. Three performance metrics were considered. First, the average message forwarding distance in a hop d is derived, and expressed as:

$$d = \frac{\omega}{1 - P_s(0)} \sum_{k=1}^{\infty} \frac{k P_s(k)}{1 + k} \tag{2}$$

where ω is the distance of the border point between the non-interference and interference regions from the sending node. $P_s(k)$ is the probability that k nodes receive the high-priority message successfully. Second, the average number of nodes N that would receive the safety message successfully is expressed as:

$$N = \frac{(1 - P_e)}{P_e} \tag{3}$$

where P_e is the probability that the forwarding of a high-priority message stops. Third, the average number of communication hops that a message travels in the network n_n is given by:

$$n_h = \frac{Z}{d} \tag{4}$$

where Z denotes the average distance that a safety message covers until its propagation terminates.

Numerical and simulation results show that the probability of a receiving node being exposed to interference increases as a function of the transmission range, and thus, increasing the transmission range does not necessarily improve the forwarding distance of safety messages, since more nodes may be exposed to interference, especially under high density scenarios. The importance of the result provided in [19] is that it can be used to study the performance of different message dissemination algorithms and to determine the optimum range assignment in VANETs.

Warning Delivery Modeling

The work in [41] also analyzes the problem of dissemination of safety messages. A safety area around the point where a hazard happens is introduced and the goal is to optimize the message dissemination approach such that all vehicles within this area can receive the message. Multiple broadcast cycles are assumed, so that within a certain time all the designated vehicles are guaranteed to be informed. Three performance measures are derived: The average delay, the probability that a vehicle is informed, and the average number of duplicate messages received by a vehicle within the defined safety area.

A linear network topology of a highway with at least two lanes is assumed. Every vehicle has a transmission range that is equal to R. Wireless channel is error-free; which means that all vehicles within the transmission range of a source node can forward a received message correctly. In addition, no initial contention phase is considered. Whenever a vehicle traveling on the highway has detected some safety condition at any point of the highway, it triggers the dissemination of a warning message by exploiting multi-hop ad hoc communications (figure 3-9). The objective is to inform all travelling vehicles within a certain dissemination area of extension d. For simplicity, we only consider the analysis of a single broadcast cycle. The number of vehicles within the dissemination area n^* is assumed to be constant. Every time a vehicle receives a new warning message, it decides, with probability α to act as relay to forward the message further. Three performance measures are derived: The average number of informed nodes (vehicles), the average delay, and the average number of duplicate messages received by a vehicle.

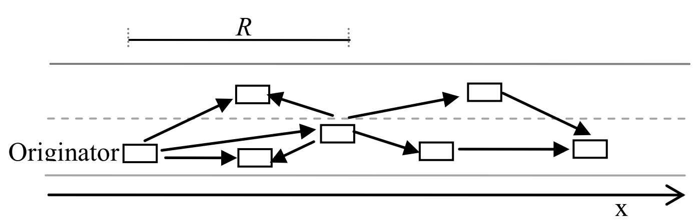


Figure 3-9: Warning Delivery Model Assumptions

Let's firstly show how the average number of informed nodes is computed. Since the probability that a node forwards the warning message is Bernoulli with parameter $\alpha < 1$, and the distance between nodes is assumed to be exponentially distributed with parameter γ; the distance between two consecutive relay nodes is exponentially distributed with $\alpha\gamma$. Let $P_r(n)$ indicate the probability that the number of connected relay nodes is equal to n:

$$P_r(n) = \begin{cases} (1 - e^{-\alpha\gamma R})^n e^{-\alpha\gamma R} & n < n^* \\ (1 - e^{-\alpha\gamma R})^{n^*} & n = n^* \\ 0 & n > n^* \end{cases} \tag{5}$$

where $n^* = \lfloor \alpha\gamma D \rfloor$, and the average number of relay nodes:

$$r = \left(1 - e^{-\alpha\gamma R}\right)^{n^*} \left(1 - e^{\alpha\gamma R}\right) + e^{-\alpha\gamma R} - 1 \tag{6}$$

Given $P_r(n)$, the distribution of the number of informed nodes, $S(n)$ can be estimated by considering the average number of nodes covered by message propagation. The average distance covered by the warning message when there are n connected relay nodes is:

$$d(n) = \frac{P_r(n)}{\alpha} \tag{7}$$

where $1/\alpha\gamma$ is the average distance between two consecutive relay nodes. The number of informed nodes can be obtained by:

$$S(n) = d(n)\gamma = \frac{P_r(n)}{\alpha} \quad (8)$$

and the average is:

$$S = \frac{(1 - e^{\alpha\gamma R})^{n^*}(1 - e^{\alpha\gamma R})}{\alpha} \quad (9)$$

Now we show how the delay *D* is computed. Assuming single broadcast cycle, *D* can be obtained from:

$$D = T_{tx} + \frac{d}{c} \quad (10)$$

where T_{tx} is transmission time of the warning message, *d* is the covered distance, and *c* is propagation speed.

Lastly here, the average number of messages *M* received by each informed node is computed as:

$$M = \left[2\alpha\gamma R - (\alpha\gamma R - 1)(1 - P_s)\right]P_I \quad (11)$$

where P_I is the probability to inform a node. Despite its simplified assumptions, this model can accurately and effectively compute the three derived performance metrics [41].

One drawback of the proposed analysis is the error-free wireless channel assumed, which means that all vehicles within the transmission range of a source node can forward the safety message correctly and collisions are not taken in consideration. It is also assumed that topology does not change during each broadcast cycle, and topology modifications are considered only at the beginning of new cycles. However, the impact of this assumption is limited, since transmission, propagation, and back-off time scales are much smaller than that of vehicles' movements.

3.3.1.2 Modeling Pull-based Data Dissemination

For pull-based data dissemination model, we specify the following two mathematical modeling approaches: Delay-tolerant Message Propagation [42], and Vehicle-Assisted Data Delivery (VADD) [7].

Delay-Tolerant Message Propagation

In [21], an analytical model is presented for delay tolerant message dissemination in VANETs. A bidirectional highway is assumed, in which vehicles and messages travel either upstream or downstream as shown in figure 3-10. Nodes traveling in one direction are separated by distances X that are exponentially distributed. For transmission range R, two vehicles are connected if $X_i \leq R$. Connectivity is modeled as the probability $P(X_i \leq R)$. The roadway is divided into cells of size l as shown in figure 10, and two bounds are defined for the cell size: an upper bound of size R, and a lower bound of size $R/2$. For the lower bound, vehicles located in adjacent cells are surely connected. While for the upper bound, vehicles traveling in two adjacent cells are not necessarily connected. Distances remain unchanged since vehicles are assumed to travel at a fixed speed.

Upper and lower bounds are derived for message propagation as a function of traffic density, vehicle speed and transmission range. Message propagation rate is the performance metric used for the evaluation of the analyzed model. Simulation results imply that the message propagation rate experiences a phase transition behavior as a function of traffic density. Extended analysis is provided in [43] for characterizing such a behavior.

Another lower bound is also presented in [44], for the probability that a vehicle receives a safety message through multi-hop communication from a source at a distance *d* away and within *t* seconds. This probability *p* is derived as a function of single-hop communication reliability. The analysis studies the tradeoff between the parameters *t*, *p* and the inter-vehicle distance, *d*. Again, it is assumed that inter-vehicles distances are fixed, which is unrealistic.

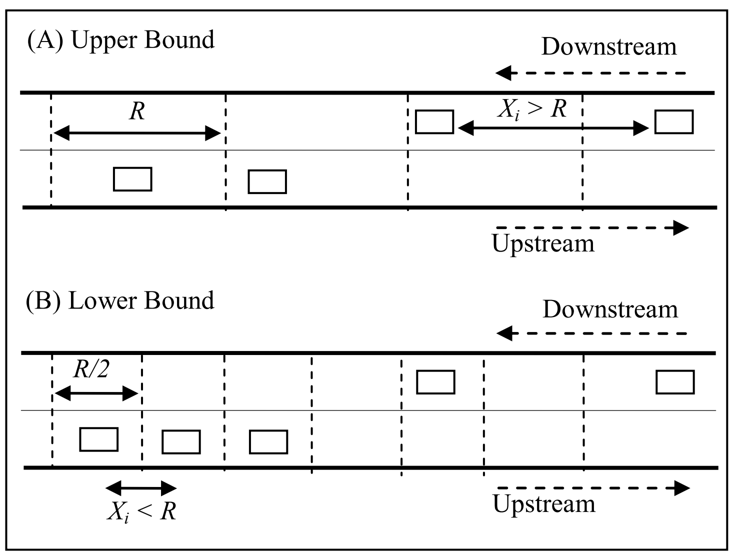


Figure 3-10: Delay-tolerant Message Propagation

Vehicle-Assisted Data Delivery (VADD)

Another approach for delay-tolerant VANETs is called Vehicle-Assisted Data Delivery (VADD) [7]. When a vehicle issues a delay tolerant data query to a certain fixed site, techniques are proposed to efficiently route the packet to that site, and receive a reply within reasonable delay, by using the predicable vehicle mobility, that is limited by traffic pattern and road layout. Based on the existing traffic pattern, a vehicle can find the next road to forward the packet with the aim of reducing the delay. Selecting the next hop that is closer to the destination is usually efficient in geographic routing, but VADD assumes sparsely connected network, where such a selection is not always possible. VADD always tries to transmit through wireless channels as much as possible. If the packet has to be carried through certain roads, the road with higher speed should be chosen. Dynamic path selection is continuously executed throughout the packet forwarding process.

VADD is analyzed in three packet modes: Intersection, Straightway and Destination based on the location of packet carrier. A stochastic model is used to estimate the data delivery delay, which is used to select the next road (intersection). Figure 3-11 shows an example of VADD delay model. For a packet at I_m, the expected delay of delivering the packet through road r_{mn} is given by:

$$D_{mn} = d_{mn} + \sum_{j \in N(n)} (P_{nj} \times D_{nj}) \tag{12}$$

where D_{ij} is the expected packet delivery delay from intersection I_i to the destination if the packet carrier at I_i chooses to deliver the packet following road r_{ij} . P_{ij} is the probability that the packet is forwarded through road r_{ij} at I_i. Finally, $N(j)$ is the set of neighboring intersections of I_j . The latter equation can be applied on a bounded area that includes the source and the destination of a certain vehicle in a connected graph, in order to find and the intersection with minimum expected delay, and select it for packet delivery. In addition to data delivery delay, two other performance metrics are considered: data delivery ratio and data traffic overhead.

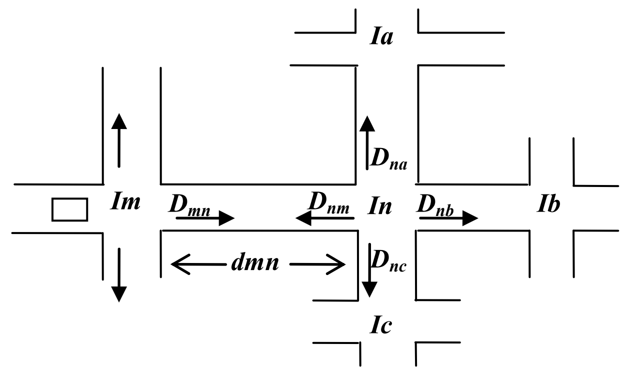


Figure 3-11: VADD Model Example

3.3.2 Discussion

Here we provide a comparison among the reviewed analytical models from the perspectives of performance metrics and model assumptions. It is worth noting that most of the reviewed modeling approaches rely on IEEE 802.11p [45] communication standard, which is an approved amendment to the IEEE 802.11 standard that aims to add wireless access in vehicular environments, by defining enhancements to the original 802.11 to support ITS applications. Reader can return to section 2.2 for more details on IEEE 802.11p.

In Table 1, we summarize the comparison among the reviewed analytical models, which are classified according to the target applications into traffic safety, and delay-tolerant models. For each model, the table shows the considered standard, metrics, assumptions and the addressed challenges.

3.3.2.1 Performance metrics

Network performance metrics can be used for the evaluation of VANET data dissemination, such as packet loss, packet error, packet delivery ratios, end-to-end delay, normalized network load, and packet duplication. However, some techniques propose other corresponding metrics that can better evaluate specific application scenarios, such as in [46].

Models for safety-oriented and convenience-oriented (delay-tolerant) applications rely on two basic performance metrics: Mean dissemination delay and Probability of successful message reception. Delivery ratio is an alternative measure for the latter. In safety-oriented applications, it is required to minimize the delay and maximize data delivery. If an accident occurs on a road for instance, it is required to disseminate a warning message in order to inform vehicles that are planning to visit the same road, so that they may decide to take an alternative route. Under high density circumstances, the arrival of more uniformed vehicles can shortly block the road, and therefore, data delivery overhead becomes significant metric, which can be measured by the average number of duplicate messages received per vehicle.

3.3.2.2 Assumptions

Analytical models should address sufficient level of complexity to simulate realistic traffic scenarios and realistic driving behavior, which is a true challenge. Since there is no standard modeling approach for VANETs, each of the reviewed models uses a different method for analysis. Specifically, to model a VANET, it is required to provide assumptions about three basic components: the road layout, vehicular mobility, and networking (including density criteria and communication approaches).

In the following, assumptions made by the reviewed models on each of those components are discussed:

Road Layout:

To model the road layout, analysis approaches usually rely on linear network topology [39], [40], [41], [42]. However, linear layout cannot be generalized, since it represents only one possible road representation, which is the simplest. For safety-oriented applications, it could be sufficient to analyze data dissemination in a simple linear layout, which is not the case in delay-tolerant models. In [7], a graph is considered to represent three different road layouts (intersection, linear road and destination) which make the model more realistic.

Mobility:

For mobility modeling, [39], [40] and [42] assume a fixed vehicular speed, since distances between vehicles were set fixed for simplicity. In [40] and [41], vehicle overtaking is assumed to provide more realistic mobility. In contrast, no constrains were assumed on the mobility of vehicles in [7].

Networking:

To model the networking characteristics, [39] assumes that all network nodes are restricted to start their message transmissions synchronously at the time moments. At the zero time moment, a message is always transmitted by its originator. In the realistic vehicular network, it could be always assumed that each vehicle has access to the global positioning system and clocks, which ensure the practical implementation for such synchronization. Consideration of asynchronous transmissions under the deterministic packet arrival process would increase the complexity of the model. Existing approaches that are dealing with asynchronous transmissions assume Poisson packet arrival process and take a benefit of memory-less nature of exponential distribution. In [39] and [41], an error-free wireless channel is assumed, and interference phenomenon is neglected. In traffic safety models, it is required to analyze the network in the worst case, by assuming a high-density network, such as in [41]. On the other hand, delay-tolerant models may assume a sparsely connected network [42], [7]. Nevertheless, it is sometimes required to analyze delay-tolerant models under high-density scenarios so as to fit different applications. For example, congestion detection is considered as delay-tolerant application, but is required to be analyzed in dense networks.

To conclude the discussion, it can be noted that modeling is generally not sufficient for evaluating dissemination in VANET, and it should be verified using simulation results, in which more sophisticated details can be considered. It is required to provide sufficient level of details for the simulation, and then evaluate the impact of assumptions simplified in model analysis, such as neglected collisions, neglected transmission delays, the constant vehicles speeds assumed while the message is propagating. In many cases, despite the simplified assumptions, the model estimations are closed to simulation results [41]. This is due to the fact that connectivity, or node density, is the factor that mainly determines the network performance in VANETs. In [47], statistical properties of the connectivity with user mobility at the steady state are studied.

There is insufficient effort in analytical modeling of data dissemination in VANETs. Existing approaches usually rely on simulation results for performance evaluation. We have focused on the analytical modeling efforts in this area by providing a review and comparison for existing modeling approaches designed for performance evaluation in VANETs.

Table 1: Performance Modeling Approaches for VANETs (Comparison Summary)

Model		Standard	Metrics	Assumptions			Addressed Challenges
				Road Layout	**Mobility**	**Networking**	
Traffic Safety	Time-probabilistic Analysis [39]	Not mentioned	(1) Mean dissemination delay	– Linear Network Topology	– Fixed speed – Fixed distances between vehicles	– Synchronous Transmission	Interference
	Modeling with Priority[40]	IEEE 802.11	(1) Average number of nodes that receives the high-priority message (2) The per-hop message forwarding distance.	– One-direction highway (Linear topology)	– Overtaking – Fixed-speed time intervals chosen from Gaussian distribution	– Two priority data classes (low, high)	External and Internal Interference
	Warning Delivery Service [41]	Not mentioned	(1) Average delay (2) Probability of successful reception (3) Average number of duplicate messages	– One-direction multi-lane highway (Linear topology)	– Overtaking – Vehicles do not move during broadcast	– Error-free wireless channel – Worst-case (high density)	-
Delay-tolerant	Delay-tolerant Message Propagation [42]	IEEE 802.11p	(1) Message propagation rate	– Bidirectional highway	– Fixed Speed – Fixed Distances	– Delay tolerance Network	-
	VADD [7]	IEEE 802.11	(1) Data delivery delay (2) Data delivery ratio (3) Data traffic overhead.	– Graph with different traffic modes: Intersection, Straightway and Destination	-	– Sparse Network	Dynamic path finding

3.3.3 Simulation-based Evaluation

Simulation is the common methodology for the performance evaluation of VANET data dissemination, routing, communication and applications. While it is crucial to test and evaluate VANETs in a real environment, simulation is widely considered as a first step not only in the development of communication protocols, but also in the validation of analytical models [28]. Unlike mathematical modeling that considers simplified assumptions as we have shown in section 3.3.1, simulation can provide detailed models for performance evaluation. A key component of VANET simulations is the mobility model, which determines the locations of nodes in the network at any given instant. Realistic mobility model should provide sufficient level of details to ensure conclusions drawn from simulation results. Two models can be distinguished according to the level of details: the macroscopic model and the microscopic model. In the macroscopic model, the basic entity is the traffic flow, while in the Microscopic model; the movement of every single vehicle on the road is simulated, assuming that the behavior of the vehicle depends on its physical ability to move, and on the driver's controlling behavior. Existing VANET mobility models are reviewed in [28], and examples on practical simulation environments can be found in [48]. In the following, we provide a brief list of existing mobility models for VANET simulations.

3.3.3.1 Manhattan Model

Manhattan model is one of the models that utilize virtual generated maps to simulate an urban environment. Examples of other models that are based on the same virtual maps can be found in [48], such as the Freeway model and the City Section Mobility model (CSM). A Manhattan map contains vertical and horizontal bidirectional roads.

When the simulation starts, vehicles are randomly positioned on the roads, and then they move continuously according to history-based speeds, and a certain safety distance is considered between them. The direction at crossroads is randomly selected. The probabilities of deciding to continue straightforward, turn left or turn right are predetermined. Despite that a vehicle can change lane at a crossroads, this model does not provide control mechanism at these crossroads, where vehicles continue their movements without stopping.

3.3.3.2 Real Map Model (RMM)

Unlike the models that are based on virtual generated maps, RMM model [48] uses real maps from an existing database to represent urban environments. For each road segment, the coordinates are extracted and converted into a graph, where the vertices represent crossroads, and the edges represent roads. Each edge has a weight that represents the estimated time required to traverse it. This weight is dynamically estimated, based on the road length, its maximum allowed speed and the number of vehicles currently traversing it. Like the Manhattan model, RMM does not define a control mechanism at crossroads.

3.3.3.3 Stop Sign Model (SSM)

Unlike the Manhattan and the RMM models, The Stop Sign Model (SSM) model [48] integrates a traffic control mechanism at intersections. In this model, every road at an intersection has a stop sign. Vehicle approaching the intersection must stop at the signal for a predefined time. Each travelling vehicle’s mobility is constrained by the vehicle in front of it. Lane overtaking is considered in multi-lane roads. Vehicles following each other to a stop sign form a queue at the intersection. Each vehicle waits for at least the required waiting time once it gets to the head of the intersection after other vehicles ahead in the queue clear up. Vehicles crossing at the intersection are not coordinated among different directions. Although it is unrealistic to have stop signs at every intersection, this model simplifies understanding the dynamics of the mobility of vehicles and its effect on the performance of VANETs.

3.3.3.4 Traffic Sign Model (TSM)

In this Model, stop signs defined in the SSM model are replaced by traffic lights. A vehicle stops at a crossroad if it encounters a red light, otherwise it continues moving. The traffic light is randomly turned red when the first vehicle stops at an intersection with a certain probability, and remains red for a predefined waiting time, forcing the first vehicle as well as the vehicles behind it to stop. After the waiting time, the light turned green and the waiting vehicles move across the intersection one by one until the queue is empty.

3.3.3.5 Simulation of Urban Mobility (SUMO)

SUMO [71] is a microscopic road traffic simulation that is considered as a realistic vehicular mobility model, which is implemented as an open-source java-based environment. SUMO can handle large road networks. It uses real maps that reflect several types of roads, in addition to traffic lights that define priorities between vehicles. It supports different types of vehicles and multi-lane roads with overtaking. It integrates many other realistic parameters such as realistic acceleration, maximum speed, the probability of turning at a crossroad, and dynamic routing. SUMO is capable of displaying different traffic scenarios such as free flow and traffic congestion. SUMO is our selection for generating realistic traffic flows for the purpose of performance evaluation.

Chapter 4: Related Work

For both of the two basic data dissemination models in VANET, broadcasting forms the basis of communication, similar to other types of ad hoc networks [49]. Since plain flooding (which is the simplest style of broadcasting) can easily lead to the broadcast storm problem, a mitigation solution can serve both dissemination models, and thus it can benefit various types of ITS applications. However, while such solutions can sufficiently support safety-oriented applications, convenience-oriented applications may favor data caching to limit data flooding. In this chapter, we focus in section 4.1 on solutions that directly mitigate the broadcast storm problem, which serve the same objective of this dissertation. We compare these solutions from a set of perspectives in section 4.2. In section 4.3, we provide an overview of data caching for further data dissemination optimization in the VANET context.

4.1 Broadcast Storm Mitigation Solutions

In plain flooding, the originating vehicle broadcasts data to all its one-hop neighbors. In multi-hop dissemination, all receiving neighbors would rebroadcast the data to their one-hop neighbors, and so on. In dense networks, flooding may easily lead to broadcast storm problem, when many vehicles in the same vicinity broadcast simultaneously and too many packets collide. Therefore, plain flooding suffers from a scalability problem, since the same data packet may be excessively disseminated, and the limited available bandwidth of the radio channel is wasted. More specifically, plain flooding is extremely costly because it may result in the following [49]:

- Redundant rebroadcasts; that occurs when a node decides to rebroadcast data to its neighbors; however, all neighbors have already received the same data before.

- Medium contention; that occurs when neighboring nodes receive a broadcast data and decide to rebroadcast the message. These nodes must contend with each other for the broadcast medium.
- Packet collisions; which result in packet loss or corrupted messages.

Since VANET is fully connected under high density, a data packet that is disseminated by plain flooding would be received by all the nodes, and every node will rebroadcast a copy of the same data. For a number of packets P, assuming N connected nodes, the total number of messages M sent through the network grows with the network density:

$$M \approx P \times (N-1) \times N = O(N^2) \tag{13}$$

The basic approach that is commonly used for data dissemination optimization is to provide a broadcast mitigation approach to decrease the percentage of data redundancy, such that the broadcasting overhead is reduced. This is basically achieved by selecting a subset of vehicles to rebroadcast [50]. Approaches designed for optimized data dissemination in VANETs present lightweight solutions in terms of data redundancy overhead. Among these approaches, two basic schemes can be distinguished: The probabilistic broadcast and the delay-based broadcast.

4.1.1 Probabilistic Broadcast

In the probabilistic scheme, a different rebroadcast probability Φ is assigned to each vehicle. Since only some of the vehicles will participate in rebroadcasting; data redundancy overhead as well as the number of collisions is reduced. The main challenge in the probabilistic broadcasting scheme is determining an optimal probability assignment function that decreases data redundancy and maintains a high delivery ratio. Simple broadcasting protocols assign a constant probability to participating vehicles, while more sophisticated protocols allow for dynamic probability assignment. Like plain flooding, when data is to be disseminated by probabilistic broadcast, the total number of messages M sent through a connected network of size N is still quadratic, but grows more slowly according to the rebroadcasting probability Φ:

$$M \approx \Phi N\left(N-1\right) \tag{14}$$

Weighted p-Persistence [16] is a well-known probabilistic broadcasting approach that uses the distance as a parameter to determine the forwarding probability of participating vehicles, where the farthest vehicles always have the highest probability to rebroadcast, as shown in figure 4-1.

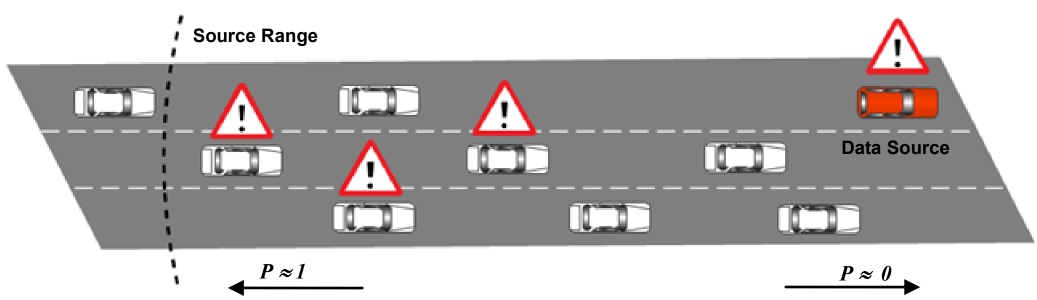


Figure 4-1: Probabilistic Broadcast

Whenever a packet is received from vehicle i; the receiving vehicle j checks the packet ID and rebroadcasts with a certain probability if it receives the packet for the first time. Otherwise, it discards the packet. The forwarding probability P_{ij} is calculated by:

$$P_{ij} = \frac{d_{ij}}{R} \tag{15}$$

where d_{ij} is the distance between i and j, and R is the transmission radio range.

Traffic density is not considered in weighted p-persistence, and therefore, it is not scalable under different densities. Another probabilistic based function that considers traffic density is described in [51], which enables each vehicle to obtain its local density, by counting the number of one-hop and two-hop neighbors.

The idea of utilizing the speed of participating vehicles is considered in [52], where the authors try to map the speed value to the rebroadcasting probability based on linear approximation of experimental data. Their probability function is compared only to plain flooding, and the shown simulation results are not analytically verified. In addition, broadcasting overhead is not considered.

4.1.2 Delay-based Broadcast

In delay-based broadcast scheme, different waiting delays are assigned to receiving vehicles. Vehicles with shorter delays would rebroadcast first, and vehicles assigned to later times would cancel their transmissions upon the receipt of data duplication, since this indicates that the data has already been disseminated, and therefore redundant rebroadcasts can be avoided. Delay-based broadcasting approaches are often referred to as “broadcast suppression” mechanisms.

Slotted 1-Persistence [16] is a delay-based broadcast suppression mechanism where vehicles are assigned to different timeslots depending on their distance to the sender, such that vehicles with highest priority are given the shortest delay before rebroadcasting. Figure 4-2 shows an example of slotted 1-persistence delay-based broadcasting with three timeslots.

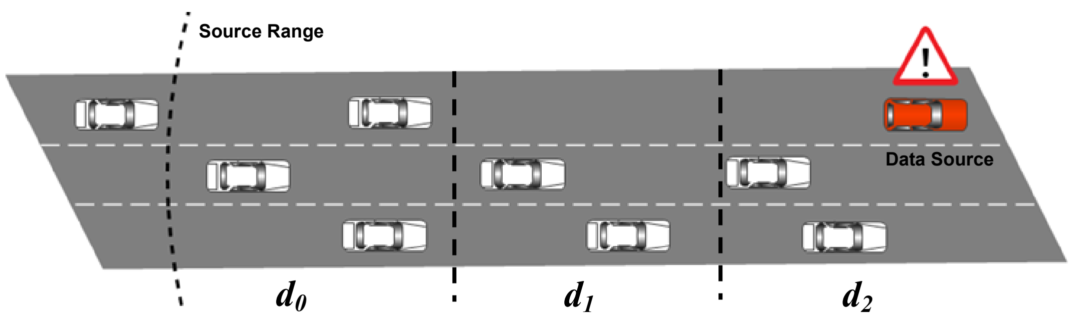


Figure 4-2: Delay-based Broadcast with Three Timeslots

When a packet is received, a node checks the packet ID and rebroadcasts with probability 1 at the assigned time slot $T_{S_{ij}}$ if it receives the packet for the first time and has not received any duplicates before its assigned time slot. Otherwise, it discards the packet. Given the relative distance d_{ij} between nodes i and j, the average transmission range R, and the predetermined number of slots N_s, $T_{S_{ij}}$ can be calculated as:

$$T_{S_{ij}} = S_{ij} \times \tau \tag{16}$$

where τ is the estimated one-hop delay, which includes the medium access delay and propagation delay, and S_{ij} is the assigned slot number, which can be expressed as:

$$S_{ij} = N_s \left(1 - \left\lceil \frac{\min(d_{ij}, R)}{R} \right\rceil \right) \tag{17}$$

N_S is a design parameter that should theoretically be a function of the traffic density. However, like weighted p-persistence, slotted 1-persistence does not provide a method for predicting traffic regime and N_S has a constant value per simulation run. Therefore, this method suffers from scalability problem under high densities.

Slotted p-Persistence is another method, which mixes the probability and the delay-based schemes by giving the highest priority vehicles the shortest delay and the highest probability to rebroadcast. Whenever a packet is received, a node checks the packet ID and rebroadcasts with the pre-determined probability *p* at the assigned time slot, if it receives the packet for the first time and has not received any duplicates before its assigned time slot. Otherwise, it discards the packet. Similar to slotted 1-persistence, this approach doesn't consider traffic density, which can support dynamic probability assignment according to the road traffic condition. Instead, it simply relies on a good choice of the forwarding probability *p*.

Distributed Optimized Time (DOT) [53] is a recent delay-based approach that provides timeslot density control. DOT does not really indicate the actual density of the traffic, but the density of each timeslot, which is a predefined value that sets the maximum number of vehicles that can be assigned to each timeslot. DOT aims at always selecting the farthest vehicles, while controlling transmission redundancy used to increase robustness. Despite the advantage of DOT, it relies on beaconing to provide neighboring data, which produce messaging overhead.

Beaconing alone can generate a high load on the network, and therefore cannot be simply regarded as “background traffic” [10]. It is shown that when all vehicles send 200 bytes beacons every 100 ms (each vehicle sends 10 packets of 200 bytes data every second), channel would be 80% loaded at the range of 300 m [11], and sending 5 packets with the same mentioned settings would cause a channel load of 40%. It is true that beacons will be part of VANET safety management, but it is important not to increase packet size to include the required neighbor knowledge, since larger packets would certainly decrease the limited available bandwidth. DOT assumes a maximum beacon size of 324 bytes, which can be easily reached under high densities.

Another novel approach for data dissemination in vehicular networks (***DRIVE***) is proposed in [17], where the main objective is to provide a broadcast storm mitigation solution, without the overhead of beaconing. In DRIVE, the authors define a “sweet spot” within an Area of Interest (AoI), such that a vehicle within the sweet spot is more likely to disseminate data further. A circle-shape communication area is divided into four quadrants. For each quadrant, one sub-area is defined as a sweet spot. In case there is no vehicle inside the sweet spot, the furthest vehicle away from each quadrant will relay the data. Despite that DRIVE can achieve high delivery ratio, the communication overhead presented by the total number of transmissions is still high. One data message has an overhead value of more than 60 duplicates under high density highway scenario.

Another work similar to [17] is proposed in [54], with the objective of addressing the broadcast storm in addition to intermittently connected networks. The overhead shown in the performance results of [54] is still high. In [55], HyDiAck protocol is proposed for data dissemination in urban VANETs, which considers dense and sparse networks. Despite the high data delivery ratio and the decreased data redundancy, slotted 1-persistence approach can still achieve lower overhead compared to HyDiAck. In addition, HyDiAck relies on local one-hop neighbor knowledge for broadcast mitigation.

4.2 A Comparison of Broadcast Mitigation Solutions

Table 2 summarizes a comparison among the broadcast storm mitigation solutions we reviewed, from six different characteristics: the broadcasting approach, beaconing requirements, density control provision, data delivery, total overhead and dissemination delay. By total overhead we mean the data redundancy overhead and/or the overhead of extra communication via beacons. We have found that existing VANET broadcast solutions rely on either the probabilistic or the delay-based scheme, while few are found to apply both schemes, such as slotted p-persistence [16]. Most these existing solutions represent light-weight algorithms without estimating traffic condition, which is essential for supporting scalability issues that arise under high density traffic scenarios.

Table 2: Comparison of Broadcast Mitigation Solutions for VANETs

Solution	Mitigation Approach		Beaconing Required	Density Control	Data Delivery	Total Overhead	Delay
	Probabilistic	Delay-based					
Weighted p persistence [16]	√		No	No	High	High	High
Slotted 1 persistence [16]		√	No	No	High	Moderate	Low
Slotted p persistence [16]	√	√	No	No	Dependent	Dependent	Moderate
DOT [53]		√	Yes	Yes	High	High	Low
DRIVE [17]		√	No	No	High	High	Moderate
HyDiAck [55]		√	Yes	No	High	High	Moderate

Few solutions try to provide a mean of density control, like DOT [53] and SAPF [52], however, we couldn't find a method that timely detects or estimates the actual traffic condition, in order to set the broadcasting probabilities and/or delays accordingly. DOT is a delay-based VANET broadcasting scheme that provides a density control among timeslots, by setting the total number of vehicles that can be assigned to a single timeslot, but it doesn't specify how to set this number. Instead, the authors noted that the best value to consider. Like other schemes that try to provide density control, DOT relies on a large-sized hello beacons for neighborhood management. SAPF is another example that adapts broadcasting according to the road condition. Unlike DOT, SAPF relies on probabilistic forwarding that usually suffers from high delays. The authors of SAPF rely on experimental speed data to propose a probabilistic forwarding function.

Existing data dissemination methods for VANETs either do not scale well under high density scenarios, or require extra communication overhead via beacon messages to support scalability. While most of the approaches maintain high data delivery ratio, they still suffer from high overhead, either due to the high percentage of redundant data (such as [16] and [17]), or because of the beaconing requirement, such as [53] and [55]. Approaches that could improve dissemination delays or achieve less redundancy present extra communication overhead through beaconing, which may have several drawbacks on the networking performance such as: wasted bandwidth, delaying of data packet and increased network congestion [9]. The communication channel may become congested especially under high densities due to the fact that beacons may be sent several times per second. Beaconing alone can generate a high load on the network, and therefore cannot be simply regarded as "background traffic" [10]. It is shown that when all vehicles send

200 bytes beacons every 100 ms (each vehicle sends 10 packets of 200 bytes data every second), channel would be 80% loaded at the range of 300 m [11].

In this work, we aim at providing an efficient broadcast mitigation solution in VANETs, by dynamically estimating traffic regime using local speed data, such that vehicles are enabled to set their broadcasting probabilities and/or delays according to the road condition without extra communication overhead. We specifically target the scalability feature in which data redundancy is minimized, while reliability is maintained by maximizing data delivery ratio without affecting delays.

While the broadcast storm solutions can sufficiently support safety-oriented applications, convenience-oriented applications may favor data caching to limit data flooding, by the utilization of already stored data. In the following section, we formalize data caching in VANET and we review existing invalidation strategies for further broadcast optimization.

4.3 Data Caching

There is limited coverage of data access issues in VANETs [56]. Caching is a commonly used technique for improving data access, in which the network performance is significantly increased, since the overhead caused by global network flooding can be reduced. Generally, VANET caching schemes rely on the cooperative approach, which allows for sharing of cached data among multiple vehicles, where the potential of the caching can be further explored. However, there exist some techniques which are non-cooperative.

Caching schemes for ad hoc networks are proposed in [57] [58]. Examples of Mobile ad hoc networks (MANETs) caching schemes can be found in [59], [60], [61].

Caching for Internet-based VANETs are also proposed [62], [63]. A large positive impact in utilizing caching techniques for vehicular networks has been proven in [64], [65], [66], [67], [68]. For the context of this dissertation, we consider caching as a further data dissemination optimization strategy that can benefit convenience-oriented applications with delay-tolerance. In a previous work [15], we prove this benefit in a form of V2V congestion-detection application. In this section, we customize a formalization approach for caching in VANETs [18] for further research (section 4.3.1). Then, we provide an overview of existing cache invalidation strategies (section 4.3.2).

4.3.1 Formalization

The vehicular network can be modeled as a bidirectional graph $G = (V, E)$, where V is the vertex set whose elements are the vehicles (or nodes) of the graph. This set is often denoted as $V(G)$ or V. E is the edge set whose elements are the edges, or connections between vertices of the graph. This set is often denoted as $E(G)$ or E. Each vehicle in the graph is connected to a set of edges d which is a subset of E that represents the vehicle's neighbors. Each vehicle stores data in a local cache of size k. Stored data are either locally generated or gathered through V2V communication. Caches are assumed to be in the steady state (each node stores k data items). The content of each cache is assumed to be completely random (resources are a uniformly random subset of the R available resources).

When an inquiring node searches for some data x, where x is available in v_x number of vehicles, x is not known to that node if it cannot be generated locally and is not already stored in the cache. The probability P that x is not known to a particular node is:

$$P = 1 - P[x \textit{ is not locally known}].P[x \textit{ is not already stored in the cache}] \tag{18}$$

since x is offered by v_x vehicles in total, we have:

$$P[x \textit{ is locally known}] = v_x / V \tag{19}$$

The number of ways to choose k elements out of a set that is composed of R elements, such that a particular element is not chosen is $\binom{R-1}{k}$. Since k elements of the node's cache are assumed completely random, we obtain:

$$P[x \textit{ is not already stored in the cache}] = \binom{R-1}{K} / \binom{R}{K} = R - k \; / \; R \tag{20}$$

Thus:

$$P = 1 - (1 - v_x / V)(R - k / R) = (V - v_x)(R - k) / V.R \tag{21}$$

To compute the number of messages in plain flooding, it is assumed that nodes reply directly to the inquiring node. If the desired data is not found at the inquiring node, there will be d transmissions to the d neighbors, in addition to the internal transmissions by those neighbors:

$$M = (1 - P) \left(d + d.m\,(t - 1)\right) \tag{22}$$

where $m(t - 1)$ are the number of messages generated at a particular neighbor and transmitted to $t - 1$ hops, which is shown to have an exponential behavior [44].

Likewise, probabilistic broadcasting also has an exponential number of messages, but this number grows more slowly according to the probability of forwarding Φ:

$$M = (1 - P)\ (d.\Phi + d.\Phi.m\ (t - 1)) \tag{23}$$

4.3.2 Invalidation Strategies

In V2X communication, it is critical to state when a certain data is no longer valid and should be removed. This process is known as cache invalidation. In the following, we show different cache invalidation strategies for vehicular networking.

4.3.2.1 Time-To-Live (TTL)

In [39], the caching support for VITP is proposed using cache-control headers that can be included in messages to act as a caching decision directive. The cache replacement policy used in VITP is TTL, which defines the maximum time for which cached data is considered valid. The evaluation of this caching support is provided in [64], with the main objective of investigating if caching extension for a proactive, location-aware communication protocol can maintain acceptable levels of information quality, while sustaining the performance of the vehicular network. Simulation results show an improvement of information accuracy of more than 65%, while the network overhead is decreased by only 12%.

4.3.2.2 Location-based Invalidation

Cache-based routing approach for VANET is proposed in [65], by utilizing the locality of vehicles' traces, without requiring global network flooding or location servers. Two basic schemes are proposed: the update scheme and the query scheme. In the update scheme, each vehicle sends update messages at intersections to disseminate location information such that each neighboring vehicle stores these information in its local cache. In the query scheme, when a vehicle v1 needs to get a route to another vehicle v2, it initiates a local flooding to search for a vehicle v3 that has the location information of v2, without considering how old the information is. When the message is received by v3, it resends the query message to the location stored in its cache that v2 had ever located in. If another vehicle that receives the query has more recent location information of v2, it redirects the query message to the newer location stored in its cache. Then, a limited flooding is used again to find v1 so as to send a reply with the newest location information found. This approach is shown to work effectively in city environments. However, it considers updating location information only at intersections, which may not be effective in other traffic scenarios.

4.3.2.3 Randomized Invalidation

Infoshare [66] is a pull-based data dissemination application for VANETs that aims at achieving the maximum spreading of information; while limiting the broadcasting overhead using a smart caching approach that can reduce useless queries and duplicated replies. Vehicles form an ad hoc network cooperate in disseminating information messages that are pulled from fixed gateways connected to the Internet and are broadcasted along the road. This cooperation is aided by on-board caches in which the information shared by nearby vehicles is preserved. Each vehicle originates a request at a random time. The request is broadcasted in a multi-hop fashion until a vehicle carrying the desired information is found, then a reply is carried back to the originator following the same path in reverse order. When the originator vehicle receives the reply, it caches the required information, which is discarded after a random time, and can be requested again later.

4.3.2.4 Probabilistic Estimation

Hamlet [67] is a fully distributed scheme that aims at providing effective data caching without swamping the storage capacity with needless information. What distinguishes Hamlet from the other caching approaches is that it does not consider a fixed scheme for invalidation. It helps the users to decide on the information to keep and for how long, based on a probabilistic estimate of what other neighbors are caching. The objective of such an approach is to avoid network flooding with query messages whenever possible, by creating a content diversity within the node neighborhood, so that a requesting vehicle can likely find the required information nearby. When consistency becomes an issue, Hamlet allows for a quick replacement of the outdated information with the most recent version. Hamlet assumes that a node can "overhear" queries and responses, which may raise a security problem in many convenience-oriented applications.

Chapter 5: The Proposed Approach

As part of previous research effort to develop a Vehicle to Vehicle (V2V) communication protocol [14], we have experienced low simulation performance while evaluating a congestion reduction application. While the performance of communication protocols developed for VANET requires evaluation under high density scenarios, many existing simulations fail to address such scalability requirement. Monitoring slow simulations leads us to a careful literature review to investigate the broadcast storm problem, which is found not to have a perfect solution yet in the VANET context.

Broadcasting is commonly required in both types of VANET applications. In the case of safety-oriented applications, broadcasting alone usually achieves data dissemination. While in convenience-oriented applications, broadcasting is usually part of the routing process. Therefore, addressing the broadcast storm problem can serve both types of applications whenever broadcasting is initiated, especially under high density scenarios.

While the broadcast storm problem is defined in Mobile Ad hoc Networks (MANETs), the VANETs context poses multiple challenges for existing mitigation strategies and solutions, basically because of the mobility feature that characterizes these environments. Those reasons have prompted this dissertation to address scalability in VANETs; in order to provide an efficient broadcast mitigation approach that can serve many types applications. We basically rely on speed data to detect traffic regime and set the broadcast accordingly.

In this chapter, we introduce our proposed approach for data dissemination in multi-hop VANETs. First, we present an overview of the approach in section 5.1.

Second, we specify our models in section 5.2. Then, we show our traffic regime estimation method in section 5.3. After that, we describe the different variations of our speed adaptive broadcasting approach in sections 5.4, 5.5 and 5.6.

5.1 Overview

In our data dissemination approach, we are aiming at achieving three main objectives: scalability, reliability and minimized overhead. First, to achieve scalability, our approach addresses the broadcast storm problem in large-scale scenarios, which are the cases of high-density traffic regime. Second, for the reliability objective, our specific goal is to reach full network coverage, by achieving the maximum data delivery ratio. Third, by minimized overhead, we mean to reduce data redundancy without any extra communication overhead.

We propose different variations of Speed Adaptive Broadcast (SAB). In the early phase of this research, we have proposed and evaluated the probabilistic SAB (P-SAB), which is a simple probabilistic-based broadcasting method that has shown optimistic results of speed-adaptive broadcast, compared to the well-known existing distance-based probabilistic broadcast. Like other probabilistic approaches, SAB mitigates the broadcast storm problem by reducing the amount of redundant data. However, it still shows high percentage of duplicate messages under high densities.

In the later phase of this research, we designed a more sophisticated delay-based technique, the slotted speed adaptive broadcast (S-SAB), which could dramatically minimize the broadcasting overhead by suppressing unnecessary broadcasts. This can be achieved by the dynamic estimation of traffic regime at each hop, based on locally detected speed data. To further limit data redundancy among vehicles with nearly simultaneous delays, we propose to differentiate their timings based on location information, by providing an improvement to S-SAB in grid-based speed adaptive broadcast (G-SAB).

5.2 Model and Assumptions

As we have specified in section 3.3.1.3, VANET requires the consideration of three different models: road layout, mobility and communication. In this section, we briefly describe each of these models we assume for our proposed approach.

For the road layout, we assume linear road topology of multiple lanes. A linear topology includes highways and straightway roads. More sophisticated urban scenarios are to be considered in our further work.

For Road traffic mobility modeling, we rely on simple macroscopic model for mathematical analysis, which represents how the behavior of one parameter of traffic flow changes with respect to another. We assume the Greenshields model [12] of traffic flow theory, which basically describes traffic flow via the speed-density relationship, since road traffic is always in a specific state that is characterized by the flow rate, the traffic density and the average speed. In figure 5-1, we show the original speed-density fundamental diagram of traffic flow theory [13]. While we utilize a simple model for simple mathematical validation, we provide realistic traffic scenarios generated by SUMO [71] for simulation-based performance evaluation. Further details on our simulation environment are provided in the next chapter.

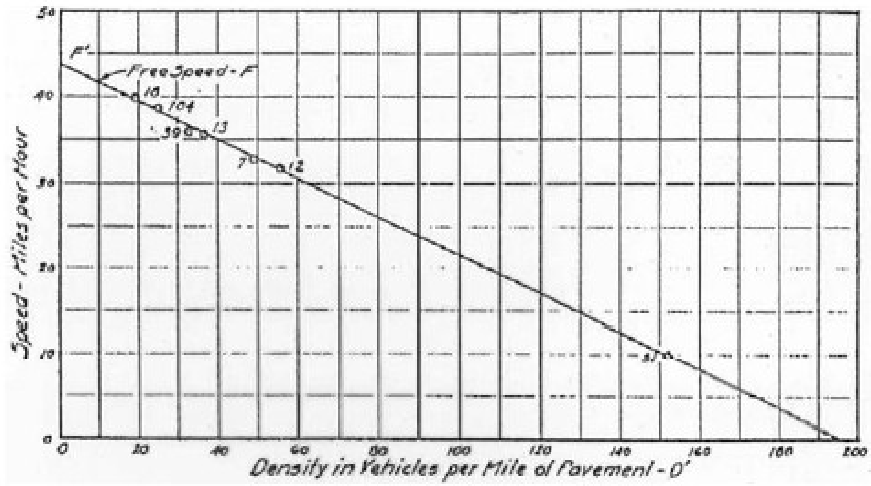


Figure 5-1: Speed-Density Relationship [13]

To model vehicular communication, we assume IEEE 802.11p [45] standard that extends 802.11 for providing wireless communications in vehicular environment. Our approach works on the top of the MAC layer. In our data dissemination approach, we assume a VANET environment as shown in figure 5-2, where each vehicle is equipped with On Board Unit (OBU) to provide wireless access.

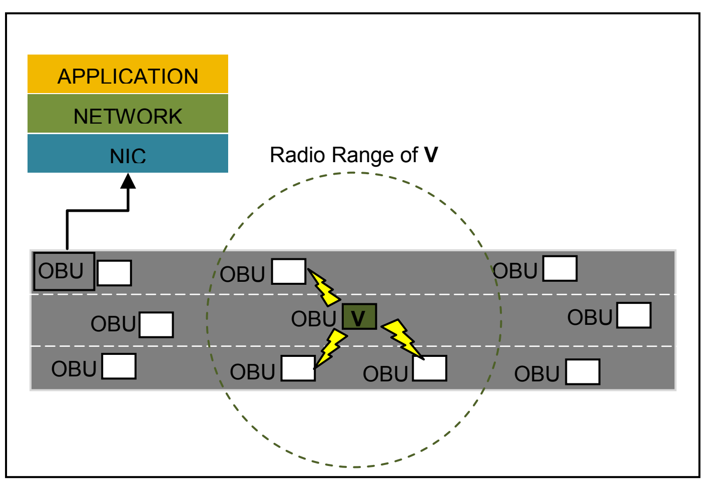


Figure 5-2: The VANET Environment

An OBU is a communication device that consists of a processor, memory resources for data storage and retrieval, a user interface to visualize communication, and a network device based on IEEE 802.11p radio technology. It logically consists of NIC (physical and MAC layer), networking layer and application unit. Each vehicle can directly communicate via its OBU with vehicles within its transmission radio range. We assume the Vehicle to Vehicle (V2V) communication mode in our approach, and Roadside Units (RSUs) are not considered. We also assume the existence of the Global Positioning System (GPS) to provide location information within the vehicular network.

Disseminated Data are in the form of WAVE Short Messages (WSMs), according to the IEEE WAVE standard for Wireless Access in Vehicular Environments [69], which determines that these messages can carry contextual data such as the vehicle's position, speed and acceleration. In particular, our data messages have the following structure:

Message ID	Timestamp	Source ID	Sender ID	Source's Coordinates	Sender's Coordinates	Sender Speed	Number of Hops

The total size of the message we consider is 100 byte, which is calculated by summing the bytes required by each message field. It is worth noting that 802.11p standard allows for a maximum message size of 2312 byte. In the following, we describe each field in our message structure:

- Message ID; which is defined as a sequence number uniquely attached to messages by the originating vehicle.

- Timestamp; which is attached to the message once created by the originating vehicle, and remains unchanged through data dissemination. Timestamp is used by a receiving vehicle to compute the local data dissemination delay.
- Source ID; which is the ID of the source vehicle that originally creates the message. We refer to this vehicle as the “message source” or “data originator”. A vehicle ID is a unique number that can be represented by the MAC address. The Source ID field is set by the originating vehicle and is not changed by forwarding vehicles through data dissemination. The combination of message ID and Source ID enables receiving vehicles to distinguish different messages.
- Sender ID; which is ID of the forwarding vehicle that has directly communicated with the receiving vehicle to send the message. This field is updated whenever the message is forwarded. Similar to source ID, the sender ID can be the MAC address of the forwarding vehicle.
- Source’s Coordinates; which indicate the geographical coordinates of the source vehicle. This field is not changed by forwarding vehicles.
- Sender’s Coordinates; which are updated by the message forwarding vehicle to enable receiving vehicles to determine their distances to the sender, so that each vehicle can determine its waiting time before broadcasting.
- Sender Speed; which is used to estimate traffic regime by receiving vehicles, in order to set the total number of timeslots accordingly.
- The number of hops propagated; which is incremented by each forwarding vehicle for statistical collection.

Whenever a vehicle traveling on a straightway has detected some safety condition at any point, it triggers the dissemination of a warning message by exploiting multi-hop ad hoc communications. The objective is to deliver the warning to all travelling vehicles within a certain dissemination area, with a single broadcast cycle. Every time a vehicle receives a new warning message, it decides, with probability α to act as relay to forward the message further. We use a similar analysis of single broadcast cycle of Warning Delivery Model [41], which is reviewed in section 3.3.1.1. Three performance measures are derived: The average number of informed nodes (vehicles), the average delay, and the average number of duplicate messages received by a vehicle.

5.3 Detecting Traffic Regime

One of our main objectives is to estimate traffic regime condition without considering traffic density as a direct parameter, since it requires each vehicle to tolerate the neighborhood management overhead. We rely on the speed data to indicate traffic density indirectly. In other words, we indicate traffic density using the speed parameter, because the latter doesn't require the overhead of neighbor knowledge that is gathered through beaconing.

The speed-density relationship on the road can be rationally explained. Under low density, people usually drive at the maximum allowed speed, while they are forced to reduce speed under high density scenarios. This negative correlation is proposed in Greenshileds model, which is part of traffic flow theory fundamentals [13]. Speed-Density relationship is formed in equation (24).

$$Q = V \times D \tag{24}$$

where Q is the traffic flow, V is the speed, and D is traffic density.

We rely on the actual speed of vehicles in multi-hop VANET broadcasting to provide two basic benefits:

- First, the actual speed of vehicles allows for an accurate indication of traffic density without extra communication overhead.
- Second, it makes the broadcasting approach scalable, since it allows for assigning different probabilities and/or delays to participating vehicles based on the road condition.

To numerically reflect traffic condition of a road, we define the speed ratio:

$$V_r = \frac{V}{V_f} \tag{25}$$

where V_r is the speed ratio, V is the current speed on the road, and V_f is the *free-flow* speed, which is the maximum speed allowed.

Greenshields postulated that a linear relationship exists between speed and density having the following form [12]:

$$V = V_f - \frac{V_f}{d_j} d \tag{26}$$

By dividing both sides by V_f we prove that the speed ratio *complements* the density ratio:

$$\frac{V}{V_f} = 1 - \frac{d}{d_j} \tag{27}$$

where d is the current traffic density and d_j is the jam density, which is the maximum road capacity. Therefore, we can use the speed ratio instead of the density ratio to numerically reflect traffic condition. From the latter equation, we can conclude the following (see figure 5-3):

- When the speed ratio V_r approaches zero, the road is under traffic congestion, and the traffic density approaches d_j.
- When V_r approaches 1, the road is under free flow velocity, and the traffic density is low.

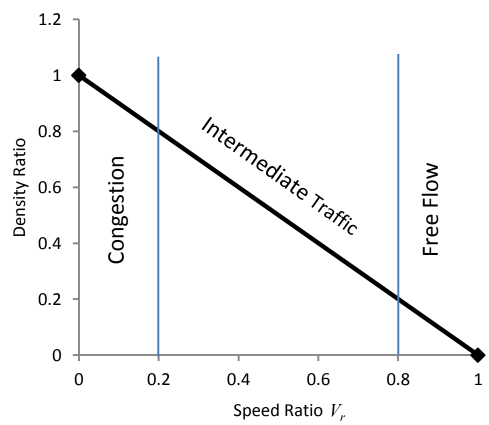


Figure 5-3: Traffic regime condition according to speed/density relation

5.4 Probabilistic SAB (P-SAB)

P-SAB is a simple probabilistic broadcasting method that was evaluated in the early phase of this research, as a preliminary step to validate the consideration of the speed of vehicles as a parameter to determine the forwarding probability and/or delay. P-SAB is totally distributed receiver-oriented method, since it does not require any sender-oriented management. It works on top of the MAC layer, as follows: Upon receiving a message at time t, a receiving vehicle i checks the message ID and rebroadcasts with a certain probability if it receives the message for the first time. Otherwise, it discards the message. Discarded messages are counted as redundant duplicates. The forwarding probability of vehicle i at time t, $P(i,t)$ is calculated locally by computing the following velocity ratio:

$$P(i,t) = \frac{V(i,t)}{V_{\max}} \tag{28}$$

where $V(i,t)$ is the current speed of receiving vehicle i at time t, and V_{max} is the maximum allowed speed (or the free-flow speed).

In P-SAB, each receiving vehicle has its own forwarding probability, which reflects the current status of traffic regime. i.e. low probability values indicate high density, since vehicles are forced to travel at low speeds, while high probability values indicate a free-flow, where vehicles are travelling at the maximum allowed speed. The probability function presented in equation (28) uses the same relation explained in equation (25) to numerically reflect traffic condition locally by each receiving vehicle.

The main advantage of P-SAB is its provision of a simple probabilistic approach that works in the absence of GPS, with no extra communication overhead. The contribution of P-SAB is its low data redundancy under high density scenarios. Simulating P-SAB provides optimistic results for speed adaptive broadcasting, especially in terms of data redundancy overhead. However, P-SAB has the following *limitations*:

- It cannot disseminate data if all the neighbors are involved in traffic congestion, since their speed values will be closed to zero.

- Data redundancy is high under low-to-intermediate traffic scenarios, because P-SAB works almost similar to flooding when the vehicles are traveling under free-flow.
- Similar to other probabilistic approaches, it suffers from dissemination delay.

These limitations have prompted the effort of this dissertation to design a delay-based speed adaptive broadcasting approach that can achieve better performance in terms of data delivery, dissemination delay and redundancy overhead.

5.5 Slotted Speed Adaptive Broadcast (S-SAB)

The Slotted Speed Adaptive Broadcast (S-SAB) is a delay-based approach that offers broadcast mitigation in multi-hop VANETs, in order to support different types of safety-oriented and convenience-oriented applications. In S-SAB, we aim at improving the broadcasting delay and redundancy overhead presented in P-SAB, by offering a suppression mechanism, such that fewer vehicles would act as relay nodes to forward data further. S-SAB allows vehicles to be assigned to a number of timeslots that is adaptively determined at each hop, according to traffic regime estimation using simple data. A timeslot can be defined as the period of time during which a scheduled broadcast waits before disseminating the scheduled message or discarding it. Figure 5-4 illustrates an example of data dissemination in S-SAB. For simplicity in illustration, the figure shows S-SAB in two-hop data forwarding, where the sender initiates a broadcasting session to all one-hop neighbors. Receiving neighbors detect a dense traffic regime and set the total number of slots accordingly, such that each vehicle can then determine the delay value based on the timeslot it belongs to. The first forwarding vehicle attaches its current speed to the message to be forwarded, such that the vehicles that would receive the message are enabled to detect traffic regime at the next hop. Forwarding vehicles are most likely the farthest vehicles, since they always have the shortest delays.

S-SAB works on top of the MAC layer, as follows: An initiating vehicle *i* creates a message and broadcasts it to its one-hop neighbors. The sent message includes the sender current speed V_i to share with other vehicles. In figure 5-5, we show the S-SAB algorithm considered by receiving vehicles. Upon receiving a message, a receiving vehicle *j* checks the message ID and the speed of the sender to determine traffic condition, only if it receives the message for the first time. Otherwise, it checks if it has already scheduled the same message with a broadcast delay. If so, it suppresses (cancels) this broadcast, and then it discards the message. Whenever a vehicle acts as a relay, it attaches its current speed to the message to be forwarded, such that receiving vehicles can estimate traffic regime at the current hop accordingly.

Whenever a vehicle receives a message, it calculates the number of timeslots using the shared speed, and then it determines to which timeslot it belongs, using its location information. After that, it schedules a message to be broadcasted with delay timer that is convenient with its timeslot. Farthest vehicles are assigned to the first timeslot, and therefore they have the shortest delay before rebroadcasting. In other words, they have the highest priority to forward the data further. Vehicles assigned to other timeslots have longer waiting delays such that they have sufficient time to suppress their scheduled broadcasts upon receiving a copy of a message they have already received. The *contribution* of S-SAB is three folds:

- First, it provides traffic regime estimation dynamically at each hop using simple speed data.
- Second, it provides scalable broadcast, since it allows for assigning different number of timeslots based on the traffic condition at each hop.
- Third, it presents minimum total overhead; by decreasing data duplication without requiring extra communication overhead.

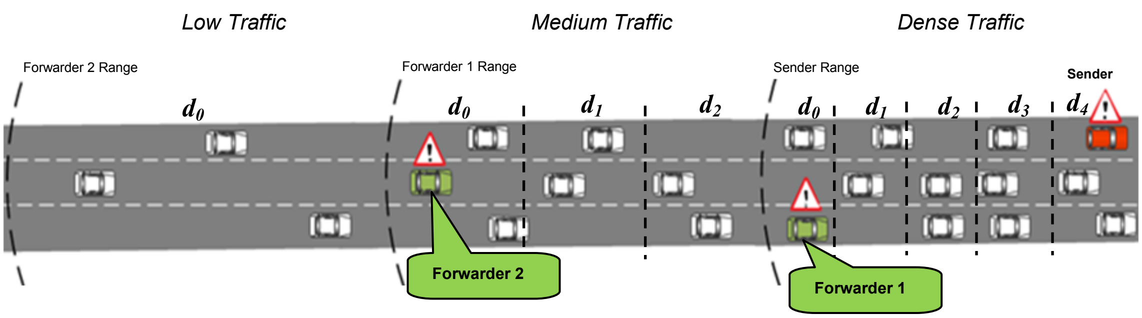


Figure 5-4: S-SAB Multi-hop Data Dissemination

Input: (x_s, y_s), //The coordinates of the sender
(x_d, y_d)//The coordinates of the receiver
message//The received data
Output: delay
Start
If (message.id exists)
    If message instance is scheduled
Cancel broadcast timer;
    End if
    Discard data;

Else
    ratio→ message.v_s / free_velocity;
    number_of_slots → ceil((-m+1) * ratio + m);
    dist → $\sqrt{(x_d - x_s)^2 + (y_d - y_s)^2}$;
    my_timeslot→ floor((1- min(dist, range)/range) * number_of_slots);
    delay→ my_timeslot * estimated_one_hop_delay;
End if

End

Figure 5-5: S-SAB Algorithm upon Receiving a Message

5.5.1 Broadcast Suppression Mechanism

The objective of broadcast suppression is to reduce the amount of redundant data, by allowing vehicles to cancel broadcast upon receiving duplicated data. In figure 5-6, the suppression mechanism of S-SAB is illustrated. When a message is received, the receiving vehicle stores the ID of the message in a list of known messages. A duplicate retrieval of the same message indicates that it has already been forwarded by another vehicle. Whenever a vehicle receives a copy of message it already knows, it checks if a broadcast of the same message is scheduled, such that it decides to cancel it, and then discard the message. For suppression mechanism to operate effectively, S-SAB provides sufficient time separation among timeslots, such that vehicles would have enough time to cancel broadcasts, as we show in the following section.

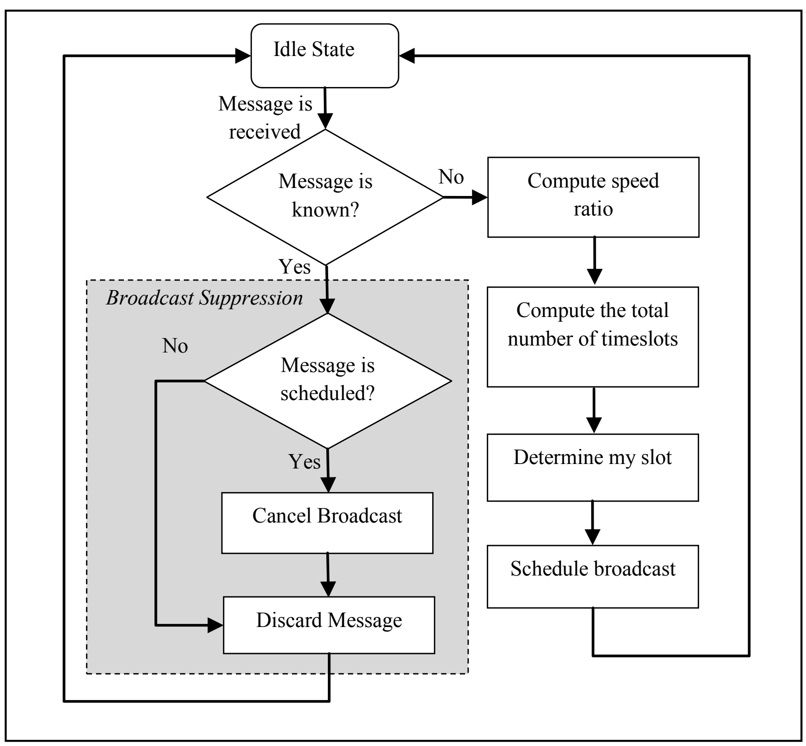


Figure 5-6: Broadcast suppression and delay-control in S-SAB

5.5.2 Delay Control

To indicate traffic condition upon message retrieval, the receiving vehicle uses the ratio V_r:

$$V_r = \frac{V_i}{V_f} \tag{29}$$

where V_f is the free-flow velocity, which is the maximum allowed speed on the road. This ratio is utilized to provide traffic regime numerical estimation with a value between 0 and 1, where 0 represents traffic jam, and 1 represents free-flow condition. When V_i is closed to V_f, the ratio V_r is closed to 1, where free-flow traffic is detected. On the other hand, when V_i is closed to zero, V_r indicates a traffic jam. V_r is used to set the total number of timeslots n, such that the receiving vehicle can then determine the timeslot to which it belongs. n is inversely proportional with V_r, and is computed using the following linear equation:

$$n = \left\lceil (-m+1) \times \frac{V_i}{V_f} + m \right\rceil \tag{30}$$

where m is the maximum number of timeslots set as follows:

$$m = \frac{R}{w} \tag{31}$$

where R is the transmission radio range, and w is the minimum width of a single timeslot, which we set by adding the assumed length of the vehicle to the safety distance considered between two vehicles. The receiving vehicle assumes timeslots of equal width along the transmission range, and then it determines to which slot it belongs using its own location information provided by the Global Positioning System (GPS).

The delay at a certain timeslot d_k is set such that farthest vehicles are assigned to the earliest timeslot, and is computed as:

$$d_k = S_k \times \tau \tag{32}$$

where S_k is the slot number, τ is the minimum theoretical one-hop delay, which is the medium access delay added to the propagation delay. k is an integer between 0 and n. S_k is computed by each receiving vehicle using the following equation:

$$S_k = \left\lfloor (1 - \frac{\min(dist, range)}{range}) \times n \right\rfloor \tag{33}$$

As shown in figure 5-7, setting the total number of slots according to the speed ratio using equation (29) allows for setting more slots under low speeds, where traffic density is high, such that few vehicles participate in message forwarding, and consequently, broadcasting overhead is decreased. On the other hand, fewer slots are set under high speeds, where traffic density is low, such that the transmission delay is not increased. Sharing the sender speed V_i allows for setting the same number of slots n among all receiving vehicles. Here we assume that the speed doesn't significantly change among vehicles within a single hop, however, n can be adaptively changed according to traffic condition by the next forwarder (as shown in figure 5-7), which will share its current speed with the receiving vehicles. Therefore, S-SAB allows for traffic regime estimation at each hop to ensure scalable data dissemination in multi-hop VANET.

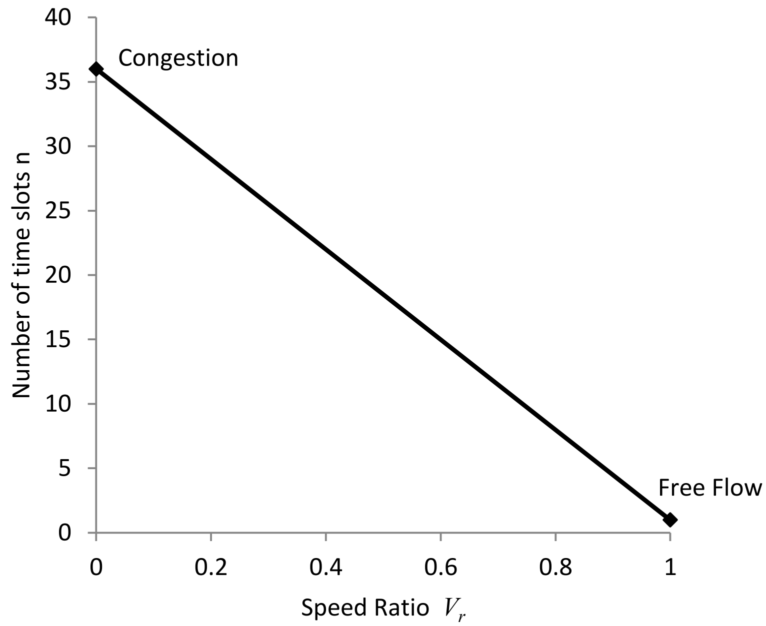


Figure 5-7: Assigning a number of time slots according to speed ratio

But can we improve S-SAB further? The main *limitation* of S-SAB is that vehicles located within the same timeslot may rebroadcast nearly simultaneously, because they don't have sufficient time to suppress an already scheduled broadcast. To avoid simultaneous broadcast and improve the overhead of data redundancy further, we propose to add time separation among different road lanes in a third variant of SAB, which is G-SAB.

5.6 Grid-based Speed Adaptive Broadcast (G-SAB)

Under high density scenarios, even with the maximum number of timeslots set via S-SAB, vehicles among different road lanes may be assigned to the same timeslot. To create time variations among vehicles within the same timeslot, such that simultaneous forwarding is avoided, we propose the Grid Speed Adaptive Broadcast (G-SAB).

G-SAB provides a slight improvement to S-SAB, by providing time variations among different road lanes. As shown in figure 5-8, the graphical illustration of G-SAB looks similar to a grid. G-SAB works similar to S-SAB, but it adds dissemination delay among different lanes in order to decrease data redundancy and possible collisions further.

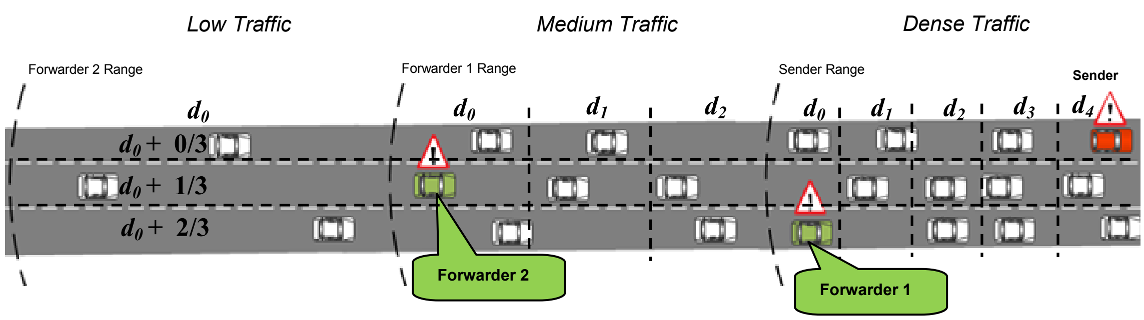


Figure 5-8: G-SAB Data Dissemination

Assuming a number of lanes l_k, the delay computed by a vehicle moving on lane l_i is computed as:

$$d_k = (S_k \times \tau) + l_i / l_k \tag{34}$$

In figure 5-8, we show the additional time assigned to the farthest vehicles located within the first timeslot. Despite that S-SAB is expected to limit data redundancy to desirable levels, G-SAB is proposed to minimize the number of possible simultaneous broadcasts within the same timeslot. There are other ways to provide time separation among different vehicles within the same timeslot, in order to avoid possible redundancy and collations. Instead of detecting the lane number, a vehicle can compute its relative distance to the sender to add a relative delay:

$$d_k = (S_k \times \tau) + (1 - \frac{D_{ij}}{R}) \tag{35}$$

Chapter 6: Performance Evaluation

To evaluate the performance of our proposed approach, we searched existing simulation options that are commonly utilized in the related community. We came up with a basic conclusion that OMNET++ [70] simulation environment can effectively address our simulation requirements, since it supports large-scale scenarios, in which we can evaluate the scalability of the data dissemination approach we developed. We implement and evaluate the performance of different variations of SAB in OMNET++. Traffic flows are generated using SUMO [71] traffic simulator. VANET is modeled using Veins [72] framework. We compare the performance of our proposed approach to Slotted 1-persistence [16] and weighted p-persistence [16] methods.

We start this chapter by describing our performance evaluation methodology in section 6.1. Then, we define our performance metrics in section 6.2. After that, we describe our simulation scenarios in section. 6.3. Simulation results of different variations of the data dissemination approach we developed are analyzed in section 6.4. We conclude this chapter by summarizing our research findings in section 6.5.

6.1 Methodology

In this section, we review our methodology for evaluating the performance of the data dissemination approach we developed. For simplified mathematical validation of our traffic regime estimation strategy, we utilize a simple macroscopic model which basically describes the speed-density fundamental relation in traffic flow. In section 5.3, we showed the validity of using the speed data instead of the density, in order to reflect traffic regime and utilize it to support scalable data dissemination.

Similar to related work in the field of study, we rely on simulation modeling for performance evaluation, since it is currently the only way in which realistic traffic flows with sufficient level of details can be provided. We have compared the available network simulation environments that are widely used by researchers and industries working in the related field, which are: OMNET++, NS-2/NS3 and JIST/SWAN.

We have found that NS-2 is not recommended for VANET research because of its complexity that makes it difficult to implement the vehicular mobility models inside the framework. In addition, it is not efficient for scalability study as its memory and CPU consumption do not allow high density scenarios. Despite that NS-3 is proposed to alleviate the problems present in NS-2, its physical layer is not suitable for VANET simulation. Another simulation option was JIST/SWAN, which has been designed with the objective of large scale network simulations. Nevertheless, it is no longer officially maintained and the latest version does not include any mobility model specifically designed for VANETs.

On the other hand, OMNET++ has been gaining large acceptance in both research community and the industry due to its very extensible and hierarchical architecture, modular component based C++ implementation, lower effective simulation runtime and high scalability. Moreover, it is equipped with a rich set of networking protocols and strong support for physical layer and MAC layer simulations. Additionally, its user friendly integrated development environment (IDE) and graphical network editor makes it very convenient and less error prone in the software development phase. We have intended to use OMNET++ due to its proven performance to develop our data dissemination approach, along with SUMO [71] for generating realistic traffic flows, and Veins [72] framework for VANET modeling.

We compare the results obtained from simulating our data dissemination methods under different traffic scenarios with the performance of the following methods:

- Weighted p-persistence [16]; which is a well-known probabilistic broadcasting approach that uses the distance as a parameter to determine the forwarding probability of participating vehicles, where the farthest vehicles always have the highest probability to rebroadcast.
- Slotted 1-persistence [16]; which is the benchmark we consider, since it currently represents the best delay-based broadcast method in terms of delivery, overhead and delay. In this method, vehicles are assigned to different timeslots depending on their distances to the sender, such that the farthest vehicles are given the shortest delay before rebroadcasting. When a vehicle receives redundant data, it suppresses (cancels) broadcasting the same data.

Our preliminary probabilistic results are compared with weighted p-persistence, which provides an optimistic indication of the effectiveness of utilizing the speed of the vehicles instead of the distance to set their rebroadcasting probabilities. The core result set we obtain is compared to slotted 1-persistence as a benchmark. To study the effectiveness of delay-based broadcast in contrast with probabilistic broadcast, we also compare the core result set with weighted p-persistence. In order to illustrate the benefit of utilizing broadcasting schemes, we also simulate data flooding which represents the simplest broadcasting style with the worst performance.

6.2 Performance Metrics

In this section, we describe the performance metrics observed during simulations. As we have previously stated, our objective is to minimize data redundancy and dissemination delay while maintaining a high delivery ratio. We define the number of received messages M_{rcv} as the total number of different messages successfully received by vehicles over the network. If a message is received by the same vehicle more than once, a data duplicate is counted. We define the number of duplicates M_{dup} as the total number of messages counted as redundant duplicates. By adding the value of M_{rcv} to M_{dup}, we obtain the total number of messages P_{total} delivered to vehicles. Here we list the metrics we utilize for performance evaluation:

- ***Data Delivery Ratio (DR)*** which measures the percentage of data messages that are successfully received by vehicles over the vehicular network. It is obtained by dividing the number of successfully received messages M_{rcv} by the number of expected messages M_{exp}, which is the number of messages to be received in the case of full coverage (100% data delivery).

$$DR = \frac{M_{rcv}}{M_{exp}} \tag{36}$$

  Assuming N vehicles, M_{exp} is computed by considering the total number of sent messages M_{sent}:

$$M_{exp} = N \times M_{sent} \tag{37}$$

  Ideally, data dissemination methods should achieve a data delivery with percentage closed to 100%.

- ***Broadcast Overhead (BO)*** which measures the average broadcast overhead per message reported by an arbitrary vehicle. We obtain *BO* by dividing the total number of duplicate messages over the network M_{dup}, by the number of different messages received M_{rcv}.

$$BO = \frac{M_{dup}}{M_{rcv}} \tag{38}$$

- ***Dissemination Delay (L)*** consists of the measured multi-hop delay at every vehicle, averaged over the network.
- ***Average Number of Hops Propagated*** which we utilize to reflect the data dissemination distance.

6.3 Simulation Scenarios

Simulation scenario is a 3-lanes highway of 5 Km length. In the early phase of evaluating P-SAB, we rely on generating congested traffic flows along the highway, such that the average speed is below the free-flow velocity. Traffic is monitored to determine the time when the traffic is congested, such that data messages are originated during congestion time to ensure scalability. The preliminary results of evaluating P-SAB performance are generated under different number of originated messages, while the core simulation set which forms the basis of SAB performance evaluation is generated under different traffic densities.

To set the physical and the MAC layer, we utilize the implementation of IEEE 802.11p available in MiXiM [73] framework. Settings of the core simulation results are listed in table 3. As the table shows, we use the frequency band of 5.9 GHz and the bandwidth of 10 MHz, and a bit rate of 6 Mbps at the MAC layer. Transmission power is set such that the transmission range is approximately 360 m. Data frequency is 5 Hz and the size of all messages is 100 byte. We rely on four density values to represent different traffic scenarios, where density is measured in Vehicle/Km. The density of 10 represents free-flow scenario. The two density values of 30 and 50 represent two scenarios of medium traffic, while the density of 70 represents congested traffic scenario. We keep a constant value of data generated through simulations, which is set to 50 messages. Finally, each point in the results graphs represents the mean of 5 simulation replications with a confidence interval of 95%.

Table 3: Performance Evaluation Simulation Settings

Physical Layer	Frequency Band	5.9 GHz
	Bandwidth	10 MHz
	Transmission Range (R)	~ 360 meter
MAC Layer	MAC Bit Rate	6 Mbps
	Mac Delay (τ)	20 millisecond
	Data Frequency	5 Hz
Scenarios	Highway length	5 Km
	Lane Max. speed	80 Km/Hr
	Message Size	100 Byte
	Number of Messages	50
	Minimum Slot Width (w)	10 m
	Simulation time	900 Seconds
	Number of runs	5
	Confidence Level	95%
	Density	{10, 30, 50, 70} Vehicle/Km

In figure 6-1, we show the effect of different density scenarios on the speed of a single vehicle during simulation time. These results are generated using the same settings listed in table 3, but with a maximum speed of 16.66 meter/second (60 Km/hr).

As the figure shows, the density of 10 represent an example of free-flow traffic, where the vehicle is generated in the middle of simulation and accelerates until it reaches the maximum allowed speed (the free-flow velocity). Then, it continues to travel with the free-flow velocity until it reaches the destination before the end of simulation. In both of the medium traffic scenarios (where the traffic density is 30 and 50 Vehicles/Km), the vehicle travels with the free-flow velocity until it enters the traffic congestion, where it decelerates during a time interval of around 100 seconds, then it starts to accelerate before its destination without reaching the free-flow velocity. Under high density scenario (70 Vehicles/Km), the vehicle speed clearly indicates a congested traffic, since it travels with low speed values after around 200 seconds from its starting point.

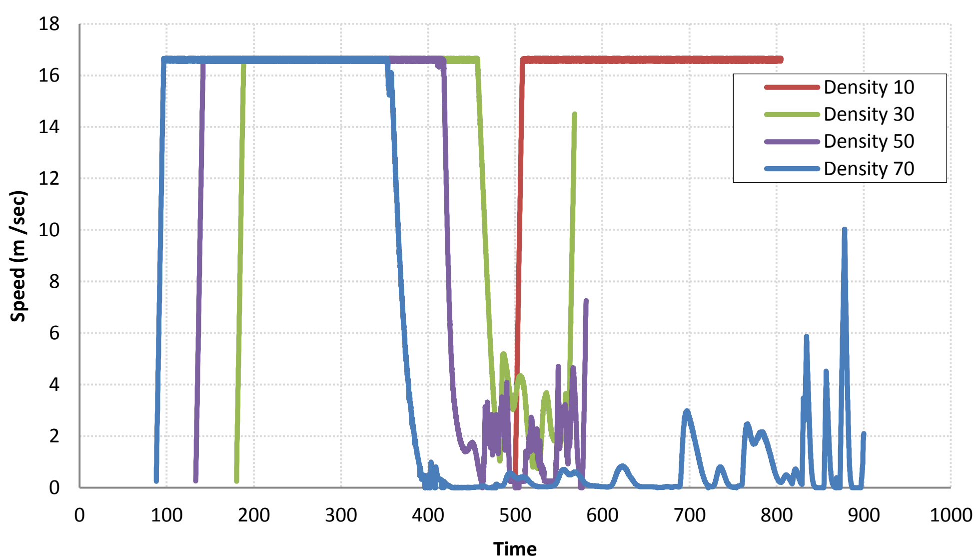


Figure 6-1: Speed Vs. Time under different density scenarios

In figure 6-2, we show the average speed and the average travel time of all the vehicles under different density scenarios. Results are generated with the settings listed in table 3. The figure clearly indicates the negative correlation between the speed and the density. It also shows the classic relation between the speed and the travel time, which are inversely proportional.

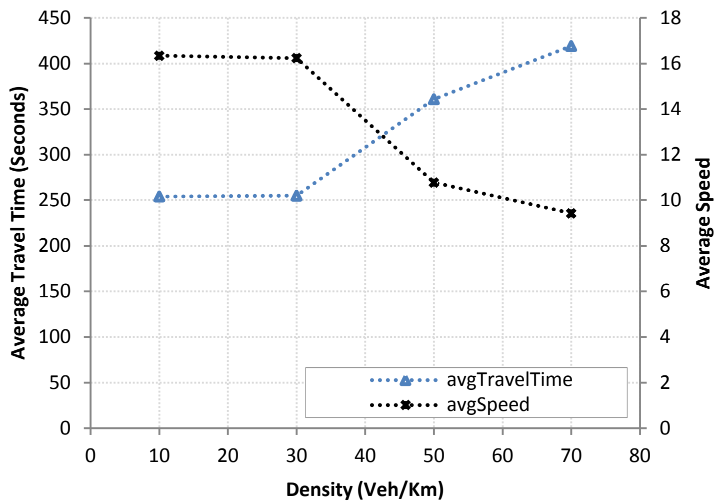


Figure 6-2: Speed and Travel Time Vs. Traffic Density

6.4 Simulation Results

In this section, we show the performance evaluation of our proposed approach. In section 6.4.1, we present the preliminary results of evaluating P-SAB according to the number of sent messages. Section 6.4.2 presents the core performance evaluation results of this research, which proves the scalability of our proposed approach based on increasing traffic density. In section 6.4.3, we show the effect of the timeslot minimum width parameter on the average number of assigned timeslots.

6.4.1 Number of Messages Sent

During early simulations, P-SAB is evaluated under different number of messages originated and sent through the vehicular network. The objective at this phase was to compare speed adaptive broadcast to distance-based broadcast approach, in order to indicate the benefit of introducing the utilization of the speed as a traffic parameter, instead of the distance that is commonly considered by data dissemination methods. This indication can be initially shown by evaluating both of the broadcasting approaches under different communication conditions. The speed adaptive broadcasting approach is presented by our probabilistic version of SAB, which is P-SAB, while the distance-based broadcasting is represented by the weighted p-persistence method, which is described briefly here and with more details in section 4.1.1. Traffic condition is observed at the points where traffic congestion occurs. To ensure scalability of P-SAB at that phase, we rely on two basic factors:

- Creating congestion at the networking level, by increasing the number of messages created and disseminated through the vehicular network.
- Creating traffic congestion points along the highway; such that data messages are sent during congestion time, by the vehicles traveling under congestion.

P-SAB is evaluated under the same congestion condition with six different values of messages originated, and is compared to weighted p-persistence method that is simulated under the same settings, which are listed in Table 4. As the table shows, 500 vehicles are simulated during 900 seconds.

Table 4: Preliminary Results Simulation Settings

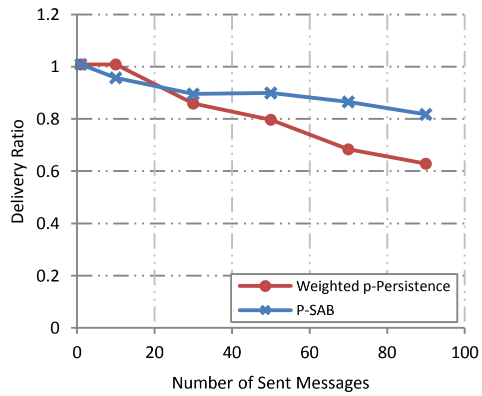
Parameter	**Value**
Frequency Band	5.9 GHz
Bandwidth	10 MHz
Transmission Range (R)	~ 360 meter
MAC Bit Rate	6 Mbps
Data Frequency	5 Hz
Highway length	5 Km
Lane Max. speed	80 Km/h
Density	500 Vehicles
Message Size	100 Byte
Minimum Slot Width (w)	10 m
Simulation time	900 Seconds
Number of Messages	{1, 10, 30, 50, 70, 90}

The early results of simulating P-SAB clearly indicate its superiority over weighted p-persistence method. Figure 6-3 shows the complete performance results at this phase. Figure 6-3(A) illustrates the performance of P-SAB with regards to the delivery ratio. It indicates a clear gain on the delivery ratio in comparison with the weighted p-persistence, where P-SAB performance increases with the increase of the number of data messages disseminated through the vehicular network. Despite the decrease of the delivery ratio for both approaches, P-SAB exhibits a slower decrease with the number of messages disseminated.

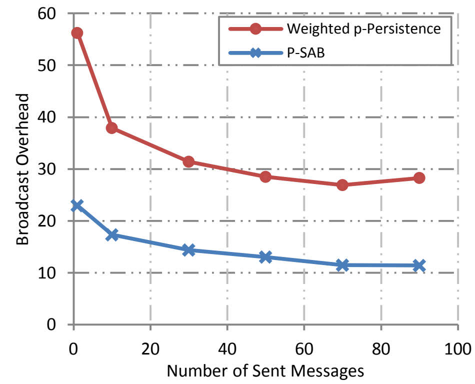
Minimizing the broadcast overhead is one of the main objectives of our broadcasting approach. As Figure 6-3(B) shows, the overhead for both P-SAB and weighted p-persistence approaches asymptotically decreases to stabilize on 30 folds (weighted p-persistence) and 10 folds (P-SAB) showing SAB's performance lower by 20 folds.

As for the dissemination delay, both approaches exhibit similar behavior with delays logarithmically converging towards 1 second. Figure 6-3(C) shows that P-SAB performs slightly better than the weighted p-persistence. This is expected as P-SAB differs from the weighted p-persistence by minimizing the probability of rebroadcast. Similarly, P-SAB and weighted p-persistence exhibits similar performance with regards to the average number of hops travelled, as Figure 6-3(D) indicates.

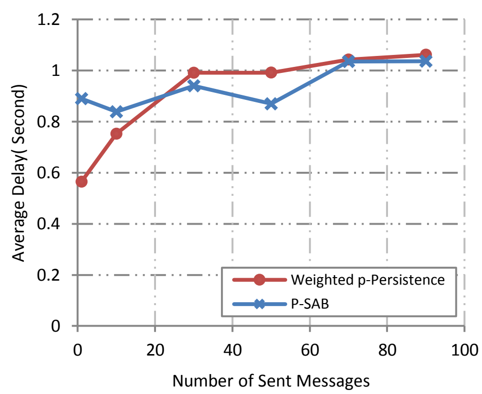
In conclusion, preliminary results show the superiority of P-SAB over weighted p-persistence. In addition to reducing the broadcast overhead by keeping the number of duplicate messages at lower values, P-SAB maintains a high data delivery ratio. One interesting observation is that with the increase of the number of generated messages, P-SAB's delivery ratio deteriorates a lot slower than of the weighted p-persistence.



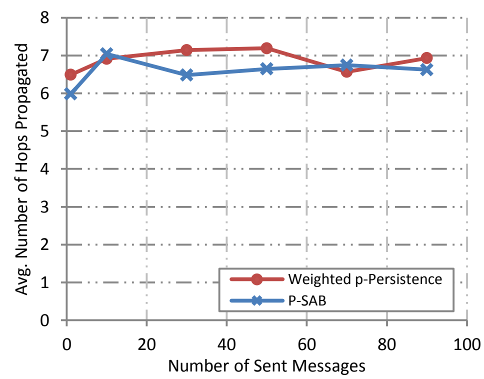
(A) Delivery Ratio



(B) Broadcast Overhead



(C) Average Dissemination Delay



(D) Average Number of Hops Propagated

Figure 6-3: Preliminarly Performance Evaluation of P-SAB

6.4.2 Traffic Density

This section presents the core performance evaluation of the proposed approach with increasing traffic density, in which the scalability feature can be proved in the different variations of SAB. The settings of all simulations analyzed in this section are listed in table 3. In section 6.4.2.1, we evaluate P-SAB. In section 6.4.2.2 we present the performance results of comparing the probabilistic broadcast with the delay-based broadcast, which was a preamble step for the evaluation of our proposed delay-based approach (S-SAB). In section 6.4.2.3, we study effect of the number of assigned timeslots in delay-based broadcast. In section 6.4.2.4, we show the performance results of evaluating S-SAB, which present the major contribution of this dissertation. In section 6.4.2.5, we evaluate G-SAB that provides extra improvement to S-SAB by adding horizontal delays for road lanes.

6.4.2.1 Evaluating P-SAB

In this section, we show simulation results for evaluating P-SAB with increasing traffic densities, ranges from free-flow traffic (10 Vehicles/Km) to congested traffic (70 Vehicles/Km). Simulation settings are listed in table 3. Generated results are shown in figure 6-4. Like the evaluation based on the number of messages sent messages, P-SAB is compared to the weighted p-persistence method.

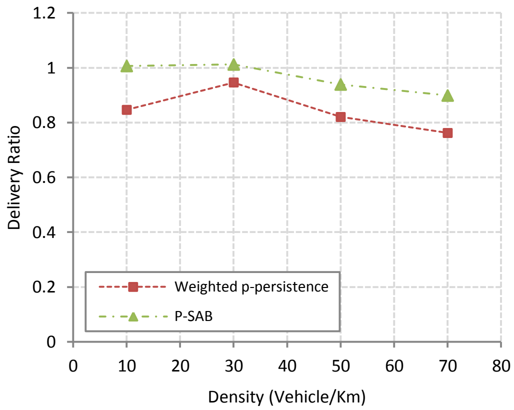
Figure 6-4(A) shows the performance results with regard to data delivery ratio, which clearly indicates the superiority of P-SAB under all density scenarios. P-SAB achieves 90% data delivery under high densities, while it achieves 100% delivery under low densities. This can be explained by the fact that the amount of data redundancy under high densities causes message collisions in which the delivery ratio is affected by 10%.

In terms of broadcast overhead, P-SAB shows a dramatic decrease in data redundancy under high densities, while weighted p-persistence shows persistence increment in the amount of redundant data, as shown in figure 6-4(B).

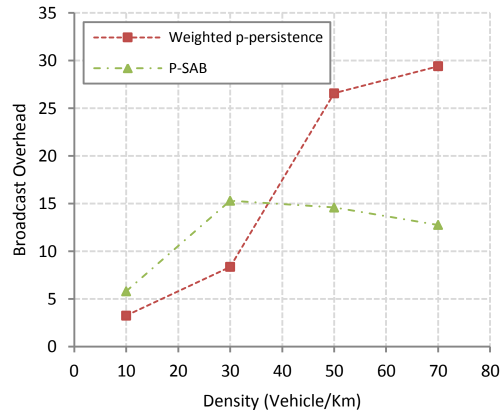
As P-SAB method shows an improvement in the percentage of data redundancy with the increasing density (compared to weighted p-persistence), it is expected that P-SAB would present better dissemination delays, since it utilizes lower probability values under high densities, which means lesser data forwarding attempts. Figure 6-4(C) illustrates this fact.

For the number of hops propagated, the methods show similar performance, which means that they both can disseminate traffic data to faraway distances.

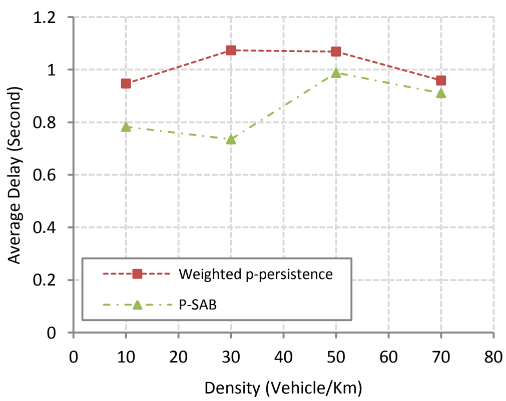
This simulation set provides optimistic results for speed adaptive broadcasting; however, we are aiming at achieving lower broadcasting overhead, which cannot be achieved by simple probabilistic-based broadcasting method. By the end of this phase, we intended to evaluate the best existing delay-based broadcasting approach in order to improve it further. In the next two sections, we present two important preamble performance evaluation steps that support the design and implementation of our proposed delay-based broadcasting method, the slotted speed adaptive broadcast (S-SAB). These steps include comparing the performance of P-SAB to slotted 1-persistence method, and then studying the effect of assigning different timeslots in slotted 1-persistence.



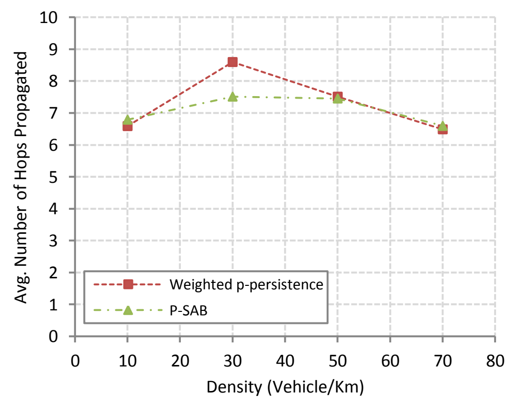
(A) Data Delivery Ratio



(B) Broadcast Overhead



(C) Average Dissemination Delay



(D) Average Number of Hops Propagated

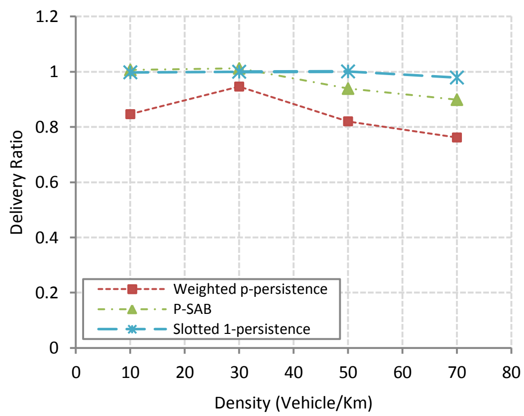
Figure 6-4: Performance Evaluation of P-SAB

6.4.2.2 Comparing Probabilistic with Delay-based Broadcast

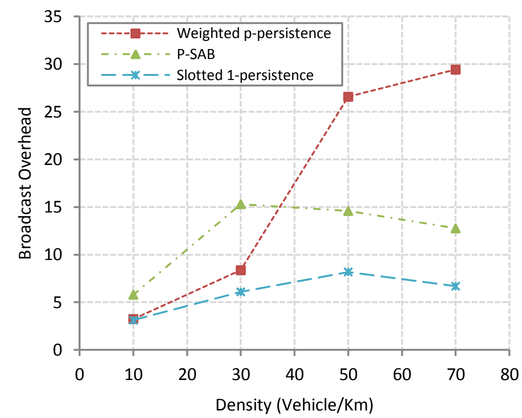
This result set aims at preparing for the design and implementation of our approach for delay-based broadcasting. For this purpose, we simulate the slotted 1-persistence method, which shows the best performance among existing delay-based broadcasting methods. Simulation settings are shown in table 3. Generated results are compared with P-SAB and weighted p-persistence, as shown in figure 6-5.

As figure 6-5(A) shows, slotted 1-persistence method outperforms the probabilistic-based broadcasting methods in terms of the delivery ratio. This is expected since the slotted 1-persistence is a delay-based broadcasting method that sets the probability of broadcasting to 1, which explains the 100% data delivery ratio. Therefore, slotted 1-persistence is a reliable broadcasting approach that achieves full data coverage.

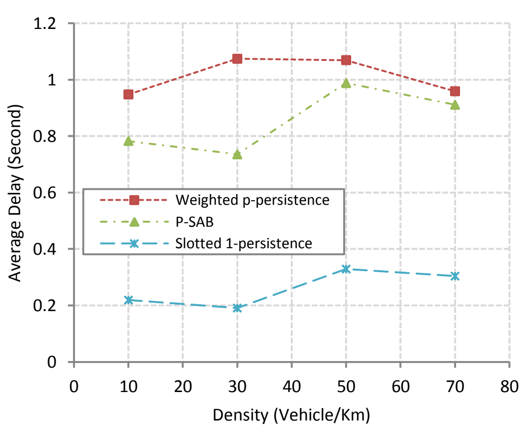
In terms of broadcasting overhead, slotted 1-persistence shows lesser overhead compared to the other two methods as shown in figure 6-5(B). This is due to the suppression mechanism that decreases the number of duplicates. Nevertheless, data redundancy is still high and it grows with the increasing traffic density, since the number of timeslots assigned through simulation time remains constant and does not reflect the current status of traffic flow. Here it is worth noting that vehicles assigned to the same timeslot re-broadcast nearly simultaneously since they don’t have the time to cancel their broadcasts. Therefore, data redundancy is unnecessarily increased in slotted 1-persistence. From this point, we thought about relying on a delay-based broadcasting approach that assigns different number of timeslots according to traffic regime, in order to achieve two main objectives; the first is to decrease data redundancy especially under high density scenarios, and the second is to maintain dissemination delay under low densities. As figure 6-5(C) shows, slotted 1-persistence outperforms the probabilistic methods in terms of dissemination delay.



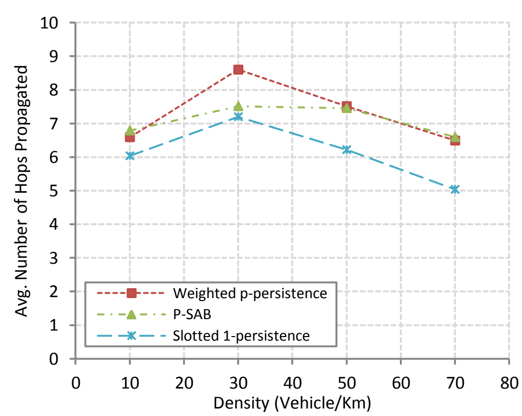
(A) Data Delivery Ratio



(B) Broadcast Overhead



(C) Average Dissemination Delay



(D) Average Number of Hops Propagated

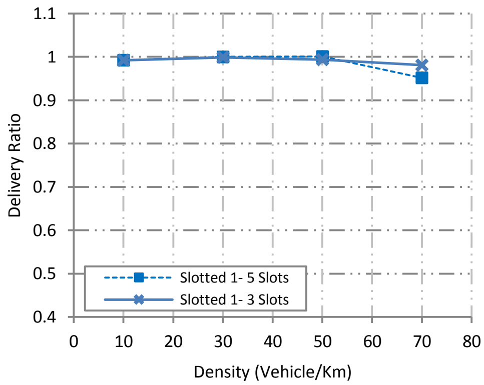
Figure 6-5: Comparing P-SAB to Slotted 1-persistence

6.4.2.3 Evaluating the effect of timeslots in delay-based broadcast

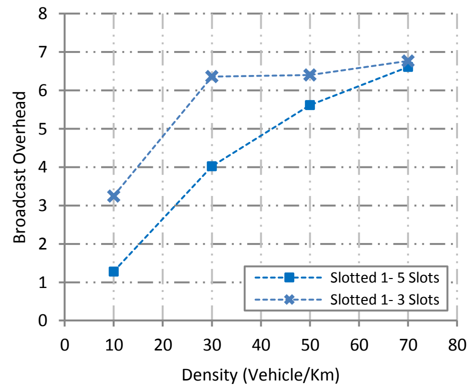
In this section, we study the effect of assigning different number of timeslots in slotted 1-persistence method. We show the results of assigning 3 and 5 timeslots in two sets of simulations in figure 6-6, with the settings mentioned in table 3. The objective of these results is to evaluate the effect of assigning more slots especially in terms of broadcasting overhead under high densities.

As figure 6-6(B) shows, assigning 5 slots in slotted 1-persistence method can significantly decrease the broadcast overhead, compared to the results achieved when assigning only 3 timeslots. This is explained by the fact that assigning more timeslots allows lesser number of vehicles to be assigned to the same timeslots, which means lesser opportunities of simultaneous broadcasts, and thus, a decreased amount of data redundancy and lesser collisions. However, under the density of 70 Vehicle/Km which represents a traffic congestion scenario, the results of assigning the two values of timeslots show similar performance in terms of overhead. This means that more timeslots are required under high density scenarios. Slotted 1-persistence method does not allow the dynamic assignment of timeslots according to traffic density, and the number of timeslots is a constant parameter that is set by the network designer.

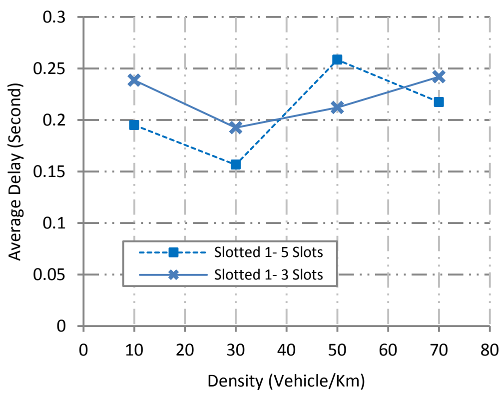
This result set completes our preliminary investigation of the performance of both the probabilistic and the delay-based broadcasting approaches, which supports the idea of designing a delay-based broadcasting approach that present the scalability feature, by assigning different number of timeslots dynamically according to traffic regime.



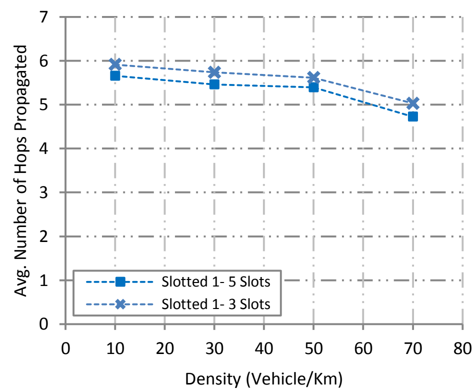
(A) Delivery Ratio



(B) Broadcast Overhead



(C) Average Dissemination Delay



(D) Average Number of Hops Propagated

Figure 6-6: Slotted 1-persistence with two different number of timeslots

6.4.2.4 Evaluating S-SAB

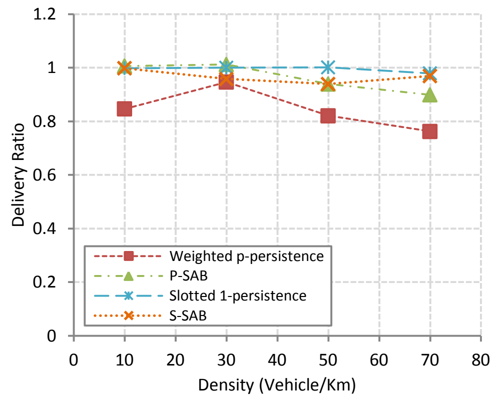
In this section we explain the performance results obtained from simulating S-SAB. The results obtained clearly indicate the superiority of S-SAB over the existing approaches. Figure 6-7(A) illustrates the simulation results with regards to the delivery ratio. It views little difference between all the approaches with a slight advantage of slotted 1-percistent and S-SAB over the others, which approach the theoretical maximum that represents a full coverage. This is explained by the nature of the delay-based broadcasting, which almost guarantees that a message is relayed at each hop, while the probabilistic approaches do not. We must note here that the delivery ratio does not really depend on the density of the traffic.

As mentioned earlier in this paper, decreasing the broadcast overhead is one of the main objectives of our proposed broadcasting approach. The superiority of S-SAB really reflects this fact. As Figure 6-7(B) shows, S-SAB decreased the broadcast overhead by more than half compared to the slotted 1-persistence, by more than 6 folds compared to P-SAB, and by almost 30 folds compared to weighted p-persistence.

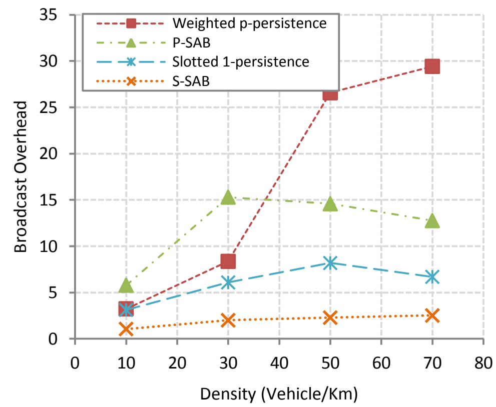
In terms of delays, and similar to the delivery ratio, S-SAB and slotted 1-persistence share the same superior performance compared to P-SAB and weighted p-persistence. As Figure 6-7(C) indicates, the end-to-end dissemination delay is decreased by almost 600 milliseconds.

In conclusion, S-SAB showed its superiority over the best dissemination approach so far, which is the slotted 1-persistence. Even though it shares the same performance with slotted 1-persistence with regards to the delivery ratio and the end-to-end delay, it outperformed slotted 1-persistence in the area where improvement in the performance was most needed, that is, the broadcast overhead. Indeed, one may say that S-SAB main contribution is in minimizing the broadcast overhead to desirable levels.

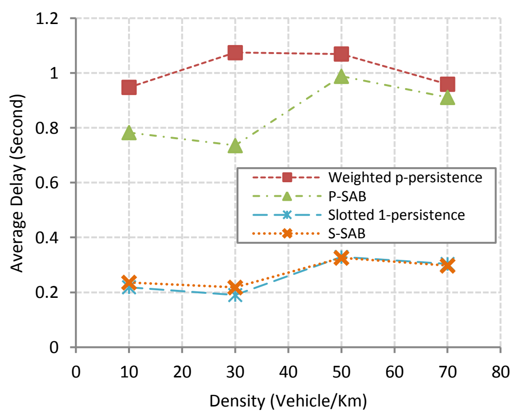
We can explain the success of our approach in minimizing the overhead by the fact that S-SAB's re-broadcast policy is based on traffic regime estimation using speed data. By adapting the number of timeslots to traffic regime, we allow S-SAB to minimize the number of neighboring nodes allowed to re-broadcast. Thus, minimizing the number of re-broadcasts at each hop leads to lesser duplicate messages and lesser collisions.



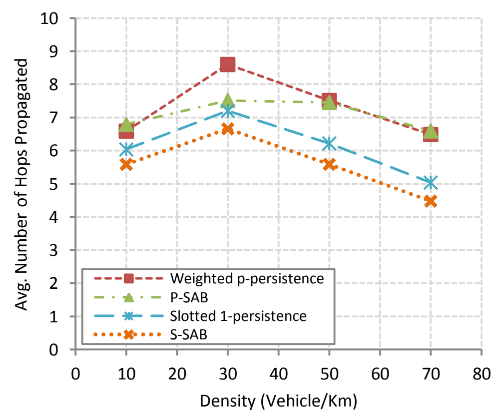
(A) Delivery Ratio



(B) Broadcast Overhead



(C) Average Dissemination Delay



(D) Average Number of Hops Propagated

Figure 6-7: Performance Evaluation of S-SAB

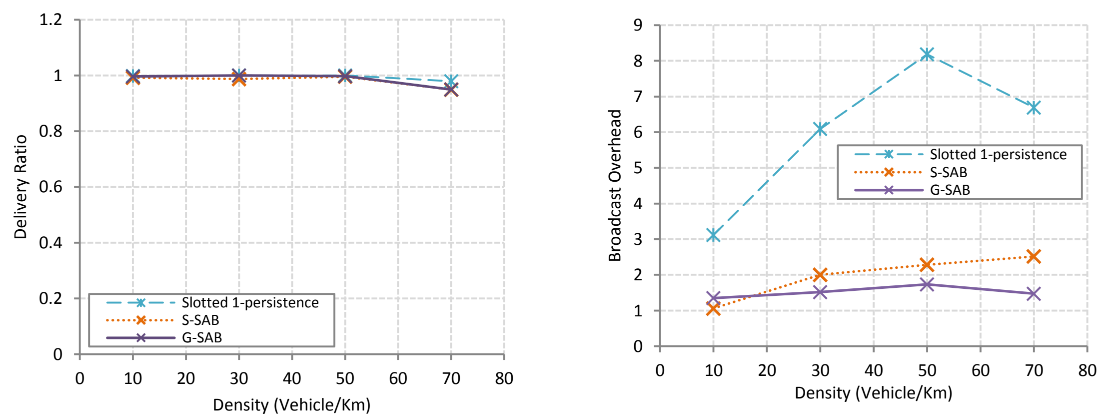
6.4.2.5 Evaluating G-SAB

In this section we explain the performance results obtained from simulating G-SAB, compared to S-SAB and slotted 1-persistence. The results obtained clearly indicate the superiority of G-SAB which slightly improves S-SAB. Figure 6-8(A) illustrates the simulation results with regards to the delivery ratio. It shows that delay-based broadcasting can approximately achieve a full coverage data delivery. This is explained by the nature of the delay-based broadcasting, which almost guarantees that a message is relayed at each hop.

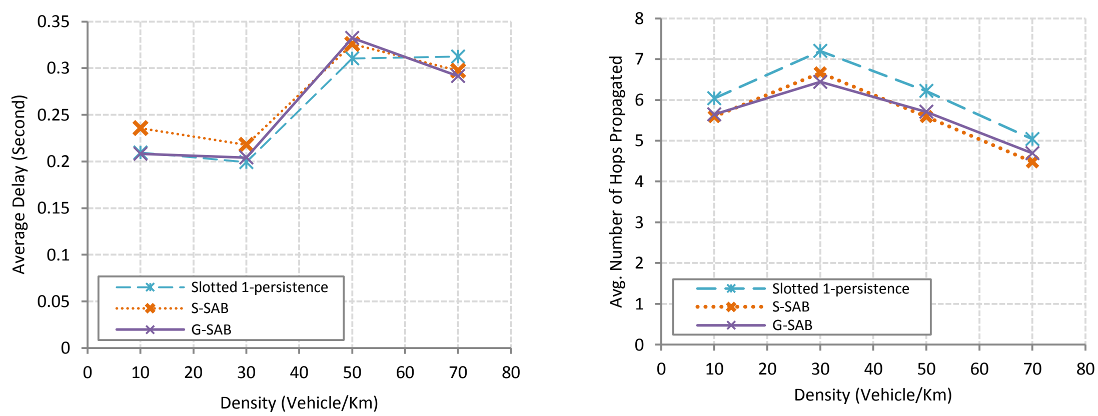
As mentioned earlier, decreasing the broadcast overhead is one of the main objectives of our broadcasting approach. The superiority of G-SAB reflects this fact. As figure 6-8(B) shows, G-SAB succeeded to achieve a minimized broadcasting overhead, which remains almost constant under different traffic densities.

In terms of delays, S-SAB, G-SAB and slotted 1-persistence share a similar performance, as figure 6-8(C) indicates. The dissemination delay is around 300 milliseconds for the propagation among an average of 6 hops, which means an average of around 50 millisecond of delay for single hop data dissemination. Therefore, our proposed delay-based broadcasting approach can successfully address the strict latency constraints of safety-oriented applications.

In general, our delay-based broadcasting approach has successfully achieved the main objective of this research, since we could minimize the percentage of redundant data and hence the broadcast overhead, while we maintain both, the ratio of data delivery and dissemination delay. A summary of results and research findings is presented in section 6.4.



(A) Delivery Ratio (B) Broadcast Overhead



(C) Average Dissemination Delay (D) Average Number of Hops Propagated

Figure 6-8: Performance Evaluation of G-SAB

6.4.3 Minimum Timeslot Width (*w*)

The minimum timeslot parameter *w* defines the minimum width of a single timeslot, which is set and remains constant through the simulation. The value of *w* is determined by adding the considered length of the vehicle to the safety distance between two vehicles. The transmission range parameter is divided by the minimum timeslot width *w* to set the maximum possible number of timeslots that can be assigned to participating vehicles, as shown in equation (31). Assuming a transmission range of 360 meter, setting the minimum timeslot width to 5 meters allows for a maximum of 72 timeslots. The minimum timeslot width parameter is previously described in section 5.6.2.

In figure 6-9, we show the effect of *w* parameter on the average number of timeslots assigned under different traffic densities. As the figure shows, the average number of timeslots increases with the traffic density, which explains the efficiency of our proposed approach that minimizes the number of vehicles assigned to the same timeslot, such that data redundancy as well as message collisions are reduced.

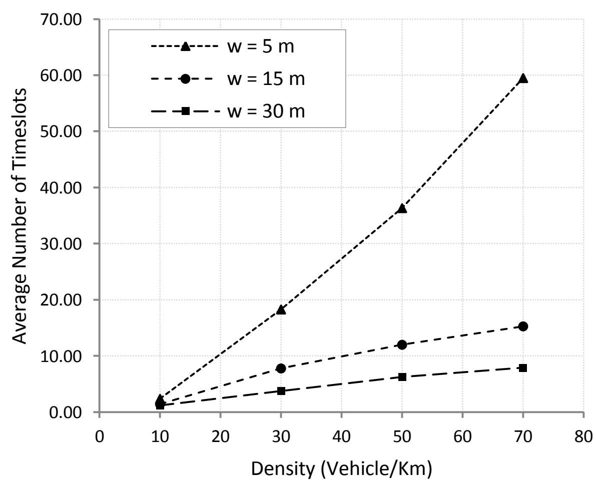


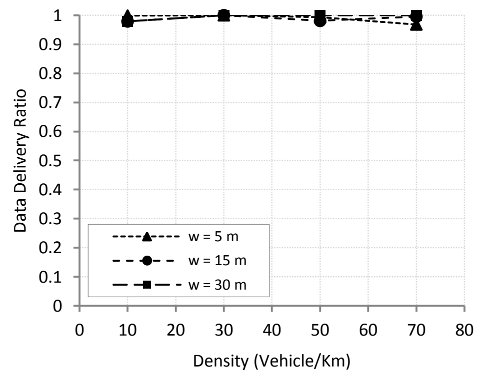
Figure 6-9: The Effect of the Minimum Timeslot Width on the Number of Timeslots

This result set aims at showing the effect of assigning different values of *w* on the performance of S-SAB. We evaluated three different values of *w*: 5 m, 15 m, and 30 m as shown in figures 6-9 and 6-10, with the settings mentioned in table 3.

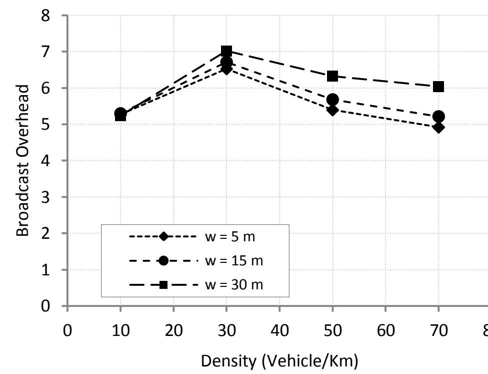
As figure 6-10(A) shows, *w* parameter does not really affect data delivery ratio if it is set to a reasonable value. However, setting *w* to a value that is greater than the vehicle width in addition to the considered safety distance would allow more vehicles to be assigned to the same timeslot under high densities, in which the dissemination overhead is increased, and thus, the expected collisions at the MAC layer may lead to data loss and the data delivery would be affected. Figure 6-10(A) shows that the evaluated *w* values achieve 100% data delivery.

Figure 6-10(B) shows similar performance under low densities for all cases, since only one or two timeslots are assigned, such that the dissemination delay is not increased. As traffic density increases, the broadcasting overhead is increased as the value of *w* increases. This is clearly due to the percentage of redundant data that is increased in wider slots, since more vehicles may participate in relaying data messages.

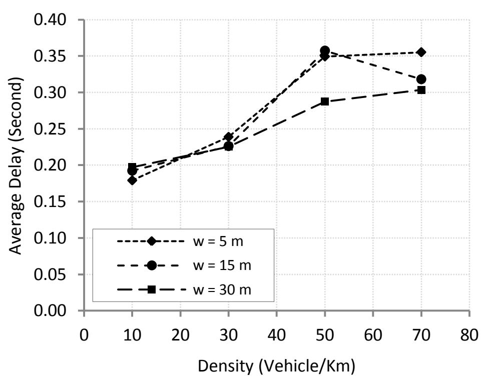
In terms of dissemination delays, the three evaluated values of *w* do not show significant variations, but a slight advantage is shown for *w* of 30 meters length, as illustrated in figure 6-10(C). The three evaluated cases show similar performance in terms of the average number of hops propagated. As it can be indicated from figure 6-10(D), the average number of hops is 6.71. Considering this average along with the average total dissemination delay of around 0.27 calculated from figure 6-10(C), the average per-hop dissemination delay is around 40 millisecond; a value that can address the critical delay requirements of safety-oriented applications.



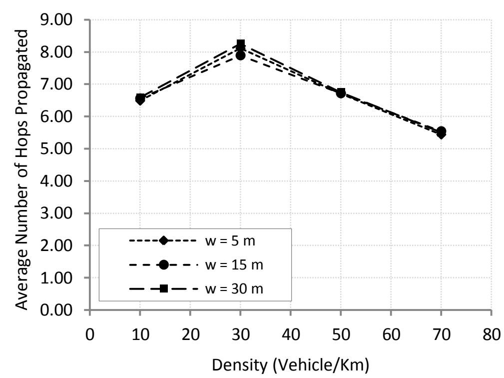
(A) Data Delivery Ratio



(B) Broadcast Overhead



(C) Average Dissemination Delay



(D) Average Number of Hops Propagated

Figure 6-10: The Effect of the Minimum Timeslot Width on S-SAB

6.5 Summary of Research Findings

In this section, we present a summary of performance results and research findings. In figure 6-11, we show the performance results of S-SAB, G-SAB and slotted 1-persistence compared to the probabilistic-based broadcasting of P-SAB and the weighted p-persistence. Each point in the graphs is a mean of 5 simulation replications with 95% confidence. This result set presents the core performance evaluation results for this research, which clearly indicates the superiority of our delay-based broadcasting approach represented by S-SAB and G-SAB. From figure 6-11, we can clearly indicate the following summary of findings:

- The superiority of delay-based broadcasting (Slotted 1-persistence, S-SAB and G-SAB) over the probabilistic approach (Weighted p-persistence and S-SAB).
- The superiority of our proposed S-SAB and G-SAB over the other approaches, especially in terms of broadcasting overhead, as shown in figure 6-11(B).
- The reliability of our broadcasting approach, since S-SAB and G-SAB can achieve 100% data delivery ratio under different traffic conditions, as shown in figure 6-11(A).
- Speed data can practically indicate traffic density and hence traffic regime, without extra communication overhead.
- Our Speed Adaptive Broadcasting (SAB) approach maintains the dissemination delay as shown in figure 6-11(C), with an average of around 50 milliseconds per hop, which means that S-SAB addresses the requirements of different safety-oriented applications which usually have strict latency constraints.

- Our Speed Adaptive Broadcasting (SAB) approach can disseminate traffic data up to 8 hops away, as shown in figure 6-11(D), which means a propagation distance of around 2880 meters with our range setting. This distance is sufficient to address the requirements of different convenience-oriented applications and delay-tolerant systems.

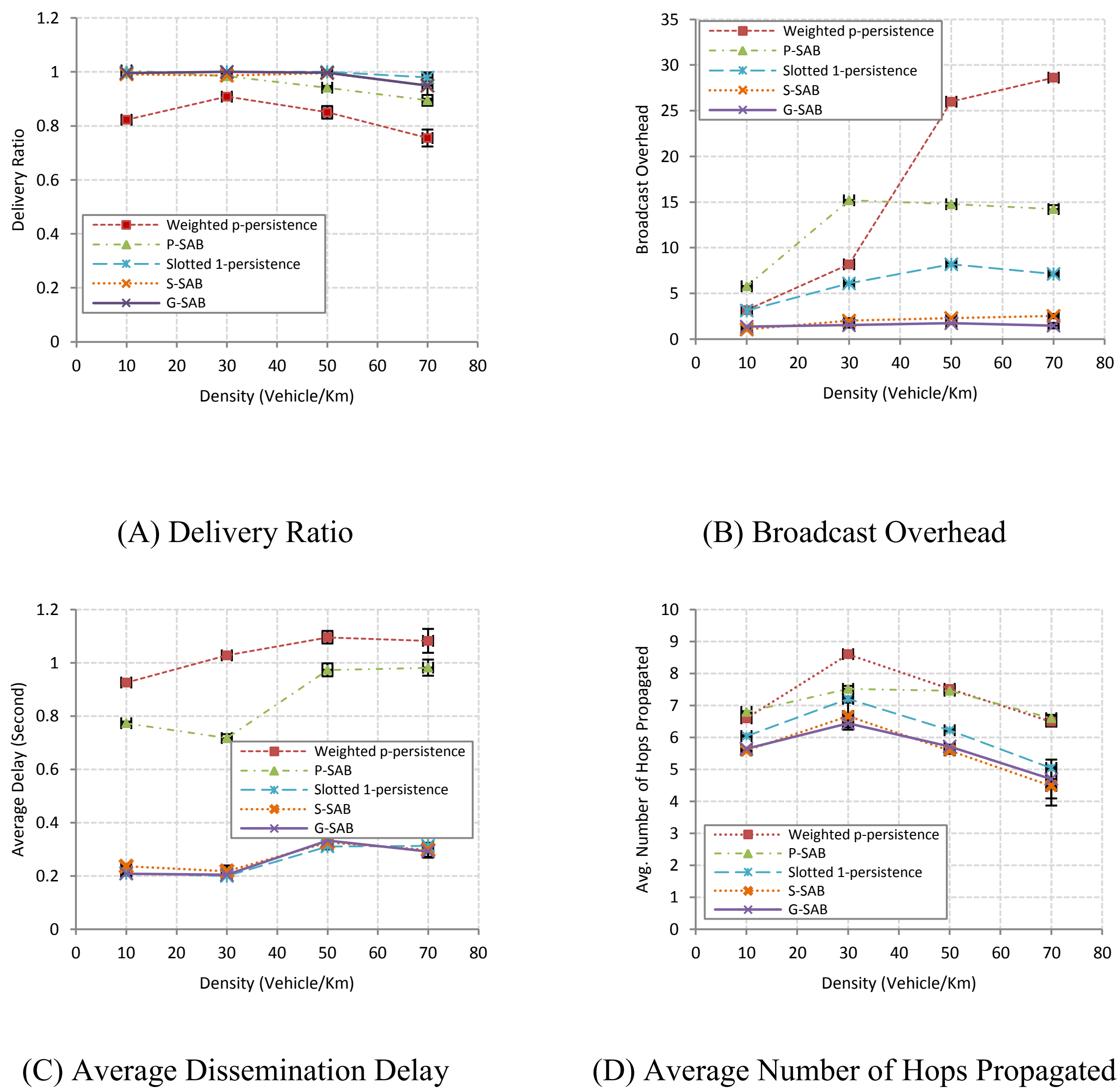
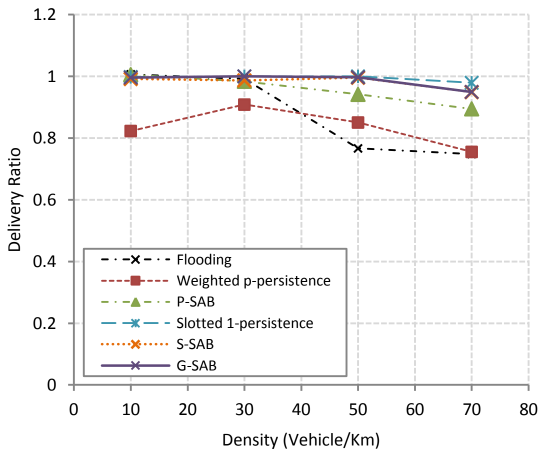


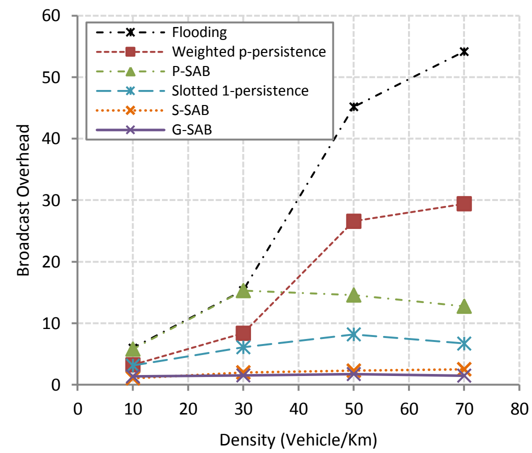
Figure 6-11: Performance Evaluation Results

In figure 6-12, we show our performance results compared to data flooding, which is the simplest style of broadcasting that can easily lead to the broadcast storm problem under high traffic densities. From the figure, we can indicate the following:

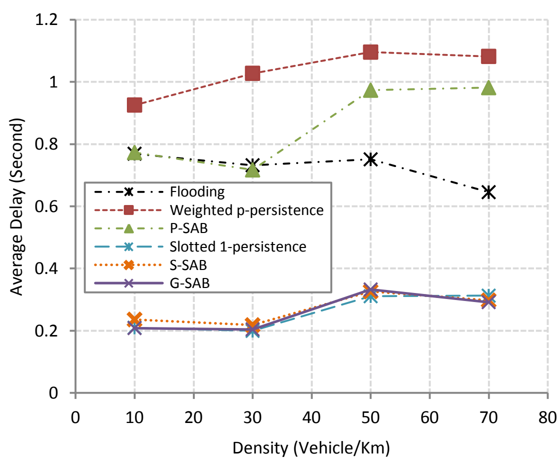
- Despite that data flooding is expected to achieve a full coverage, figure 6-12(A) shows that the data delivery ratio of flooding slightly decreases under high density scenarios. This can be explained by the broadcast storm problem that can easily occur under dense traffic, which affects data delivery due to collisions at the MAC layer.
- Data flooding, in addition to other probabilistic broadcasting methods show an incremental overhead with the increasing traffic density, as shown in figure 6-12(B), while our delay-based SAB shows a constant overhead under different traffic densities, which indicates its superiority over existing data dissemination solutions.



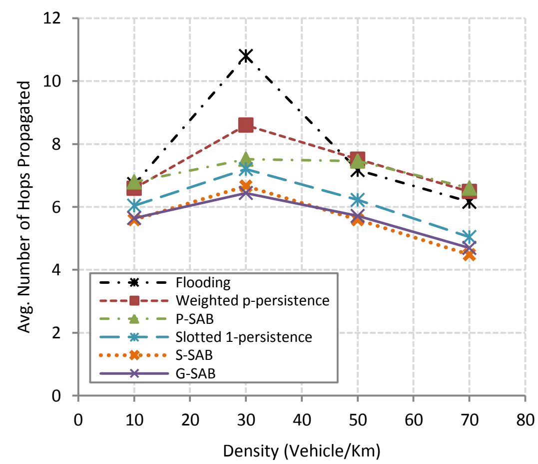
(A) Delivery Ratio



(B) Broadcast Overhead



(C) Average Dissemination Delay



(D) Average Number of Hops Propagated

Figure 6-12: Performance Evaluation Results Compared to Flooding

Chapter 7: Conclusion

Broadcasting forms the basis of all types of communication in vehicular networks. Therefore the broadcast storm problem should be addressed by broadcasting schemes in order to achieve two major objectives: the first is to avoid unnecessary loss of important data during a broadcast cycle, and the second is to minimize data redundancy overhead. However, it is still challenging to achieve low dissemination overhead while maintaining high delivery ratio and minimum broadcasting delay.

This dissertation aims at studying data dissemination solutions for vehicular ad hoc networks that fulfill the requirements of different applications. In particular, we concentrated on providing a scalable data dissemination solution for V2V communication. We proposed different variations of speed adaptive broadcast, which can effectively estimate traffic regime using simple speed data. Simulation results show that we could achieve high delivery ratio with low dissemination overhead. Therefore, in addition to the improvement we achieved over existing approaches, our approach's merit lays in the fact that it is free from the overhead of any neighborhood management.

This dissertation has successfully answered the following three basic research questions we raised in the initial phases:

Can a broadcast mitigation approach achieve low overhead while maintaining high ratio of data delivery?

This question was raised after a careful literature review; where we indicated that existing data dissemination approaches do not significantly reduce the overhead of data redundancy. We started by comparing existing solutions for broadcast mitigation in VANETs to identify the best existing approaches in terms of redundancy overhead.

Compared to existing approaches, we have successfully proposed a broadcast mitigation solution that minimizes broadcasting overhead to desirable levels. In particular, we could achieve a constant overhead even under high density scenarios.

How to evaluate the performance of data dissemination in the VANET context?

To answer this question, we studied different performance evaluation methods for VANETs. We have found that there is no standard evaluation methodology. Few studies rely on mathematical modeling and the majority of existing approaches rely on simulation results. We studied and compared existing mathematical modeling approaches to select the best model that matches our requirements. This study supports us to define the performance metrics for the evaluation of our proposed approach. We have defined four different metrics to measure the delivery, overhead, delay and propagation distance. For simulation-based performance evaluation, we searched existing simulation environments that support scalability, in order to enable the evaluation under high density scenarios. OMNET++ was the best choice that meets our design requirements.

What traffic parameters to utilize in order to achieve the research objective?

We thought about the speed of vehicles, since it does not require gathering neighborhood information. In addition, we intended to use the reasonable relation between the speed and the density. We have searched existing traffic flow theory to prove the utilization of the speed parameter in data dissemination for VANETs. We could utilize speed data to numerically reflect traffic regime, such that we adapt data dissemination accordingly.

In the rest of this conclusion, we present the benefits of our proposed broadcasting approach to different VANET applications. We then propose further research work and after that we summarize our future directions.

7.1 Benefits to Applications

In this section, we show how our proposed broadcasting approach can benefit different VANET applications. More information on safety-oriented and convenience-oriented applications can be found in section 2.3.

Safety-oriented applications:

The basic requirements of safety-oriented applications can be summarized in high data delivery and low dissemination delays. The proposed approach not only addresses the basic requirements of safety-oriented applications, but also minimizes the data dissemination overhead, a characteristic that is essential under high density scenarios. High dissemination overhead can lead to the broadcast storm problem, where packet collisions may affect the delivery of safety critical data.

Convenience-oriented applications:

Convenience-oriented applications are travel comfort applications that can make our every day travel more efficient, by detecting congestion points or estimating the arrival time to destinations. These applications usually referred to as delay-tolerance, since they tolerate more dissemination delays compared to safety-oriented applications. However, they require the data to travel to relatively faraway distances. Our delay-based broadcasting approach S-SAB can travel up to eight hops away, which makes it beneficial for such applications.

Since convenience-oriented applications usually follow the request-reply communication to get answers of user-specific query within reasonable delay, S-SAB or G-SAB can be integrated in a pull-based request-reply protocol to offer scalable broadcast for these applications. More specifically, a request-reply protocol routes a request to a destination location following a multi-hop path, and then it routes a reply back to the requesting node. Such a protocol relies on broadcasting for data dissemination at each hop, where the integration of S-SAB or G-SAB can offer scalable routing. Here it is worth noting that most of the existing routing protocols rely on flooding for data dissemination at each hop [74].

In a recent publication (which can be found in the list of publications [6]), we proposed to utilize pull-based data dissemination for shortest-time route finding application. We utilize simple flooding as part of a request-reply routing protocol, where we experienced high percentage of data redundancy. Integrating S-SAB in such applications would certainly decrease the redundancy overhead to desirable levels.

7.2 Further Work

In this section, we briefly discuss three possible further works to improve our data dissemination approach, mainly by considering different urban traffic scenarios, where low traffic problems can be addressed in addition to the broadcast storm problem that is correlated to high density traffic.

Considering traffic direction:

In addition to the distance parameter that is commonly utilized to determine the rebroadcasting probability and/or delay, recent studies consider traffic direction to support variety of traffic scenarios [75] [76] [77]. We propose to improve and evaluate

S-SAB to share direction data, such that data dissemination is not affected by the traffic condition of the opposite direction road. Initially, we will consider bidirectional traffic in highways: the West to East (*WE*) direction, and the East to West (*EW*) direction. Particularly, if the data that is sent from a source vehicle V_1 is received by a vehicle V_2, V_2 will check the direction of the data if it receives it for the first time. If V_2 is at the same direction of V_1, V_2 will utilize the shared speed data to detect traffic regime as we have previously described in S-SAB. If they are not travelling in the same direction, V_2 will detect traffic regime of its current road before attempting to re-broadcast. This way, timeslots are set in each direction according to its traffic condition, since the vehicular network may be sparsely connected in one direction, while the traffic is congested in the other direction. Here the objective is to propagate traffic data to the maximum possible distance in both directions.

Evaluation in urban scenarios:

We propose to further improve our broadcasting approach to address the requirements of sophisticated urban scenarios, such as [55], where other traffic flow models would be involved to deal with interrupted traffic. When the speed of the source vehicle is zero, it is not realistic to always consider a traffic jam, since other conditions may force a travelling vehicle to stop. In these conditions, S-SAB may be improved to utilize other traffic regime estimation method. However, in its current version, S-SAB can still work effectively under these scenarios. It considers a traffic jam whenever the speed is zero and assigns vehicles to the maximum number of timeslots. If the source vehicle is stopping for a reason other than traffic congestion, S-SAB limitation in this case is that the delay may be slightly increased, especially if traffic regime is low.

Considering low traffic problems:

In addition to the broadcast storm problem that occurs under high density traffic scenarios, other problems are correlated to low traffic conditions, where the vehicular network is sparsely connected [17] [54] [78]. We are planning to address the network partition and fragmentation problems in further work.

Enhancement with data caching for the integration in delay-tolerant networks

Despite that delay-based SAB can provide several benefits to safety-oriented and convenience-oriented applications, further improvement can be implemented for convenience-oriented applications with delay-tolerance, by providing a caching scheme that utilizes previously stored data, instead of trying to fetch it through another broadcasting attempt.

Exploring the benefits of V2I communication in data dissemination

In this dissertation, we were only concerned with V2V communication mode. In a further work, we plan to explore the benefit of V2I communication to provide scalable broadcast. For instance, the status of the traffic may be estimated by RSUs mounted on traffic lights. Vehicles can utilize traffic information through V2I communication before initiating V2V data dissemination.

7.3 Future Direction

With the rapid development of computation and communication technologies, and due to the increasing number of vehicles being connected to the Internet of Things (IoT), the conventional Vehicular Ad hoc Networks is being evolved into the Internet of Vehicles (IoV), which is attracting the interest of research and industry [79]. The Internet of Things (IoT) aims at interconnecting our everyday life items, by providing them with information processing capabilities to enable them to sense, integrate, present, and react to all aspects of the physical world [80].

The objective of IoV is to provide the best connected communication capability, by integrating multiple users, multiple vehicles, multiple things and multiple networks. Therefore, efficient wireless access solutions will be essential for manageable and credible IoV. Moreover, efficient methods will be required for the sustainability of service provision as vehicles will become a part of the global network. Furthermore, new methods will be needed to assure a good quality IoV experience [79]. We are planning to contribute in developing solutions for IoV in our future research.

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