SPEED ADAPTIVE INFORMATION DISSEMINATION IN VEHICULAR AD-HOC NETWORKS

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SPEED ADAPTIVE INFORMATION DISSEMINATION IN VEHICULAR AD-HOC NETWORKS

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A significant issue in vehicular ad hoc networks (VANETs) is the design of an effective broadcast scheme which can facilitate the fast and reliable dissemination of emergency warning messages (EWM) in the vicinity of an unexpected event, such as a vehicle accident. In this work we propose a novel solution to this problem, which we refer to as Speed Adaptive Probabilistic Flooding (SAPF). The scheme employs probabilistic flooding to mitigate the effects of the broadcast storm problem, typical when using blind flooding, and its unique feature is that the rebroadcast probability is regulated adaptively based on the vehicle speed to account for varying traffic densities within the transportation network. The motivation behind this choice is the identification of the existence of phase transition phenomena in probabilistic flooding in VANETs which dictates a critical probability is affected by the varying vehicle traffic density, and shown to be linearly related to the vehicle speed (a locally measurable quantity). The protocol enjoys a number of benefits relative to other approaches: it is simple to implement, it does not introduce additional communication burden, as it relies on local information only, and it does not rely on the existence of a positioning system (e.g. GPS) with its associated high signaling overhead for the exchange of beacon messages for mutual awareness. The scheme is evaluated on different sections of the freeway system in the City of Los Angeles and Cyprus, using an integrated platform combining the OPNET Modeler and the VISSIM simulator. Simulation results indicate that the proposed scheme fulfills its design objectives, as it achieves high reachability and low latency of message delivery in a number of scenarios. The scheme is shown to be independent of the number of lanes of the freeway where it is applied, and it continuous to perform as required when uni-directional traffic is replaced by bi-directional traffic. Moreover, the SAPF algorithm has been shown to outperform blind flooding in all scenarios and especially in cases of heavy congestion. Its robustness with respect to different number of hops, different speed limits on the freeway where it is applied, and different transmission range of the vehicles participating in the VANET has also been demonstrated. Finally, the performance of the SAPF algorithm is shown to be comparable to schemes which offer increased opportunities to exhibit superior performance by assuming the presence of GPS positioning systems on board the vehicles.

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LIST OF ACRONYMS, SYMBOLS & ABBREVIATIONS

Ad-Hoc	Network formed with little or no planning
BF	Blind Flooding
DGPS	Differential Global Positioning System
DOT	Department of Transportation
ETSI	European Telecommunications Standards Institute
EU	European Union
EWM	Emergency Warning Message
GPS	Global Positioning System
H1N1	Swine Flu
IVHS	Intelligent Vehicle Highway System
IETF	Internet Engineering Task Force
IP	Internet Protocol
ITS	Intelligent Transportation Systems
ITU-T	International Telecommunication Union - Telecommunication Standardization Sector
OPNET	A network communication simulator
PeMS	Performance Measurement System
PF	Probabilistic Flooding
QoS	Quality of Service
SAPF	Speed Adaptive Probabilistic Flooding
VANET	Vehicular Ad Hoc Network
V2I	Intelligent Infrastructure
V2V	Intelligent Vehicle System
VISSIM	A road traffic simulator
WAVE	Wireless Access in Vehicular Environments
WLAN	Wireless Local Area Network

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Chapter 1

Introduction

In this chapter we provide a brief introduction to the problem of emergency warning dissemination in vehicular ad-hoc networks and discuss briefly some of the proposed existing solution approaches. Furthermore, we introduce the proposed solution approach and its salient characteristics. Also, in this chapter we have highlighted the contributions and list the publications stemming form this thesis.

1.1 Emergency Warning Message Dissemination in VANETs

In 2008, around 850 million people worldwide were using their vehicles as a means to carry their business or personal tasks every day. Such high volume of vehicles has led to several other problems such as: congestion, in some cases nearing collapse, of road transportation networks, environmental hazards, increased oil prices, and above all traffic accidents [1]. In 2008 (2006) alone, about 6 million (1.3) traffic accidents in the U.S. (EU) accounted for 37,231 (38,600) fatalities, 2.35 (1.6) million injuries and \$230 billion in damaged property [1]. It is anticipated that these terrifying numbers will keep increasing since it has been projected that by the year

2030 we will have 2 billion vehicles worldwide [38]. Significant efforts have been made by governments' transportation authorities, automobile manufacturers and the academic community to accelerate the developments of an intelligent transportation system (ITS) for safe, efficient and convenient driving. ITS exploits advanced electronics and a broad range of wireless and wire line communications to disseminate critical information into transportation infrastructure and vehicles themselves. The benefits of using ITS in the transportation systems are to relieve congestion, improve safety and provide better usability of the transportation resources. ITS is divided into Intelligent Infrastructure System (V2I) and Intelligent Vehicle System (V2V). V2I system enables vehicles to use roadside units that are located along the road every few kilometers to obtain access to the network. V2V communication could be established by forming a group of intelligent vehicles which are equipped with wireless communication devices. This kind of group it also referred as Vehicle Ad Hoc Network, VANET, where its members could exchange information among them, and where the formation of a communication network is established using ad hoc networking techniques. There are many applications that could be used over VANETs such as vehicle entertainment, vehicle torrent, regional advertising, pavement conditions, toll road payments, cooperative traffic congestion, accident prevention, and cooperative accident warning. It is obvious that there is potential for a broad range of applications where each application's requirements may vary significantly. It is the responsibility of the underlay network to provide the mechanisms to match the application's requirements. In case the underlay network fails to match the application's requirements, the information that will be provided to the driver may be outdated and useless. The preferred link layer wireless technology for the ITS is the 802.11p standard [2], a successor of the 802.11a, which adds wireless access in vehicular environments (WAVE). In this thesis we focus only to vehicle to vehicle communication.

The 802.11p standard [2], which is part of the IEEE WAVE protocol stack, supports both vehicle-to-vehicle and vehicle-to-infrastructure communication allowing the formation of vehicular ad-hoc networks which are envisioned to accommodate the new generation of cooperative safety applications. VANETs can extend the information horizon of the drivers, and cooperative hazard warning applications may utilize this spatially broader view of the surrounding environment to alert drivers of potentially dangerous situations at an earlier stage. In case of an unexpected event such as a traffic accident, a weather hazard or a road works hazard, a vehicle appropriately equipped to detect the event will become an abnormal vehicle and utilize the underlying vehicular ad hoc network to issue emergency warning messages (EWMs) to all neighboring vehicles warning them of the imminent danger. A major challenge in such a scenario is the design of the information dissemination scheme which will facilitate the reliable and low-latency transfer of the emergency warning message to all vehicles in the vicinity of the unexpected event. It is critical that all vehicles within the area of interest receive the emergency warning message with high probability, since a single uniformed vehicle can cause a traffic accident, and it is also significant that the transfer is completed with the minimum possible delay in order to give additional time to the driver or the automated collision avoidance system to respond to the potential danger and improve the safety level on the road.

Our aim is to design a new broadcasting scheme which ensures high reachability to all vehicles in the message warning area, whilst offering low latency of message delivery at all times. The new scheme should be: simple to implement; effective in reaching a given percentage of vehicles within the emergency warning zone; has low communication overhead; and does not rely on the existence of GPS device, which may require excessive signalling for mutual awareness. A major objective is to mitigate the effect of the broadcast storm problem, typical when utilizing blind flooding, or similar techniques to implement the broadcast scheme. However, the design of information dissemination protocols in VANETs is highly challenged by the rapidly changing traffic characteristics, the confined movement of vehicles on the roadway system, the high mobility, the changing road topologies and the presence of buildings which can pose difficulties in the successful transmission of messages.

1.2 Solution Approach

A straightforward solution to the aforementioned problem is blind flooding [55], a scheme which involves each vehicle rebroadcasting the emergency warning message whenever it receives it for the first time. However, the ability of blind flooding to fulfil the design objectives is challenged by stressed communication channel conditions in cases of high vehicular traffic densities. Blind flooding is known to work effectively in sparse and moderately dense networks, however its performance degrades significantly in highly dense networks where a large number of redundant messages are generated. These redundant messages lead to unnecessary collisions, increased contention and high latency, which challenges the stringent delay requirements of the considered application. The problem is widely known as the broadcast storm problem [55] and a number of solutions have been proposed in the literature to mitigate its effects ([25], [48], [37], [57], [58], [60], [63], [66], [36] and [59]). The main idea has been to reduce the number of nodes rebroadcasting the message without affecting the total number of nodes receiving the message. The various proposed solutions then differ in the method with which this restricted set of nodes is chosen.

Specifically for VANETs, the most popular approach has been to choose vehicles which lie on the boundary of the transmission range of the vehicle transmitting each message [46], [44], [35]. However, this method assumes the availability of a positioning system, such as GPS, with its associated high signalling overhead for the exchange of beacon messages for mutual awareness.

Our main contribution in this work is to develop Speed Adaptive Probabilistic Flooding (SAPF), a new broadcast scheme which does not rely on the existence of a positioning system and is shown to work effectively in a number of scenarios [70], [52], [53], [54]. The scheme is intended to serve cooperative hazard warning applications in freeway settings, however, it can easily be adapted to serve similar applications in city streets. The protocol employs probabilistic flooding [61] to mitigate the effects of the broadcast storm problem and has the unique feature of being able to adapt to changing traffic densities, ensuring high reachability and low latency of message delivery at all times, by regulating the rebroadcast probability based on the vehicle speed. Low vehicle speeds in a freeway setting imply large vehicular densities in which case low rebroadcast probability values are sufficient to achieve the posed design objectives of high reachability and low latency of message delivery. It is known that probabilistic flooding in mobile ad hoc networks is characterized by phase transition phenomena [43], similar to the ones observed in the context of random graphs and percolation theory [39], which suggest the existence of a critical rebroadcast probability value beyond which high reachability is achieved with high probability. For a particular traffic density, this critical probability is the desired rebroadcast probability value, as it achieves the lowest latency of message delivery among all rebroadcast probability values whilst achieving high reachability. Speed Adaptive Probabilistic Flooding is able to calculate and adopt this critical probability at all traffic densities by means of a suitable rebroadcast probability function whose input variable is the vehicle speed.

The protocol enjoys a number of benefits relative to other approaches: it is decentralized and simple to implement; it does not rely on the existence of a positioning system which may not always be available; it does not introduce any additional communication burden as it relies on local information only (the vehicle speed); it does not require additional exchange of beacon messages for mutual awareness; and above all it mitigates the effect of the broadcast storm problem, typical when utilizing blind flooding. The scheme is evaluated on different sections of the freeway system in the City of Los Angeles and in Cyprus freeway system as well. For all our simulations we have used an integrated platform combining the OPNET Modeler [3] and the VISSIM simulator [4]. The reference traffic models are generated on the VISSIM simulator and are used to generate traces of the vehicles involved. These traces are then fed into the OPNET Modeler which is used to model the communication networking aspects of the proposed system. The simulation results indicate that the proposed scheme fulfills its design objectives as it achieves high reachability and low latency of message delivery within the area of interest in a number of scenarios reflecting different topologies and traffic conditions. The scheme is shown to be independent of the number of lanes of the freeway where it is applied, and it continuous to perform as required when uni-directional traffic is replaced by bi-directional traffic. Moreover, the SAPF algorithm has been shown to outperform blind flooding in all scenarios and especially in cases of heavy congestion. Its robustness with respect to different number of hops, different speed limits on the freeway where it is applied, and different transmission ranges of the vehicles participating in the VANET has also been demonstrated. Finally, the performance of the SAPF algorithm is shown to be comparable to schemes which offer increased opportunities to exhibit superior performance by assuming the presence of GPS systems on board the vehicles, however at much reduced overhead and simplicity.

1.3 Contributions

Information Dissemination is a critical issue in Vehicular Ad-Hoc networks as its ability to provide timely information to drivers can greatly assist in extending their line of sight promptly, thus significantly reducing the probability of traffic accidents and improving safety. In this thesis we address the information dissemination problem in VANETs and we propose a novel scheme which can facilitate the fast and reliable transfer of emergency warning messages in case of an unexpected event such as a traffic accident. The proposed scheme utilizes local vehicle speed measurements to adapt to changing traffic conditions and maintain good performance independent of the traffic state. The scheme is shown through extensive simulations to satisfy its design objectives in a variety of conditions and settings. Our contributions, however, go beyond the proposal of a new protocol and includes valuable observations and tools which have emerged from the overall design procedure. The main contributions are summarized below:

- Our main contribution has been the development of a new multi-hop broadcast scheme for vehicular ad hoc networks which takes advantage of traffic information within the transportation network to efficiently disseminate critical messages in a specific area around an unexpected event. Similar to other approaches which appear in the literature, the scheme mitigates the broadcast storm problem by restricting the number of neighbors rebroadcasting the critical message. However, the latter is achieved by employing a novel technique which decides on the set of neighbors rebroadcasting the critical message taking into account the current traffic state, which is dictated by the vehicle speed, and specific characteristics of the freeway topology where the dissemination process takes place, which are expressed by speed-density curves obtained from past data. The scheme mitigates the broadcast storm problem by employing adaptive probabilistic flooding. Each vehicle upon receiving the critical message decides to rebroadcast the message with probability p and not to rebroadcast the message with probability 1-p. A unique feature of the proposed scheme is that the probability p is determined based on the speed of each vehicle. The reasoning behind this design choice is that low vehicle speeds in a freeway setting imply large vehicle densities and thus low rebroadcast probabilities suffice to achieve high reachability. For this reason we refer to the proposed scheme as SAPF (Speed Adaptive Probabilistic Flooding).

- The proposed scheme enjoys a number of benefits such as:
    - It is decentralized and simple to implement.
    - It does not introduce additional communication burden, as it relies on local information only (the vehicle speed). It is totally distributed and besides the dissemination of the critical message, it does not require any exchange of messages (zero overhead).
    - It does not rely on the existence of a positioning system which requires significant additional exchange of beacon messages for mutual awareness. Furthermore, a GPS device may not always be available and functioning.
    - It mitigates the effect of the broadcast storm problem, typical when utilizing blind flooding, or similar approaches, in a freeway setting.
- Another contribution has been the verification of the existence of phase transition phenomena when probabilistic flooding is employed in vehicular ad hoc networks and the utilization of these phenomena in the design of the proposed SAPF algorithm. The existence of phase transition phenomena in unstructured mobile ad hoc networks has been shown in literature, however, their existence in VANETs which are structured by the roadway network has so far been unexplored. We have shown through simulations that for a specific vehicle density, as we increase the rebroadcast probability there exists a threshold value beyond which the achieved reachability is close to 100%. This threshold value is the desired rebroadcast probability for the proposed probabilistic flooding scheme as it achieves the highest possible reachability with the minimum number of messages exchanged. However, for different vehicle densities within the transportation network the threshold probability changes. One way to estimate the average vehicle density is via a beaconing system which notifies each vehicle of its neighbors. However, such an approach adds significant communication burden

and so in this work we adopt a novel approach which estimates the vehicle density via speed density curves which are readily available. For a specific road topology, one can use real time measurements to obtain speed density curves which can then be used to map the speed of each vehicle to the traffic density. In this way each vehicle can decide the rebroadcast probability based on the vehicle speed. Through simulations we have shown that a scheme designed for a 4-lane freeway topology is robust and insensitive to changes in the number of lanes (2 to 5 lane freeways were tested).

- Another major contribution of this thesis has been the development of a new simulation environment which has been used to evaluate the proposed SAPF scheme in a variety of settings. This environment has been developed by appropriately interfacing the OPNET simulator with the VISSIM simulator . A number of custom simulators have been developed in the literature specifically for VANETS, however, these simulators fail to implement in detail both the full network behavior and the traffic and driver behavior. In this work we use OPNET, a powerful communication network simulator and VISSIM, a road powerful traffic simulator which is able to provide realistic vehicle traces at both the microscopic and macroscopic level. These well established simulators are combined in a platform which can be used in the design of a number of protocols for VANETs. The interfacing of the two simulators involves the development of appropriate script code which automates the procedure of feeding the vehicle traces extracted from VISSIM into the OPNET simulator, for simulation of the communication networking aspects of the combined system.

1.3.1 Publications

In this section, we provide a complete list of publications and submissions stemming from the work in this thesis.

- Mylonas Y., Lestas M., Pitsillides A. and Ioannou P., Speed Adaptive Probabilistic Flooding for Vehicular Ad-Hoc Networks, IEEE Computer Communications. June 2010. Submitted.
- Mylonas Y., Lestas M., Xeros A., Andreou M., and Pitsillides A., ”Probabilistic Information Dissemination in Vehicular Ad Hoc Networks”, Book Chapter in Advances in Vehicular Ad-Hoc Networks: Developments and Challenges (edited by Prof. Mohamed K. Watfa), by IGI Global, ISBN13: 9781615209132, June 2010.
- Mylonas Y., Lestas M. and Pitsillides A., ”Speed Adaptive Probabilistic Flooding in Cooperative Emergency Warning”, Proc. First International Workshop on Wireless Vehicular Networking (VINT-08), held in conjunction with The Fourth Annual International Wireless Internet Conference (WICON 2008), Maui, Hawaii, November 17-19, 2008.
- Mylonas Y., Pitsillides A. and Lestas M., ”Speed Adaptive Probabilistic Flooding in VANETs”, Proc. International Trade And Freight Transportation Conference (ITFTC2008), Ayia Napa, Cyprus, September 1-2, 2008, pp. 66-73.
- Mylonas Y., Pitsillides A. and Lestas M., ”Probabilistic Flooding in VANETs”, In Proc. OPNETWORKS2008, Washington, DC, USA, August 25-29, 2008.
- Mylonas Y., Pitsillides A. and Lestas M., ”Probabilistic Flooding Scheme in VANETs”, In Proc. 1st Cyprus Workshop on signal Processing and Informatics, Nicosia, Cyprus, July 8, 2008.

1.4 Thesis Overview

The current thesis is organized in the following manner: In Chapter 2, we introduce the VANETs area by discussing the evolution of the Intelligent Transportation Systems (ITS), then we discuss the different categories of the VANETs' applications, and subsequently we show the ITS communication architecture. Thereafter we discuss data dissemination methods for VANETs, and we present the related work in the area of data dissemination in VANETs. In Chapter 3, we present the rationale behind our design choices and the adopted design methodology that has been used to develop the SAPF algorithm. In Chapter 4, we evaluate the performance of the proposed system with respect to different number of lanes, to different number of hops, to different transmission range, to different speed limits of the freeways, and to a bi-directional traffic topology, comparing performance to Blind Flooding. Furthermore, we compare the SAPF algorithm with GPS-based algorithms using simulations. Finally in Chapter 5 we offer our conclusions and future research directions.

Chapter 2

Background and Related Works

In this chapter, we introduce the VANETs area by discussing the evolution of Intelligent Transportation Systems (ITS), then we discuss the different categories of VANET applications, and subsequently we show the ITS communication architecture. Thereafter we discuss data dissemination methods in VANETs, we present the related work in the area of data dissemination in VANETs, and discuss appealing solution approaches.

2.1 The Evolution of ITS

In 1991, it was assigned to the U.S Department of Transportation (DOT) the program Intelligent Vehicle Highway Systems (IVHS). IVHS goals were to increase safety, ameliorate congestion, reduce pollution and conserve fossils fuel while vehicles use the transportation system of the nation. With the help of the Intelligent Transportation Society of America (ITSA) a non-profit organization whose members come from academia and industry, they developed a procedural framework wherein IVHS services could be systematically planned, defined and integrated. National Intelligent Transportation Systems Architectures (NITSA) is using this framework as a master plan for the ITS initiatives for the past 13 years. In 1997, the ITSA requested from the

Federal communication (FCC) 75 MHz bandwidth in the 5.9 GHz band, with the specific goal of supporting dedicated short range communications (DSRC) for ITS. In October of 1999 the petition was granted by FCC, which licensed the DSRC to use the frequency spectrum of 5.85-5.925GHz, 75MHz range. In the time frame of 2003-2004, FCC adopted the recommendation of the ITSA to use a single standard for the physical and medium access control layers of the architecture. The recommendation was to adopt an architecture that was based on 802.11 [5] and was developed by the American Society for Testing and Materials the (ASTM) E2213-02 [6]. After the adoption of the E2213-02 the IEEE task group, TGp, started modifying this standardization to support the needs of the transportation systems. The outcome of this work was named IEEE802.11p [7]. Furthermore another team, WG 1609, has under taken the task of developing specifications to append more layers in the protocol suite. The IEEE 1609 standard consists of four documents IEEE 1609.1 [8], IEEE 1609.2 [9], IEEE 1609.3 [10], and IEEE 1609.4 [11]. Since both standards, the IEEE802.11p and IEEE1609.x, are used to facilitate the provision of wireless access in vehicular environment, the acronym WAVE is used to refer to both of the standards. The IEEE 802.11p working group is working on the amendment of the 802.11p, and according to the official web page of the IEEE802.11p, it is scheduled to be released by November 2010. In Europe, the Architecture Task Force group worked closely with Car2Car Communication Consortium [12] and other standardization bodies such as the Internet Engineering Task Force (IETF) [13] and the International Standards Organization (ISO) [14] to prepare a European standard (see Fig. 1) to be submitted to the European Telecommunication Standards Institute (ETSI) [15]. The first public version of the document named ”The European ITS Communication Architecture” was published in October of 2008. It entails an overview of the basics of the ITS architecture in Europe that was applied by a new research project named PREparation for DRIVing implementation and Evaluation (PRE-DRIVE C2X) [16].

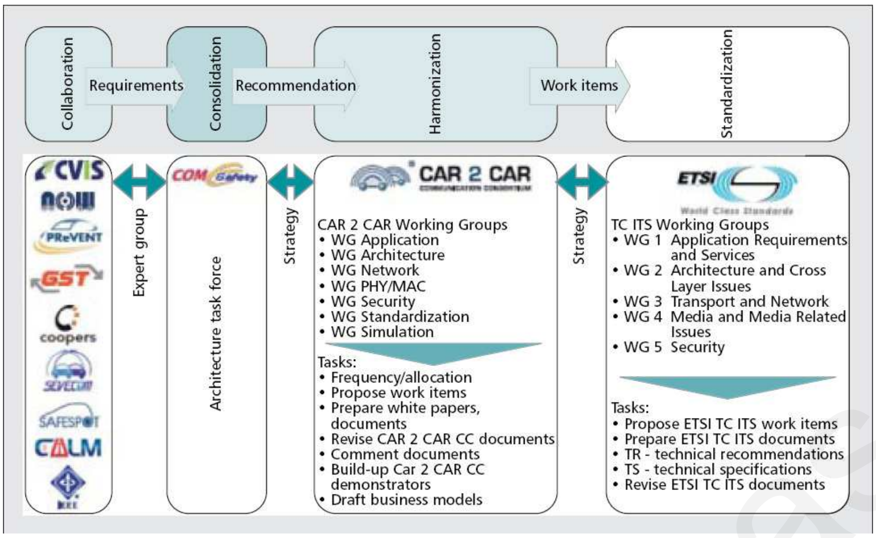


Figure 1: European consolidation, harmonization and standardization of cooperative ITS systems [47].

2.2 Applications in VANETs

The need to reduce traffic accidents, lower the time spent in a congested traffic, and offer comfort and entertainment to passengers and driver, has led to the development of a broad range of applications. In this section, we provide an overview and a categorization of the vehicular ad hoc network applications. Several researchers worked on categorizing and analyzing VANET applications [51]-[69], based on the aim of the application. VANET applications could be categorized in four categories: active safety, public service, improved driving, and business or entertainment applications. Considering the active safety category, imagine the following scenario: In a freeway setting with a moderate traffic, a vehicle with 4 passengers (vehicle C) is following a truck (vehicle B) with a speed of 100km/h. Suddenly a vehicle (vehicle A) which is ahead of the truck hits the breaks hard to avoid an obstacle/accident in the freeway. The truck driver manages to bring its truck to a complete stop avoiding to collide with vehicle A. Unfortunately, the driver of vehicle C collides with truck due to a limited visibility and not having enough time to react on time. This is what would have happened in a traditional transportation systems. Now imagine exactly the same scenario but with each vehicle equipped with an on board unit (OBU) which will enable a wireless communication among vehicles. In this case, at the time the driver of vehicle A hits the breaks hard, immediately a message is generated and transmitted to all approaching vehicles, including vehicle C, where the driver of vehicle C will have more warning so as attempt to bring his vehicle to a complete stop, thus avoiding the collision with the truck. At worst if the driver of the vehicle C does not manage to bring his vehicle to a complete stop, then the OBU would have prepared the vehicle for collision, lowering the risk of serious injuries. The precrash sensors would have taken measurements and actions such as raising the windows up, seats stiffen, seatbelts pre-tension, raising dampers, and enable the pre-crash brake assist. Another scenario is where a driver doesn't stop at traffic lights with a RED signal. In this case the vehicle could have communicated with the traffic light sensors and brought the vehicle to stop, or inform the other vehicles at the cross section to be aware of the danger that is approaching. These type of applications fall under the **Active Safety** category, and will form the main focus for the thesis.

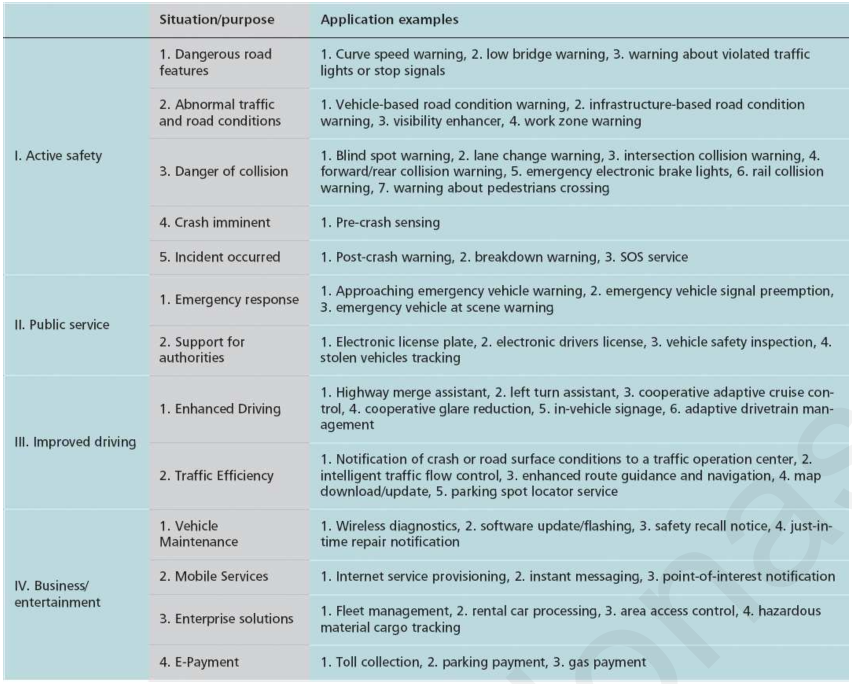
An extension of the above scenario is the postcrash scenario which takes place right after the accident. In postcrash scenario an extra step is taken to inform emergency public services such as the Police Department, the Fire Department and the closest Hospital/Ambulance the soonest possible, providing the exact location of the emergency. Sometimes valuable time is wasted to explain where the accident has taken place and the severity of the accident. These problems can be minimized by the OBU of the vehicles which will immediately inform these departments and even make an assessment of the seriousness of the accident based on the impact of the accident. The emergency vehicles will arrive to the scene the soonest possible by choosing a route with the least traffic possible, by controlling the traffic lights ahead of time to have priority and by warning the surrounding drivers that an emergency vehicle is approaching with an indication in the computer on board of their vehicle. Another scenario is where a catastrophic physical disaster is approaching and there is a need to evacuate a certain geographic area or a city. All these applications fall under the same category of the **Public Service** category.

The next category is the **Improved Driving** category where the applications that fall in this category assist the driver to enjoy and enhance his/her driving experience. For instance, informing the driver that a vehicle is approaching from a merging lane, assisting the driver to give a priority to the approaching vehicle, or be cautious of the vehicle. On the same time, the driver is informed in advance to avoid certain freeways due to traffic jams or road hazards while offering an alternative route. Another service is to provide information whether there is a parking availability providing the location of the free spots in the parking and even offer the option to make a reservation in advance.

Lately, the **Mobile Bussiness/Entertainment** category include applications which provide information services to the drivers. For instance: the driver may choose to download any kind of music that the children may like to listen, while he enjoys the journey with his/her family; the passengers may download a movie and watch it until they reach their destination; toll fee payments or payments for parking without having to use cash; receiving an advertisement whenever the driver enters a new area regarding restaurants' offers, and the driver may choose the best deal. Fig. 2 shows an overview for VANETs applications' categorization, and Fig. 3 shows an integrated scenario of ITS.

2.3 ITS Communication Architecture

In this section, we analyze the ITS communication architecture and present how the components of this architecture could be used to form an ITS network. There are four main units of the ITS architecture: the vehicles, the roadside equipment, the central equipment and the personal devices. For the formation of an ITS network these units must have an ITS station which will



	Situation/purpose	Application examples
I. Active safety	1. Dangerous road features	1. Curve speed warning, 2. low bridge warning, 3. warning about violated traffic lights or stop signals
	2. Abnormal traffic and road conditions	1. Vehicle-based road condition warning, 2. infrastructure-based road condition warning, 3. visibility enhancer, 4. work zone warning
	3. Danger of collision	1. Blind spot warning, 2. lane change warning, 3. intersection collision warning, 4. forward/rear collision warning, 5. emergency electronic brake lights, 6. rail collision warning, 7. warning about pedestrians crossing
	4. Crash imminent	1. Pre-crash sensing
	5. Incident occurred	1. Post-crash warning, 2. breakdown warning, 3. SOS service
II. Public service	1. Emergency response	1. Approaching emergency vehicle warning, 2. emergency vehicle signal preemption, 3. emergency vehicle at scene warning
	2. Support for authorities	1. Electronic license plate, 2. electronic drivers license, 3. vehicle safety inspection, 4. stolen vehicles tracking
III. Improved driving	1. Enhanced Driving	1. Highway merge assistant, 2. left turn assistant, 3. cooperative adaptive cruise control, 4. cooperative glare reduction, 5. in-vehicle signage, 6. adaptive drivetrain management
	2. Traffic Efficiency	1. Notification of crash or road surface conditions to a traffic operation center, 2. intelligent traffic flow control, 3. enhanced route guidance and navigation, 4. map download/update, 5. parking spot locator service
IV. Business/ entertainment	1. Vehicle Maintenance	1. Wireless diagnostics, 2. software update/flashing, 3. safety recall notice, 4. just-in-time repair notification
	2. Mobile Services	1. Internet service provisioning, 2. instant messaging, 3. point-of-interest notification
	3. Enterprise solutions	1. Fleet management, 2. rental car processing, 3. area access control, 4. hazardous material cargo tracking
	4. E-Payment	1. Toll collection, 2. parking payment, 3. gas payment

Figure 2: Overview of applications for VANETs [62].

provide the means for communication among the units. Furthermore some of the units may also have a gateway component which is used to communicate with legacy systems. There are different types of communications that could be established such as: vehicle to vehicle and vehicle to infrastructure whether the communication takes place directly or indirectly. Since there are various versions of the ITS architecture we will briefly present the generic communication schemes that apply for almost all the architectures and later we will concentrate on the WAVE architecture which appears to be more mature at the moment.

2.3.1 Central Unit

The Central Unit, could be a remote site where an organization is providing services to mobile users. These services could be any of the aforementioned services we discussed in section 2.2.1. A typical example of a central unit could be a traffic management center controlling roadside

Figure 3: ETSI TC ITS scenario [47].

infrastructure, or an even advertisement company that uses the roadside infrastructure to advertise to mobile users based on their location.

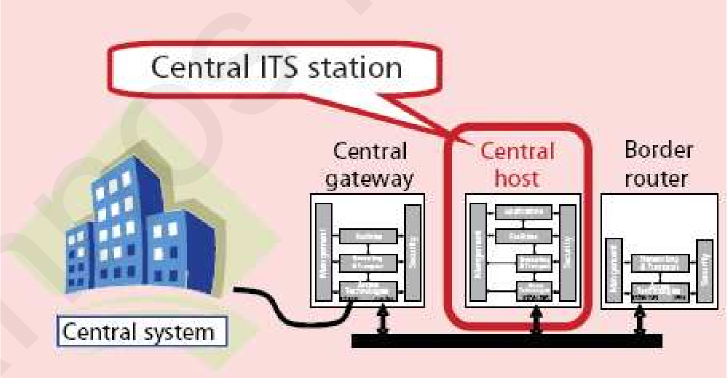
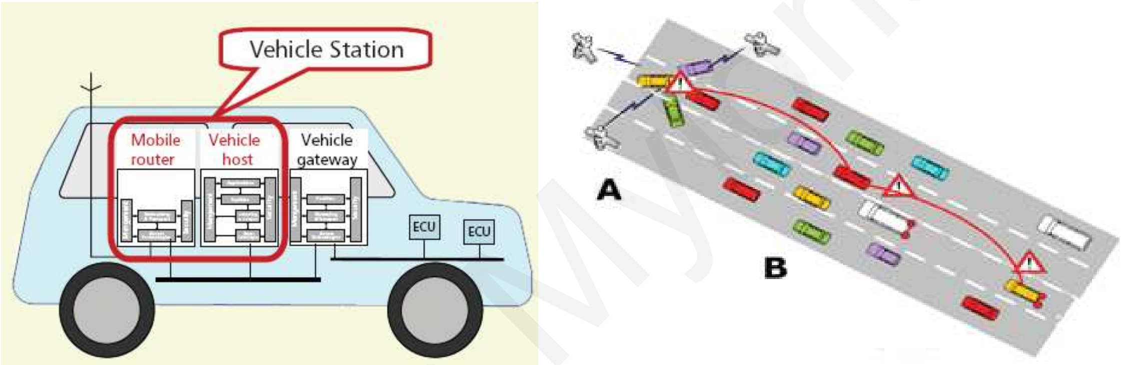


Figure 4: ETSI TC ITS scenario [47].

2.3.2 Vehicle to Vehicle Communication

For a vehicle to participate in any kind of ITS network it must have an onboard unit (OBU) which is responsible for the wireless communication with other vehicles and roadside units. The

OBU collects data from other vehicles for later exploitation or provides access to wireless Internet. The vehicle may obtain information or services from a central unit, which is located at a remote site and where the applications and services are located. A vehicle may have different functions/services to operate at once; the way it handles this is by splitting its task to several different physical nodes which communicate among them over a local area network, see Fig. 5. A coordinator for the communication of these nodes is the mobile router which is embedded in the ITS station and it is responsible for the communication of the vehicle with other vehicles or with the infrastructure, see Fig. 6. In this thesis we focus on vehicle to vehicle communication.



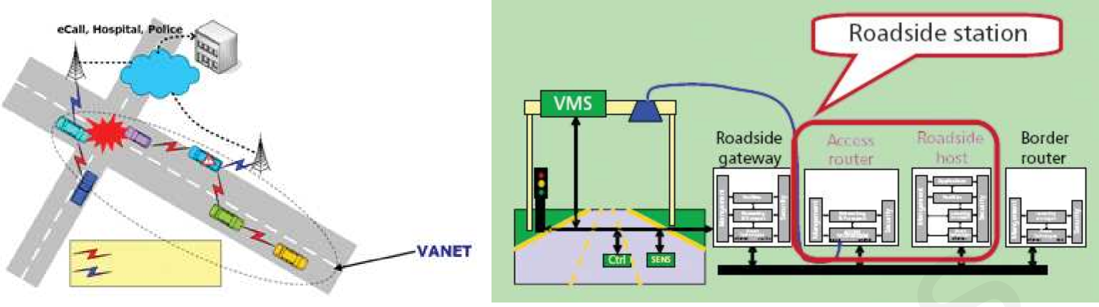
(a) Vehicle: Internal architecture of an ITS vehicle.

(b) Vehicle to Vehicle communication at the event of a traffic accident.

Figure 5: Internal architecture of the ITS vehicle and its application in real life [47].

2.3.3 Vehicle to Infrastructure Communication

Roadside units are located either along the freeway every few kilometers or at different locations in a city such as traffic lights, toll payments, cameras etc. In either case, the roadside units are equipped with hardware to communicate with vehicles and the central units. The vehicle to infrastructure (V2I) communication takes place through the wireless communication unit either directly or indirectly through multi hops. A Roadside unit could be used as a gateway to access various services from a central unit or Internet services. Furthermore roadside units support variable message signs (VMSs), see Fig. 6.



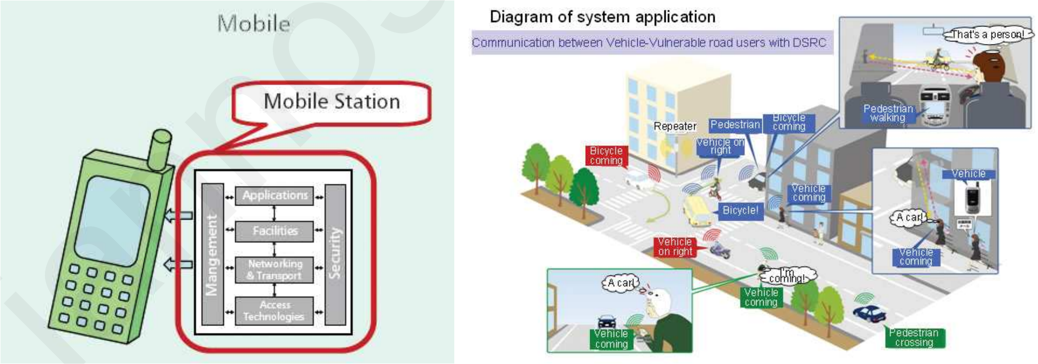
(a) Vehicle: Vehicle to Infrastructure communication

(b) roadside station and its internal architecture.

Figure 6: Internal architecture of the the roadside unit and its application in real life [47].

2.3.4 Personal Device

Personal device could be a PDA, a Mobile Phone or a Global Positioning System which could be part of the intelligent transportation network and may assist the drivers or pedestrians for better and safer driving experience, see Fig. 7.



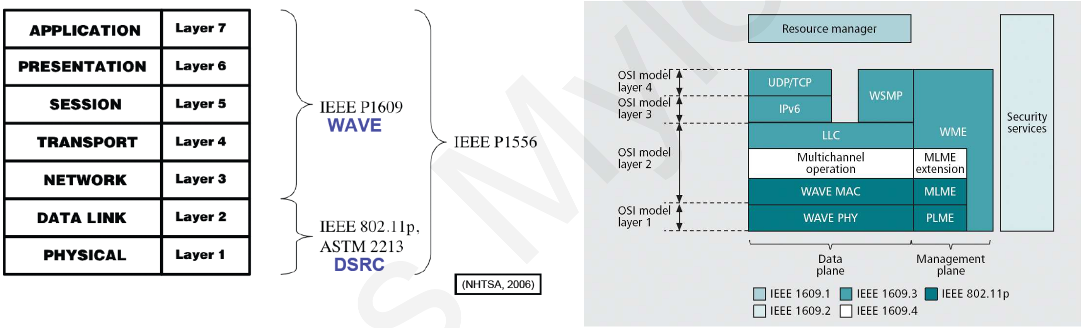
(a) Mobile Device: Mobile Station Architecture.

(b) Pedestrian is alerted for a possible danger.

Figure 7: Internal architecture of the mobile device and its application in real life [47].

2.4 WAVE System Architecture

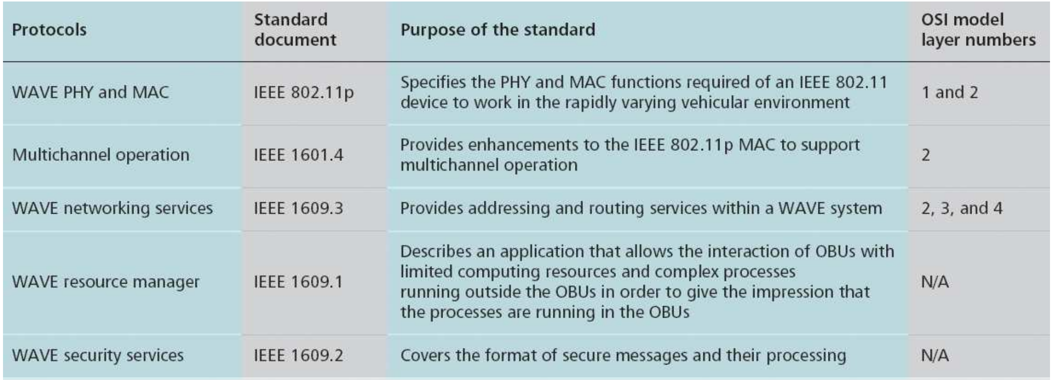
The WAVE architecture contains similar units as the ones described above. Although to form a small vehicular ad hoc network using the WAVE architecture one needs a WAVE basic service set (WBSS), which is similar to the service sets that are used in the 802.11. The members of the network could exchange information among them or through the roadside unit using one of their radio channels known as service chancels (SCHs). There are two protocols stacks for the WAVE architecture, the traditional Internet Protocols version six (IPv6) and the WAVE Short-Message Protocol (WSMP); both protocols use the same physical and data link layer but differ on transport and network layer, see Fig. 8.



(a) Protocol Stack for ITS. (b) WAVE communication stack.

Figure 8: The protocol Stack of the ITS communication

Fig. 8a shows the protocol stack of the ITS architecture which consists of the IEEEP1609 and the IEEE802.11p. The IEEE1609, commonly known of WAVE, represents the layers 3 through 7 and the IEEE802.11p the layer 1 and 2, which represent the physical and the data link layer. The Fig. 8b shows the architecture of the Wave communication stack of the IEEE1609 which has four components the IEEE1609.1, IEEE1609.2, IEEE1609.3 and IEEE1609.4 where each one is responsible for the following services: the WAVE security services, the WAVE resource manager, the WAVE networking services and the Multichannel operation respectively; see Fig.9.



Protocols	Standard document	Purpose of the standard	OSI model layer numbers
WAVE PHY and MAC	IEEE 802.11p	Specifies the PHY and MAC functions required of an IEEE 802.11 device to work in the rapidly varying vehicular environment	1 and 2
Multichannel operation	IEEE 1601.4	Provides enhancements to the IEEE 802.11p MAC to support multichannel operation	2
WAVE networking services	IEEE 1609.3	Provides addressing and routing services within a WAVE system	2, 3, and 4
WAVE resource manager	IEEE 1609.1	Describes an application that allows the interaction of OBUs with limited computing resources and complex processes running outside the OBUs in order to give the impression that the processes are running in the OBUs	N/A
WAVE security services	IEEE 1609.2	Covers the format of secure messages and their processing	N/A

Figure 9: The protocols of the WAVE communication stack

The necessity for two protocols was driven by the aforementioned applications which have different requirements and needs to be satisfied by the underlay network. The WSMP protocol is used for time sensitive applications which can not tolerate large delays. Based on the specification of the WAVE, units may split the time of transmitting between the service channels and the control channels. This is specified in the IEEE 1609.4 and it is implemented in the OSI layer two. The physical and the data link layer has similar properties as the 802.11a which was the predecessor of the 802.11p. The main requirements and characteristics of the 802.11p are listed in Table 1.

Table 1: 802.11p requirement and characteristics

- communications in a highly mobile environment
- 10-MHz channels; one-half the data rates of 802.11
- Control channel and six service channels
- Unique ad hoc mode
- Random MAC address
- High accuracy for the received signal strength indication (RSSI)
- 16 QAM used in the high-speed mobile enviroment
- Spectral mask modification
- Option for more severe operating enviroment
- Priority Control
- Power Control

The IEEE1609.4 protocol provides the means to the WAVE device MAC layer to support multichannel operation using one control channel and multiple service channels for its needs. Based on the standard IEEE1609.4 [11] there are four services, the channel routing, user priority, channel coordination, and the MSDU data transfer, which are managing the channel coordination and supporting MAC service data unit (MSDU) delivery. The networking services are defined in the standard IEEE1609.3 [10] which are represented by the IEEE1609.3 protocol. The WAVE networking services are broken into two categories the Data-plane services and the Management-Plane services. It is at the data-plane where the IPv6 and the WSMP protocol are implemented. The data-plane is responsible for carrying the traffic for emergency application and traditional applications such as http, FTP, and etc. For the emergency applications the WSMP protocol is used and for the traditional applications the IPv6 protocol is used. The Management-Plane services are specified in IEEE1609.3 and Table 2 shows the services that are included.

Table 2: Management-Plane Services

- Application registration
- WBSS management
- Channel usage monitoring
- IPv6 configuration
- Received channel power indicator (RCPI) monitoring
- Management information base (MIB) maintenance

The Resource Manager (RM) is defined in the IEEE1609.1 [8] whose job is to provide access to certain processes to the system communication resources. The RM could be installed in OBU or in a roadside unit. The applications which run on the mobile device units and are located remotely from its hosts are called resource management applications (RMAs) whose goal is to use the resource of one or more OBUs. The RM acts as a mediator to relay commands and responses between the OBUs and RMAs.

The protocol WAVE security services is defined in the IEEE1609.2 and it is responsible for the security and processing of the secure messages of the ITS network. It is crucial to secure the V2V communication and V2I communication from potential threads such as eavesdropping, spoofing, alternation and replay attacks. However any secure mechanisms that will be used must be flexible, scalable and maintain low overhead over the network. There are mechanisms that ensure the confidentiality and the authenticity and integrity of the messages.

2.5 Data Dissemination in Mobile Networks

Based on the aforementioned applications of VANETs, and especially safety applications, it is evident that it's crucial to disseminate the information as quickly as possible, and to as many interested vehicles as possible, regardless of the volume density and the mobility pattern of the vehicles. Therefore, the dissemination method that will be used to propagate the information in the network must have the ability to propagate the information to a given area of interest. This could be achieved, either by having a high power transmission allowing us to transmit the information to the given area of interest with one hop transmission, or maintaining low power transmission propagating the information through intermediate/forwarding nodes, which is called multi-hop data dissemination method. The simplest approach is to disseminate the information in one hop transmission over a large area, however, due to the high electromagnetic radiation fields caused by high power transmission communication, the use high power communication is prohibited since it may cause health problems to human life, in addition to higher interference to other users. Also, in terms of total power consumed, it can be shown that multi-hop communication can be more efficient (recall inverse distance power law). Therefore, we adopt multi-hop data dissemination despite its complexity and increased diffusion delay and perhaps reduced reachability and increased delay. The interplay between increased power vs. multi-hop is interesting and will form a subject of further study. VANETs due to their topology have the ability to use multi-hop data dissemination which extends the network coverage beyond the one hop, by enabling intermediate nodes to act as a relay nodes, to retransmit the information to the rest of the network.

Multi-hop data dissemination and dissemination methods in general are used and encountered in our daily life basis and have demonstrated their ability to spread the information quickly over a large area. A recent prominent example is the ”virus dissemination” and more specifically the swine flu. Not long ago, the first outbreak of swine flu (H1N1) [17] was reported in Veracruz, Mexico, in April 2009. Despite the efforts of the Mexican government to confine the virus in the country, the virus continued to spread globally and kept spreading worldwide. As has been expected, a few months after, H1N1 has been reported in Cyprus, despite the fact that Cyprus is 12000 kilometers away from the city of Veracruz. H1N1 has been spreading so fast over a large worldwide area, due to its ability to traverse from person to person, transmitting the disease. The virus is transmitted from person to person through coughing or sneezing by people with H1N1 (hop-to-hop). Therefore, travelers from Mexico who had the H1N1 have disseminated the virus to other countries, where each contaminated person carried its virus to other persons, either colleagues or family, as he/she moved from place to place, and so on. Two contributing factors for the rapid explosion of the virus is the human mobility and human density. The question now is how is ”virus dissemination” related to computer networks? As in our example above, we have a patient who is sick and disseminates the virus to other people, the same analogy could be made in computer networks. The sick person is represented by the source node which carries the information that we want to disseminate across the network, and the people who are contaminated are represented by the routers or the intermediate nodes that act as relay nodes to propagate the information in the network. In the flooding approach of data dissemination, the sender node transmits the data to its neighbors, where each of its neighbors retransmits the data to its neighbors and so on. VANETs and H1N1 example have some common characteristics, such as high degree of mobility and different level of densities, which affect how quickly the information will be propagated over a geographic area [73]. Consequently multi-hop data dissemination method is promising and has a lot to offer in the VANETs case.

To establish a communication among two vehicles which are further apart than one hop transmission range, in order to support multi-hop data dissemination, an intermediate node is required to act as a relay node or forwarding node. The process of finding this intermediate node(s) is accomplished by a data dissemination algorithm or a routing protocol. However, before this process can take place each vehicle in the network should have a unique address so that it can be reachable, by any other vehicle in the network or through an access point. Usually, this procedure is underestimated and assumed that it can be done in negligible time. However, at times this may not be correct, as shown by Bychkovsky et al. [33], lifetime of a connection in a city setting varied from 5 to 24 seconds and may waste from 12.5% to 60% of the time to obtain an address. There are several studies aiming to address this problem, as for example [26] and [40].

A common approach for supporting multi-hop data dissemination is to assume: first the knowledge of node locations, and second a method of forwarding packets towards their destination. The first requirement can be achieved by using a Global Positioning System (GPS) and exchanging their locations through beacons. The second requirement can be accomplished either through broadcasting techniques such as flooding, or using a routing protocol (which will maintain the network topology and forward the packets via, shortest path' to the destination(s)) or by a combination of the location service and a method of forwarding packets [67]. It is worth noting that a global positioning system beyond the high signalling requires to exchange location information, it must also offer the following key characteristics: availability anytime and anywhere, high accuracy of position and high reliability.

Most of the dissemination and routing algorithms that have been proposed are taking advantage of localization techniques to find the physical location of vehicles that reside in the network

[67], [71] and [27]. Then each forwarding vehicle could easily make a decision as to which vehicle could be the next hop. This is accomplished by refereing to its neighborhood table, a table which includes all the vehicles that reside in one hop transmission including the physical location of each vehicle, thus locating the vehicle which is closest to the destination. This approach can potentially extends, the coverage and reduce unnecessary retransmissions. However, beyond the high signalling overhead, GPS systems do not come without deficiencies. The current GPS units are not very accurate, with an error of 10 to 30 meters, and not reliable to provide services in all locations such as tunnels, and city settings with tall buildings. Based on the above reasoning, GPS alone is not the best solution for emergency applications. GPS could be used for obtaining an approximate location of a vehicle but not for emergency applications, which needs a quick response, with low signalling overhead as well as much higher accuracy, see Fig. 11a. For applications that require a very accurate position of a vehicle a GPS could be used along with some other techniques such as Dead Reckoning, Image/Video Localization, MAP Matching, Wireless Sensors or even Cellular Localization [30], see Fig.10. In addition, Differential GPS (DGPS) which uses a known fixed location as a reference point can reduce its error to less than a meter. A comparison of these techniques is presented in Fig. 11b. It is apparent from the figure that none of the existing

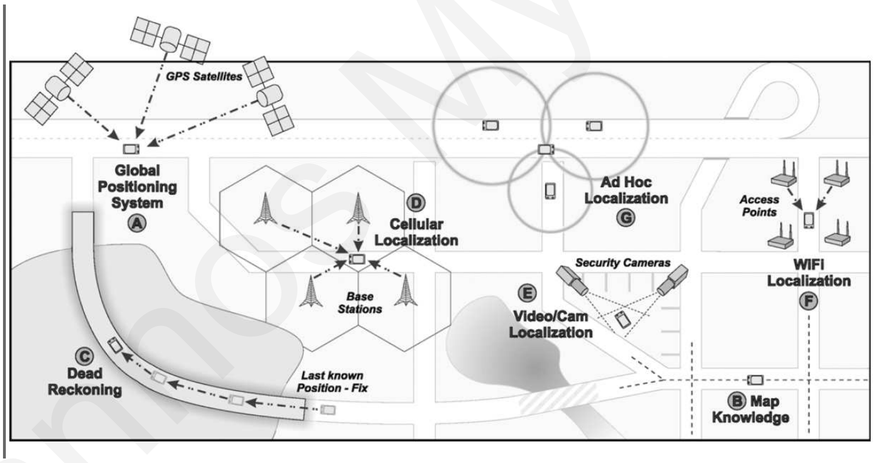
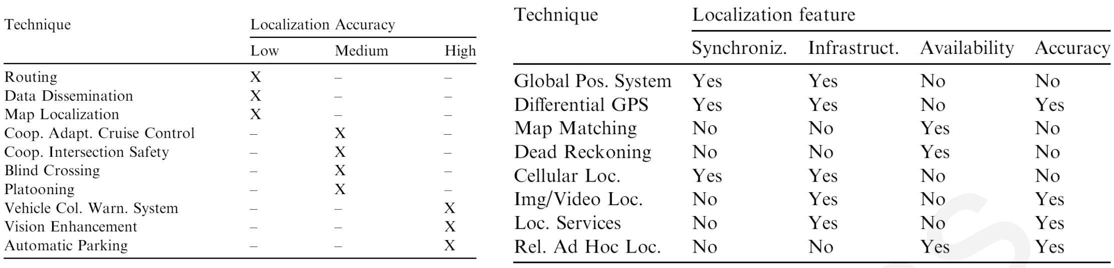


Figure 10: Localization techniques applied in VANETs[30].

techniques independently could satisfy the requirements of the critical safety applications. Some of the key characteristics that the localization technique must offer are to be available anytime and anywhere, have high accuracy of position and have high reliability.



Technique	Localization Accuracy		
	Low	Medium	High
Routing	X	–	–
Data Dissemination	X	–	–
Map Localization	X	–	–
Coop. Adapt. Cruise Control	–	X	–
Coop. Intersection Safety	–	X	–
Blind Crossing	–	X	–
Platooning	–	X	–
Vehicle Col. Warn. System	–	–	X
Vision Enhancement	–	–	X
Automatic Parking	–	–	X

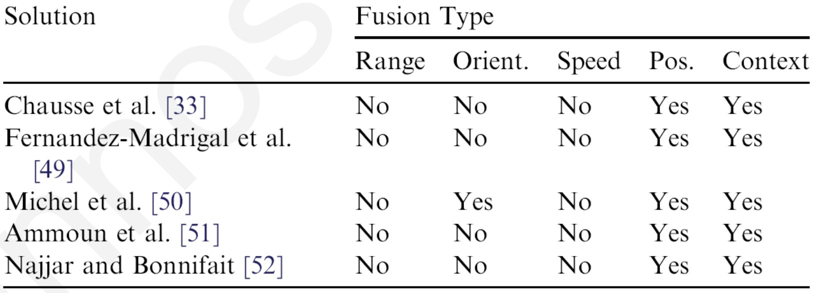
(a) Level of accuracy needed by VANETs' applications

Technique	Localization feature			
	Synchroniz.	Infrastruct.	Availability	Accuracy
Global Pos. System	Yes	Yes	No	No
Differential GPS	Yes	Yes	No	Yes
Map Matching	No	No	Yes	No
Dead Reckoning	No	No	Yes	No
Cellular Loc.	Yes	Yes	No	No
Img/Video Loc.	No	Yes	No	Yes
Loc. Services	No	Yes	No	Yes
Rel. Ad Hoc Loc.	No	No	Yes	Yes

(b) Comparison of the Localization techniques

Figure 11: Localization Techniques for VANETs [30]

A combination of these techniques, also using advanced Data Fusion techniques such as Kalman and Particle Filter can enhance the accuracy of the vehicle position [30]. Fig. 12 depicts a summary of the solutions of the Data Fusion techniques; for further information for data fusion techniques the reader could refer to the article by A. Boukerche et al.,[30].



Solution	Fusion Type				
	Range	Orient.	Speed	Pos.	Context
Chausse et al. [33]	No	No	No	Yes	Yes
Fernandez-Madrigal et al. [49]	No	No	No	Yes	Yes
Michel et al. [50]	No	Yes	No	Yes	Yes
Ammoun et al. [51]	No	No	No	Yes	Yes
Najjar and Bonnifait [52]	No	No	No	Yes	Yes

Figure 12: A summary of data fusions solutions for Localizations VANETs[30].

It is apparent that due to the high signalling overhead, and as well as the limited availability of GPS systems in vehicles and due to the challenges and deficiencies the common GPS systems have demonstrated in [30] its use in a dissemination scheme may be problematic. In this thesis, we aim to propose, a new multi-hop broadcasting scheme, which should have the following characteristics:

1) does not rely on the existence of a positioning system, 2) it is traffic aware, and 3) all decisions are made locally without needing any external information.

2.6 Related Work

The existing bibliography on VANETs may be categorized, into three categories Unicast, Multicast, and Broadcast data dissemination methods. Unicast method is the process to find a path from a source to a destination in VANETs, and to exchange information only between them. Secondly the Multicast method is a process for delivering information from a source to multi recipients. The recipients must be a member of a multicast group to receive data from the source. In Broadcast method the source broadcasts the information to all vehicles in its transmission range. All three methods are depicted in Fig. 13. Furthermore one can identify three subcategories for each category: simplistic routing, Geographic Routing and Geocasting routing. The subcategories are divided based on the methodology used to find the delivery path for each algorithm. Under the subcategory of Simplistic Dissemination we include the fundamental and simple algorithms which do not use any global positioning systems. The second subcategory is the Geographical Dissemination where algorithms that fall under this category use a global positioning system, or other means, to acquire the position of the vehicles in the network in order to discover valid path towards the destination. The third subcategory is Geocast Dissemination, Geocast Dissemination is the delivery of Geocast packets inside a geographic area targeting some of the vehicles in this area or all of them. An example of the Geocast dissemination is to disseminate a message inside a geographic area where the message is targeted for only the pedestrians of this area and not the vehicles. The proposed scheme of this thesis can be included in the broadcasting method under the simplicity subcategories. Therefore in this section we concentrate on the literature that uses the broadcasting method for disseminating the information in a VANET.

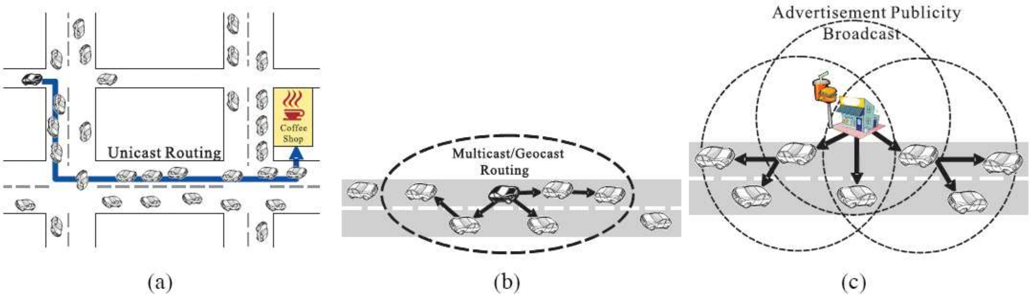


Figure 13: Shows the three basic methods of routing Unicast, Multicast, and Broadcast[71].

2.7 Broadcast Methods

The broadcasting method for information dissemination is much simpler than unicast and multicast methods. Basically, the sender broadcasts the message to all vehicles on the area of interest in the network, through multi-hop communication. Each vehicle that has received the message rebroadcasts the message to the network again until the maximum of the hop count (distance of interest) is reached. Broadcasting is applied in many routing protocols due to its simplicity and its ability to reach a large number of receivers without necessarily knowing their location or the neighbors of the sender. However, the basic flooding type of broadcasting algorithm exhibits the well known Broadcasting Storm problem becoming ineffective in high density VANETs in an emergency situation. The broadcast storm problem occurs when a large number of nodes are trying to rebroadcast the message at the same time causing massive collisions and retransmissions, as a result causing throughput degradation (can affect disseminations) as well as also causing high latencies. This section reviews popular existing solution approaches that address the broadcasting storm problem.

2.7.1 Simplistic Dissemination

The authors in [45] propose two protocols to mitigate the broadcast storm problem. The first protocol is the directional broadcast protocol where the source assigns the vehicle that lies at the outermost of its transmission range to be the rebroadcasting vehicle without knowing any information in advance regarding that vehicle. The second protocol is an intersection broadcast protocol where it handles the intersections forwarding. The first protocol uses an RTS/CTS mechanism to locate and assign the rebroadcasting vehicle. Protocols that use RTS/CTS mechanism cause extra overhead and an increase of the latency values. Therefore, excessive signalling, especially in high congestion areas, such as in an accident zone can seriously degrade the performance of these algorithms.

2.7.2 Geographical Dissemination

Geographical dissemination exploits the nodes' position which may be acquired through a GPS system and disseminates the information to the interested parties only. The main idea in the geographical dissemination is to find the rebroadcasting vehicles, using the geographic coordinates of each vehicle. The geographic coordinates of each vehicle may be disseminated inside the network through beacons or obtained through a location service. Many protocols using this idea were proposed, including:

a) Vector-based Tracking Detection (V-Trade) by Sun et al. [64] is one of the earliest works in broadcasting in VANETs. The authors use a GPS system to select the furtherest vehicle they can reach, given their own location and direction of the road, in order to rebroadcast the information. Due to a massive control overhead that is generated by vehicles to broadcast their location including the traffic of the opposite direction they degrade considerably in performance, especially under high road traffic density.

b) VADD, protocol which was proposed by Zao et al. [72], performs well in various types of topologies. VADD protocol assumes that all vehicles are equipped with a GPS system and with an external static digital which includes traffic statistics such as vehicle speed on the roads and traffic density of the road at various times. VADD uses the carry-and-forward method for data delivery for the case where there are not any wireless channels available. For the case where the carry-and-forward method is used the road with the highest speed limit is chosen. The main objective of the VADD protocol is to disseminate the information with the lowest packet delivery delay. VADD protocol assigns a mode in each packet. The modes are the following: Intersection, Straightway and Destination mode. An appropriate mode is used according to the position of the vehicle which is carrying the packet. For instance, if the packet is approaching an intersection then the packet operates at the Intersection mode, if the vehicle is in a highway where there are only two directions then it is in straightway mode and if the node is approaching the destination then it operates in Destination mode. VADD protocol has several ways to choose the appropriate vehicle for disseminating the information in the network. The methods that are used from VADD protocol are the following: Location First Probe VADD (L-VADD), Direction First Probe (D-VADD), Multi-path Direction First Probe (MD-VADD), and Hybrid Probe VADD (H-VADD). Among all of these methodologies the Hybrid Probe VADD performs better in terms of packet loss, delivery ratio and message delay. However, this scheme can also generate excessive signalling and complexity.

c) Distributed Vehicular Broadcast [65], DV-CAST, protocol is a multi-hop broadcasting position based protocol. The authors have indicated three traffic scenarios in VANETs: dense traffic scenario, regular traffic scenario and sparse traffic scenario. According to the state the vehicle is when a new message is received, the vehicle will act appropriately. For instance if the vehicle is in a freeway where there is sparse traffic it will adopt a carry-and-forward method. In case the vehicle is in dense traffic freeway then it uses Persistence Broadcasting. In the event the vehicle is located in regular dense traffic, then there is a possibility that some of the vehicles can use store-and-forward and some other the Persistence Broadcasting schemes. The DV-CAST protocol requires that each vehicle knows: whether the intended recipient of the message is; whether it is moving in the same direction as the source; whether it is the last vehicle in the group; and whether it is connected with at least one vehicle of the opposite direction. Again this protocol can generate excessive signalling and complexity.

2.7.3 Geocast Dissemination

Geocasting is an extension of the geographic dissemination but instead of addressing a specific nodes address, they address a geographic region. The main objective of Geocasting is to send a message from a sender to a specific geographic region.

a) Briesemeister et al. [32], they proposed a simple geocast algorithm to alleviate the Broadcast Storm Problem. Their idea was to locate the vehicles that reside the furthest away in senders' transmission range and assign one of these vehicles as the forwarding vehicle. The decision of which vehicle will be the forwarding vehicle is taken locally and independently by each vehicle. So each vehicle measures the distance between itself and the sender and uses it to calculate its waiting time before rebroadcasting the message that it has received. If in the meantime the vehicle does not receive the same message again and the waiting time has expired then it rebroadcasts the message. The further the vehicle is from the sender the less waiting time is assigned. The message is discarded after it reaches the maximum number of hops.

b) In [41], the authors propose broadcasting methods for VANETs for emergency information dissemination. The main idea is to disseminate the emergency information only to the vehicles that are affected by the emergency and not to all vehicles in the area. The emergency information contains two categories, the emergency vehicle approach and the traffic accident. In the case of emergency-vehicle-approach, the information should be disseminated in front of the vehicle since only the vehicles that are ahead of the vehicle are affected and need to know that an emergency vehicle is approaching. This is achieved by the emergency vehicle transmitting a broadcast message including its location, forward movement direction, available relay range and available notification range. Utilizing this information they manage to limit the area of disseminating the message. In case of a traffic accident the vehicles of interest are the vehicles behind the accident and using the same method the broadcasting is limited only to the vehicles that are approaching and to the vehicles that reside in that area. The authors have simulated and implemented their methods and confirmed that the broadcast takes place in the desired area.

c) Multi-hop Vehicular Broadcast [56], MHVB, protocol was proposed by Tatsuaki et al., to disseminate emergency information in a VANET using a flooding protocol. MVHB assumes the availability of a positioning system in all vehicles. The idea is that MHVB protocol disseminates the information allowing them to store this information in their local database for later exploitation by the vehicles. MHVB contains two algorithms the Backfire algorithm and the Traffic congestion Detection algorithm. The Backfire algorithm is used to locate the forwarding node that is closest to the destination, by calculating the distance between itself and the sender, and relating this distance as to the time that should wait before it transmits the information. Consequently the further the node is from the source the less time it waits for retransmissions. The Traffic Congestion Detection algorithm is used to find which nodes are located in the middle of the traffic congestion. The vehicles that are located in the middle of the traffic congestion expand their interval of transmitting their own information.

d) The enhanced MHVB [49] is based on MHVB [56] and both are using flooding protocols. The Backfire algorithm of the enhanced MHVB forms a sectorial shape and not a circular as it was in the MHVB. They have added an angle parameter which can be adjusted accordingly to the area to cover. In the enhanced MHVB protocol, a dynamic scheduling algorithm has been added so in case the nodes are further than 200 meters away from the source, they transmit earlier than all other nodes in the network. The results that the authors have obtained from simulations show that enhanced MHVB performs better than the MHVB [49].

In all the algorithms presented above, there is a very high complexity, as well as signalling requirement. In the next section we examine simple solution approaches, with a view to investigate whether they can provide us with effective dissemination.

2.8 Solution approaches based on flooding

As we have discussed earlier, among the leading solutions are those based on flooding and its variants. Our approach will also be based on flooding aiming to design a scheme which has the simplicity of it, whilst offering effective dissemination with minimal overhead. Next we introduce and analyze a number of existing techniques, highlighting some of their problems, before we introduce our approach.

2.8.1 Blind Flooding

A straightforward approach for solving the aforementioned problem is Blind Flooding (BF) [24]. BF is a scheme which involves each vehicle rebroadcasting the emergency warning message whenever it receives it for the first time. However, the ability of BF to fulfil the design requirements is challenged by stressed communication channel conditions in cases of high vehicular traffic densities. BF is known to work effectively in sparse and moderately dense networks [65], however its performance degrades significantly in highly dense networks, where a large number of redundant messages are generated, which may be the case after an accident. This is amplified later in the thesis our comparative evaluations.

2.8.2 Broadcast Storm Problem

A well known problem caused by broadcasting algorithms in wireless communication is the broadcast storm problem [55]. The broadcast storm problem occurs where there is a large number of nodes trying to rebroadcast an emergency warning message causing unnecessary communication packet collisions, increased contention, high latency and an abundant number of redundant messages. These effects challenge the stringent delay requirements of the considered application. Since the considered application lies in the active safety area, immediately after the traffic accident all the endangered vehicles must be informed on time, as discussed earlier in Chapter 3.

2.8.3 Proposed solutions aiming to alleviate the broadcast storm problem

A large number of solutions have been proposed in the literature to mitigate its effects (e.g. [25], [48], [37], [57] , [58], [60], [63], [66] , [36] and [59]). The main idea is to reduce the number of nodes rebroadcasting the message without affecting the total number of nodes receiving the message. Some of the methods that have been proposed by researchers to reduce the number of rebroadcasting vehicles while maintaining high reachability are the following: 1) assigning shorter waiting time prior to rebroadcasting the message to more distance receivers [31], 2) allowing the furthest vehicle within the transmission range of the source to be the only vehicle rebroadcasting the message [46], 3) using a probabilistic method to compute some probability p to probabilisticly choose which vehicles rebroadcast the message. Some of these methods are GPS assisted which require the exchange of periodic messages to discover their neighborhood causing a massive exchange of messages and an extra overhead in the network. The size of the overhead is affected by the periodicity of the hello messages which affects the accuracy of the position held within the database of the neighboring vehicles of the vehicles in the network. The accuracy of the position of the vehicles in these schemes is important in order to avoid stale positions of the vehicles [34], due to hello messages. Stale positions affect the performance of the network since a non existing vehicle will be assigned to propagate an emergency warning message in the network, with an outcome to have large delays. Note that if, the density of the freeway is taken into account before setting the time interval of the hello messages, the number of unnecessary messages will be reduced, since a highly dense freeway the periodicity of hello messages will decrease. Interestingly, none of the proposed solutions estimate the density through the speed of the vehicle. This is an interesting follow up research direction.

2.8.4 Probabilistic Flooding: An appealing solution

Given the discussion in the previous section, it is evident that the probabilistic method is a promising candidate which may comply to the above requirements such as reduce the number of rebroadcasting nodes in the network whilst maintaining high reachability and low latency, under differing road traffic conditions. In order to make the scheme apply equally well to all road traffic conditions, we set out to provide an adaptive algorithm, which will be responsive to the changing road traffic conditions. As a first step towards accomplishing this goal, a key observation is the probable existence of phase transition phenomena in probabilistic flooding. The concept of the **phase transition phenomena** will be discussed and analyzed in depth in the next Chapter, as it forms a cornerstone in the effectiveness of our algorithm.

2.8.5 Concluding Remarks

In this chapter we discussed in great detail the ITS architecture as well as the 802.11p technology which is the preferred wireless technology for VANETs. Furthermore, based on the related work section we noticed that most of the proposed solutions use a GPS positioning device for their solutions. One of the problems with GPS devices is the need to exchange location information among vehicles which causes a large overhead in the network. Another problem is their inaccuracy with respect to the location they provide which requires to employ an acknowledgement mechanism to ensure the information is disseminated beyond one hop. Due to these problems we focus our attention into probabilistic flooding which seems a much simpler and more promising approach for disseminating information in a such a dynamic environment. In the next chapter we investigate further probabilistic flooding as a candidate effectively disseminate information in VANETs.

Chapter 3

Speed Adaptive Probabilistic Flooding Algorithm

In this chapter, we present the problem statement, some key observations, such as phase transition phenomena in VANETs, the rationale behind our design choices and the adopted design methodology that has been used to develop the SAPF algorithm. Furthermore, we present our first initial results of the proposed algorithm comparing to blind flooding algorithm.

3.1 Problem Statement

3.1.1 Road safety improvement using VANETs

Most traffic accidents are caused by human error since drivers may not be able to react on time to an event of an emergency situation. It usually takes in the order of a second for a human to react to an emergency situation. Additionally, drivers may also be hindered by a limited awareness of their surroundings, mainly due to the limited visibility of the road conditions. Basically, a human driver may not see much further ahead than the vehicle in front. Let's assume a very simple scenario where we have 3 vehicles in a freeway: vehicle A and C are normal vehicles, and vehicle B is a lorry. Vehicle A, which is in front of all vehicles, is engaged in an accident. The driver of vehicle B brakes abruptly to avoid engaging in the accident as well. Due to the obstacle, the driver of vehicle C does not realize the accident ahead of him, since the lorry is blocking the driver's view. By the time the driver realizes the accident the driver has to immediately brake hard to bring the vehicle into a complete stop in order to avoid the accident. It may happen that vehicle C has an accident with the lorry since the driver does not have enough time to react. This and similar kind of incidents are taking place in everyday life, where by they could be avoided, or at least minimized, by somehow informing the drivers in the vicinity of the accident at the same instant an accident takes place, and not depend on the visibility and alertness of the driver alone.

This can be achieved by using the latest technology on vehicles, where the vehicle could be equipped with sensing and communication devices to assist our driving in becoming safer and more enjoyable. The task of the sensing devices is to detect any unexpected hazard that may lie ahead. Some of these hazards could be weather hazards, oily road, icy roads, and abrupt braking. The task of the communication devices is to propagate the incident to all approaching vehicles in the area of the accident. Any vehicle that has on board sensing devices and communication device may participate in a vehicular ad hoc network, VANET. VANETs may extend the visibility of the driver to a greater distance and assist the driver and the passengers to avoid or handle any abnormal situation, hence contributing toward a safer and more enjoyable journey.

3.1.2 Problem Setting

We consider the following example to illustrate how VANETs can contribute to the safety of the transportation systems. In the event of an unexpected hazard condition such as traffic accident, a weather hazard or a road works hazard, a vehicle appropriately equipped to detect any of the aforementioned hazards will become an abnormal vehicle (AV) which can utilize the underlying VANET to take actions such as: issue emergency warning messages (EWMs) to all neighboring vehicles warning them of the imminent danger, notify the closest safety public services such as traffic management center, hospital, police department, fire department, and towing companies and hover the road hazard information over a specific geographic area. Effective dissemination of EWMs is therefore crucially important for ITS and this thesis aims to effectively address this.

3.1.3 Problem Description

Our objective is to design an effective information dissemination scheme which disseminates emergency warning messages to all interested parties reliably, efficiently and on-time. The scheme must be reliable since drivers will depend on it to obtain crucial information regarding emergency situations that may arise during their journey; any false information will create confusion and traffic jams in the freeways. This scheme must be efficient in respect of creating as few emergency warning messages as possible to avoid congesting the network with an abundance of redundant messages which may even lead to communication link throughput collapse, especially for IEEE 802.11p, the adopted link layer communication model, due to excessive communication packet collisions. Of course it is crucially important to deliver the emergency warning messages as fast as possible to all interested parties so the information is usefully acted upon by the interested parties. What makes rather challenging the design of such a scheme is the wireless communication links which are lossy and unreliable, as it is well known, the high mobility of the vehicles due to the high speed that can be achieved in the freeways and the unpredictable traffic conditions of the freeway.

3.1.4 Requirements of the Problem Solution

Knowing the problem we are facing to solve, we need to identify the requirements for a good solution. The requirements include the following: high reachability, high scalability, and low latency.

- **Reachability**: Reachability can be measured in term of the percentage of vehicles that received the emergency warning message in the area of an accident. The ideal is to have reachability approaching 100%, at least within a given ”safety distance”. Next we discuss ”safety distance” in the context of VANETs:

  ”Safety Distance”: can be thought of as the minimum distance that the EWM should be disseminated. The safety distance is calculated based on the following equation:

  *Safety Distance=((Thinking Distance+Reaction Distance+Stopping Distance+Guard Distance)*Number of vehicles)*

  where

  Thinking Distance: denotes the drivers’ ability to see the unexpected hazard, identify the fact there is a threat and then decide how to react (brake / change lane etc). If the driver lacks concentration or is distracted by talking/listening to the radio then he may take up to 2 seconds. Considering a vehicle speed of 100km/h this can be translated to 55.4 meters.

  Reaction Distance: denotes the time the driver needs to hit the brakes.This is usually around 0.7 seconds. Considering a vehicle speed of 100km/h this can be translated to 19.4 meters.

  Stopping Distance: denotes the distance that the vehicle needs to come to complete stop after the driver hits the brakes.

  Guard Distance: we add an extra distance providing more time to the drivers to react. It should be as high as possible to give the drivers more time to react, including some unexpected behavior by some driver. For the case of this simulations we set at about 30 meters.

For the case where the vehicle is moving at 100km/h and it takes about on average 1.5 seconds for the driver to realize there is an accident and react then the stopping distances are the following:

Thinking + Reaction = 1.5s * 27.7m/s = 41.5 meters (before the driver hits the brakes) and

Stopping Distance at 100km/h= 28.5 meters

Guard Distance= 30 meters

Safety Distance (for one vehicle)= (41.5m + 28.5m + 30m) = 100m

Safety Distance (N=10 veh.)= 100m * 10 vehicles = 1000m

The actual safety distance for one vehicle is 70 meters (thinking + reaction + stopping distance), however to make sure that the driver will have enough time to stop, we have added the guard distance which provides the driver with an additional time to stop. In this time (distance) one has to include the delay to disseminate the EWM. It is obvious that we would like to make the EWM dissemination as short as possible, hence increase the available Guard time. It is worth noting that in the event of an accident there are not only the vehicles that are right behind of the abnormal vehicle which are in danger, but also the vehicles that are approaching the scene or they are just outside of the computed safety distance of 1 vehicle. Hence, to inform the approaching vehicles which might also be in danger we multiply the safety distance of 1 vehicle by 10 which gives the distance that the EWM will be disseminated. Above calculations are on the conservative side. It is evident that the sooner a driver is informed the greater his guard distance may become. A comprehensive analysis of safety distance is beyond the scope of this thesis. A safety distance of 1000 meters will be adopted for the rest of the thesis.

- **Scalability**: The algorithm must perform equally well under all traffic conditions, including heavily or sparse vehicle densities.
- **Latency**: The time interval between the instant the emergency warning message is transmitted by the vehicle detecting the road hazard and the instant that the last vehicle within a ”safety distance” in the network receives the message. The objective is to have a maximum latency which is well within the reaction time of the driver and the vehicle, in order to avoid or at least minimize the effect of an emergency situation. Given that it takes from 0.7 to 2 seconds for a human driver to react to an emergency situation [42], and considering that a vehicle traveling at the speed of 100km/hour can cover almost one meter in 36ms, the delivery delay for the emergency warming message should be in the order of milliseconds. The earliest the warning is received the more the reaction time left for the driver.

3.2 Design Rationale-Key Observations

As we have discussed in chapter 2, section 2.8.4, probabilistic flooding approaches are appealing, in comparisons to other approaches, mainly due to their simplicity and effectiveness. In the next section we design a probabilistic flooding algorithm making use of a number of key observations.

3.2.1 Phase Transition, Percolation Theory and Random Graphs

Phase transition or phase change is a phenomenon where a system undergoes a sudden change of state or behavior in response to a small change in a chosen parameter set [29]. The phenomenon is of great importance as it has been observed and analyzed in a number of systems pervading our physical and engineering world. Two areas of research where phase transition has been extensively studied are percolation theory and random graphs [28]. The study in these areas has led to abstract mathematical frameworks which can serve as solid starting points to investigate other systems where phase transition is relevant, as for example probabilistic flooding in wireless mobile ad hoc networks [61]. Percolation theory [28] deals with fluid flow[1] (or any other similar process) in random media (describes the behavior of connected clusters in a random graph).

In a percolation model, given that there is a probability p that there is an open path and 1-p that there is no path, it has been observed that a phase transition can occur at the change of state between having finite numbers of clusters and having one infinite cluster. The existence of a phase transition in percolation theory infers the existence of a critical threshold probability, p_c where the phase transition occurs [29]. Given this observation, we will investigate the possible application of the same theory to the probabilistic flooding problem in VANETs. Such an application can provide valuable insights to the observed behavior and also lead to analytically verifiable designs. Phase transition has also been observed and studied in the context of Random Graphs. In mathematics, a random graph is a graph that is generated by some random process [43]. Different choices of the random process yield different random graph models. Various models have been studied in literature such as the Fixed Edge Number Model, the Bernoulli model, the Fixed Radius model and the Dynamic model. In the case of a Bernoulli model with N vertices and probability of an edge existence between any two nodes equal to p, it has been shown that for values of p greater than log(N)/N, the graph is connected with high probability [39]. This result not only verifies the existence of phase transition phenomena in random graphs but also quantifies the critical point. The problem of obtaining similar results for the Fixed Radius model which is an ideal representation of Mobile Ad Hoc Networks is a challenging open research problem. Since random graphs are relevant to wireless ad hoc networks, it is not surprising that recently, phase transition phenomena have been reported in various contexts in wireless ad hoc networks [29]. In

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[1] A usual setting here is that some liquid is poured on top of a porous material. The question is whether the liquid is able to make its way from hole to hole and reach the bottom.

the context of probabilistic flooding, phase transition can be extremely cost-efficient to observe, as it implies that there exists a critical probability beyond which all nodes receive the transmitted message with high probability.

Consider the scenario where a node in a wireless ad hoc network broadcasts a query message and then each node rebroadcasts the message with probability p and discards the message with probability 1-p. In [29] they observe that there exists a certain critical threshold, beyond which all nodes receive the message with high probability. In Fig. 14 we reproduce the graph of the probability that the message reaches all nodes versus the probability of rebroadcasting the message. For the given setting, for probability values above 0.55, all nodes receive the message with probability greater than 0.9. This critical probability depends on the transmission range / average node-degree, therefore the critical probability decreases as the number of neighbors that each node has increases.

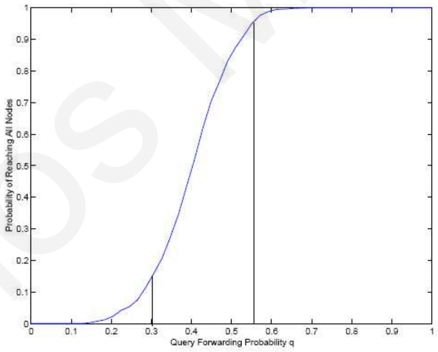

Figure 14: Phase Transition Probability

3.2.2 Verification of Phase Transition Phenomena in VANETs

In the previous section, we discussed the existence and the significance of the phase transition phenomena in wireless ad-hoc networks. In this section, we question whether the phase transition phenomena exists in VANETs as well. To answer this question we run several simulations aiming to establish the existence of a critical probability [52]. As we discuss in Chapter 4, all simulation-based experiments that were contacted in this thesis use a powerful integrated platform combining two simulators, VISSIM, a road traffic simulator and OPNET Modeler, a communication network simulator. The assumed setting is the following: A vehicle that detects an unexpected road hazard becomes an abnormal vehicle (AV) and transmits instantly an early warning message (EWM) to warn approaching vehicles of the imminent danger. Following the specifications of the 802.11a standard, the transmission range of all vehicles is set to 300 meters; for the simulation parameters see Table 3. Upon reception of the EWM for the first time a vehicle decides to rebroadcast the message with probability p, or decides not to rebroadcast the message with probability 1-p. Below we present the pseudo code for the probabilistic flooding.

The probabilistic flooding algorithm is as follows:

```
while (node $n$ receives EWM for a first time AND it is not the originator of the EWM AND TTL $\geq 0$)
    broadcast EWM with probability $p$ or discard with probability 1-$p$
    endif
endwhile
```

WLAN Parameters	Values
Transmission Power	0.00039W
Transmission Probability	0-1 (steps:0.1)
Time to Live	2
Data Rate	12Mbps
Packet Size	1024bytes
Destination address	Broadcast
WLAN Type	802.11a

Table 3: Simulation Parameters

The chosen test site is a typical two lane freeway which spans a distance of 6Km, see Fig. 15. We conducted a number of experiments to reflect different scenarios. In these set of simulations we were interested mostly in one metric, reachability, i.e. how many nodes will receive the message in a certain region. So our objective has been to examine the reachability as we change the rebroadcast probability and the vehicle density. The rebroadcast probability values were varied from 0 to 1 in steps of 0.1, applying this to different scenarios with different vehicle densities such as: 5, 10, 20, 30, 40 and 50 vehicles per kilometer per lane. All values obtained are averages over 10 simulation experiments. Fig. 16 shows the percentage of vehicles receiving the emergency warning message as we change the rebroadcast probability and the vehicle penetration rate. For a particular rate it is evident that there exists a critical threshold probability beyond which the number of vehicles receiving the message suddenly increases and stays almost constant.

Figure 15: A two lane section of the Nicosia-Limassol freeway which spans 6km

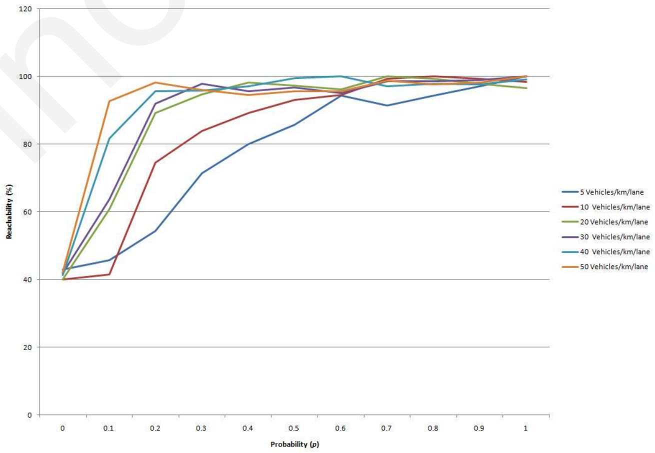

Figure 16: Phase Transition in VANETs

This sudden change is compatible with phase transition phenomena observed in the literature of random graphs and percolation theory, and thus we can expect this behavior to hold in the case of VANETs. In the next section we discuss another important observation, which is how the critical probability is affected by varying traffic density.

3.2.3 Critical probability affected by density

In the previous section we have shown through simulations that the phase transition phenomena occurs in VANETs. Using the same figure, Fig. 16, we also observe that the critical probability is affected by the traffic density. It is obvious that as we increase the traffic density the critical probability decreases. In Fig. 17, we have plotted the critical probability vs. the corresponding penetration rates.We observe an almost linear decrease of the critical probability as the penetration rate increases up to a saturation point (50 vehicles per kilometer per lane) after which the critical probability stays constant. This is a very important observation which we will use in our proposed design, as discussed in the next section.

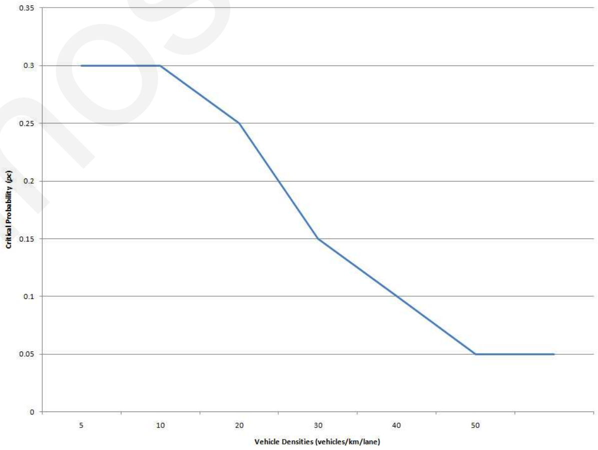

Figure 17: Critical Probability vs. Vehicle Densities

3.2.4 Density can be deduced by speed

Knowing that the critical probability is affected by traffic density, and since our objective is to find the critical probability for a specific traffic density, we need to obtain the traffic density at the event of an accident. Traffic density could be obtained using different methods such as 1) through a GPS service, 2) using a beaconing system, and 3) using the speed of the vehicle [68]. The first method requires a GPS system on board, with possibly a subscription to some service that will provide the vehicle density, at rates required for real time dissemination needs and which will be reporting in the region of milliseconds. To be effective, this service should also have universality, as well as every vehicle must have an always on GPS, and at the same time, the GPS device must be functioning under all weather and topological conditions. If a universal service to provide the density is not available, then an efficient protocol for the exchange of information between vehicles to establish traffic density will be required. Given above, this approach is not expected to be efficient, or even practical. The second method uses hello message which could contain vehicle location (again assuming the existence of an always functioning GPS device) and its identity, at time scales in the region of milliseconds. Each vehicle has to process all hello messages that it receives in order to create its neighborhood. This method creates an extra overhead, in the network, especially in high traffic densities, where the network will be further congested with hello messages. The third method appears to be a more promising approach since it estimates the density of the freeway through the speed of the vehicle. The only required information that is needed is the vehicle speed which could be obtained locally without any exchange of hello messages. This is based on the fact that there is a relationship between speed and density [68]. Fig. 18, which was obtained through real time measurements in [68], shows the relationship between vehicle speed vs. the traffic density in a two lane freeway. An almost linear relationship exists where low vehicle speeds in a freeway setting imply large vehicular densities and high vehicle speeds in a freeway setting imply low vehicular densities.

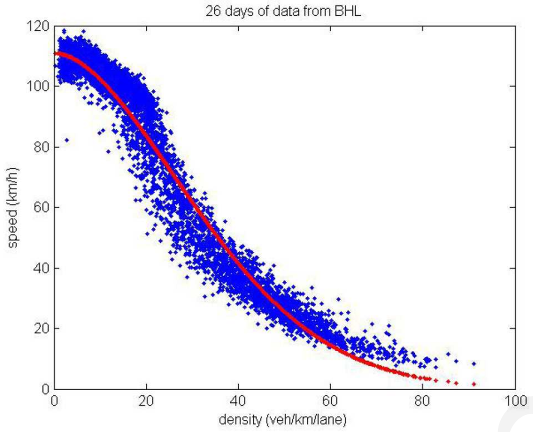

Figure 18: Vehicle Speed vs. Vehicle Density

3.2.5 Rebroadcast probability determined using vehicle speed

In the previous section, we have shown that traffic density can be deduced from vehicle speed. Therefore, for a particular traffic density (vehicle speed), it is expected that a desired rebroadcast probability value can be derived, which is expected to achieve low latency of message delivery among all rebroadcast probability values, whilst maintaining high reachability. Given above, we aim to design a Speed Adaptive Probabilistic Flooding scheme which is expected to adapt to road traffic density conditions by means of a suitable rebroadcast probability function whose input variable is the vehicle speed. The protocol enjoys a number of benefits relative to other approaches:

- It is decentralized and simple to implement.
- It does not introduce additional communication burden as it relies on local information only (the vehicle speed).
- It does not require additional exchange of beacon messages for mutual awareness.

- It does not rely on the existence of a positioning system which may not always be available.
- It is expected to mitigate the effect of the broadcast storm problem, typical when utilizing. blind flooding

Next we will formalize our proposed speed adaptive probabilistic approach.

3.3 Design Methodology

In this section we describe the design methodology of the proposed Speed Adaptive Probabilistic Flooding (SAPF) algorithm. The design methodology is broken into three phases, as shown in Fig. 19. In phase 1, we extend our preliminary investigation of phase transition phenomena in VANETs. We also compare the probabilistic flooding with blind flooding and verify its advantages. In Phase 2, we design the SAPF algorithm by combining the Critical Probabilities graph vs. Vehicle Densities graph with the Vehicle Speed vs. Vehicle Density graph to create a new relationship which represents the Critical Probabilities vs. Vehicle Speed. In Phase 3, we evaluate and compare our initial SAPF algorithm against Blind flooding. Given the knowledge gained through the initial simulative evaluations, in Chapter 4 we thoroughly evaluate SAPF.

All the simulation experiments were conducted using the integrated platform combining the VISSIM and OPNET simulators, briefly, described in Chapter 4. The topology of the reference simulation model is a section of the I-110N freeway in the Los Angeles Area from the Slauson Exit until the Vernon Exit, see Fig. 20. This is a four lane freeway section spanning a distance of approximately 7km. In all experiments, we assumed an accident occurring on the considered topology 1km before the Vernon exit, approximately 12 minutes after the start of the simulation. This provided sufficient time for the system to converge to its equilibrium state prior to the unexpected event. Just after the accident, we assumed the vehicle becomes an abnormal vehicle

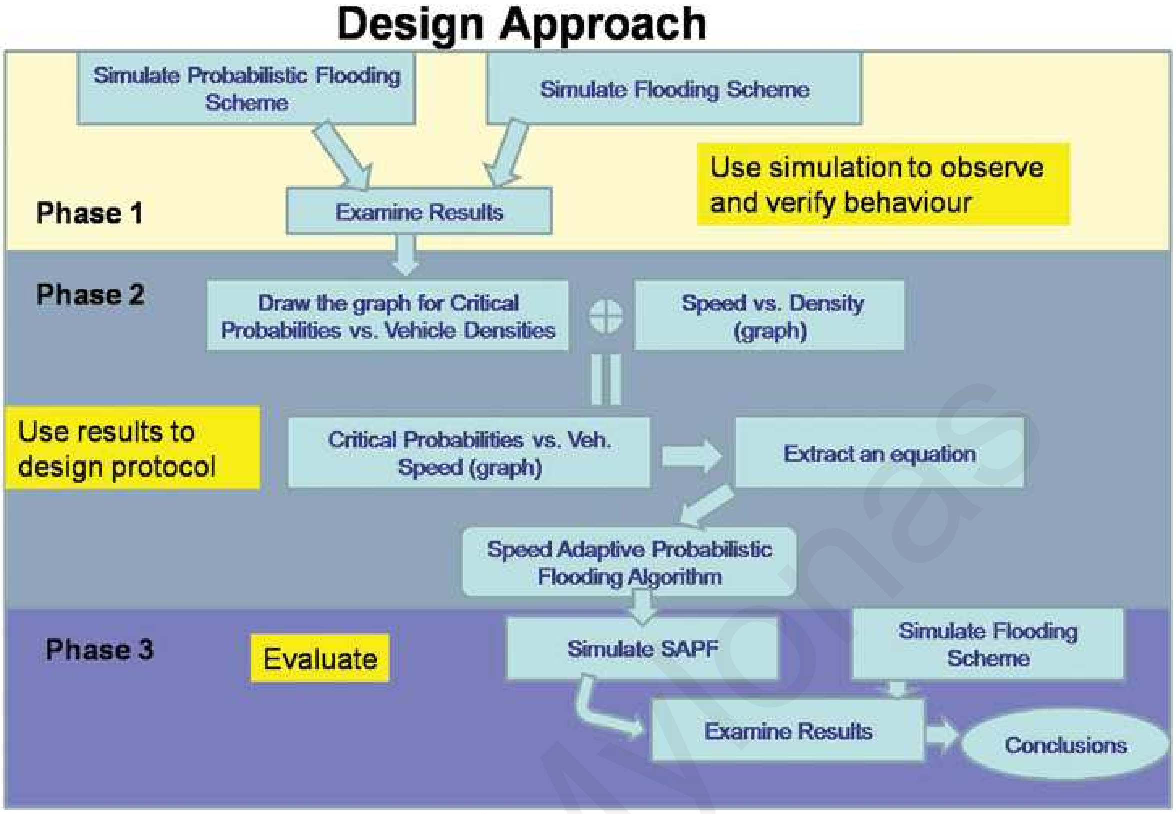

Figure 19: Design Approach for SAPF algorithm.

and employs 3-hop probabilistic flooding[2] to communicate an emergency warning message to all vehicles in the vicinity of the unexpected event. The values extracted for each of the variables considered in this study were averages over 10 repetitions of the same simulation experiment. For all the simulation experiments, the performance metrics that we consider are the number of vehicles which receive the transmitted emergency message (Rechability), latency, and protocol overhead (Number of Backoffs and Number of Rebroadcasts). Reachability and Density were defined in section 3.1.4. Number of Backoffs and Number of ReBroadcasts are defined below:

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[2] The proposed algorithm is evaluated further in Chapter 4, including different number of hops.

- **Number of Backoffs**: The total number of Backoffs which occurred in the area of an accident, within a given ”safety distance”. A node enters a backoff state before each transmission and after the medium is sensed to be non-idle and is an indicative measure of the protocol contention.

- **Number of ReBroadcasts**: The number of vehicles that have rebroadcasted the emergency warning message in the area of an accident, within a given ”safety distance”.

Figure 20: A section I-110N freeway in the Los Angeles area from the Slauson Exit until the Vermon Exit.

3.3.1 Phase 1: Phase Transition Phenomena and Probabilistic Flooding vs. Blind Flooding Scheme

In this section, we investigate further the existence of the phase transition phenomena in VANETs and illustrate the advantages that probabilistic flooding enjoys compared to blind flooding. The first step in this design procedure is to choose a set of vehicle density values. The values chosen were 2.5, 5, 7.5, 10, 12.5, 15, 20, 25 30, 35, 40, 50, 60, 70 measured in vehicles per kilometer per lane. In the simulation experiments that we conducted, the vehicle density was set by appropriately setting the vehicle penetration rate in the test site under consideration. For each vehicle density value, a reachability vs rebroadcast probability graph was obtained. Rebroadcast probabilities in the range 0 to 1 in steps of 0.05 were considered, see Table 4. Fig. 21 shows the reachability values obtained as we varied the rebroadcast probability for a subset of the vehicle density values under consideration.

WLAN Parameters	Values
Transmission Power	0.00039W
Transmission Probability	0-1 (steps:0.05)
Time to Live	2
Data Rate	12Mbps
Packet Size	1024bytes
Destination address	Broadcast
WLAN Type	802.11a

Table 4: Simulation Parameters

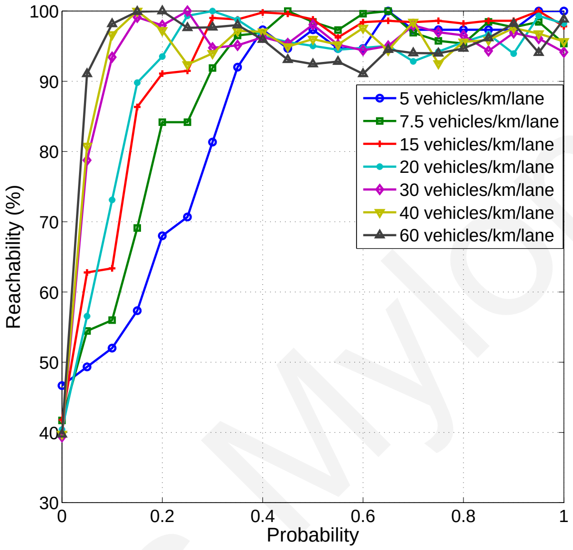
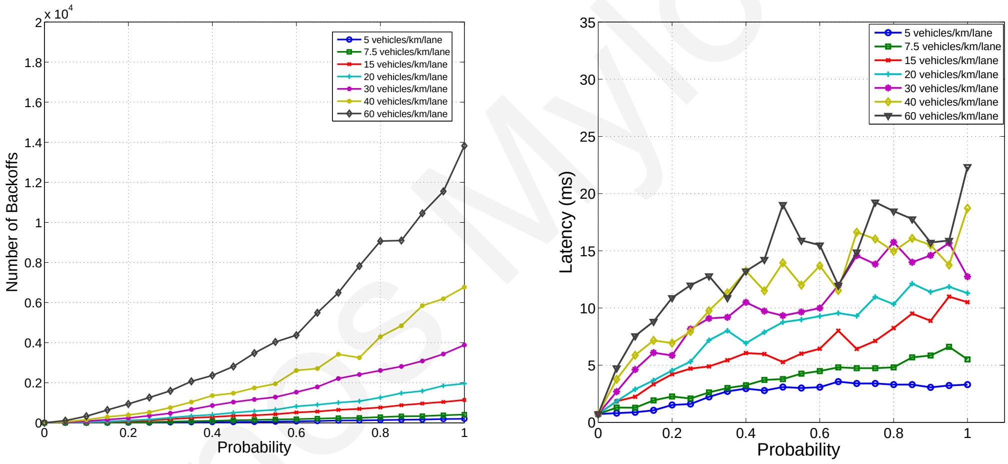


Figure 21: Reachability achieved as a function of the rebroadcast probability for different vehicular densities in a section of the I-110N freeway in the Los Angeles Area.

For each vehicular density, the reachability exhibits a strictly increasing and concave behavior as the rebroadcast probability increases and eventually converges to values close to 100%. Thus we reinforce for a four lane freeway here, that there exists a critical threshold probability beyond which almost all vehicles receive the emergency warning message with high probability. As we discussed earlier, this behavior is compatible with phase transition phenomena observed in the literature of random graphs and percolation theory [43]. In this work we define the critical probability as the rebroadcast probability which achieves a reachability value equal to 95% of the value to which it eventually converges. For each vehicular density this critical probability is the desired rebroadcast probability. The reason for this is that among all rebroadcast probability values which achieve almost 100% reachability this is the one which minimizes the latency, the number of rebroadcasts and the contention, whilst ensuring that an adequate % of vehicles becomes informed. This is a result of these quantities relating to the rebroadcast probability through strictly increasing functions. This behavior is verified in Fig. 22 for the topology under consideration. The figure shows plots of the number of backoffs and the latency of message delivery as we increase the rebroadcast probability. Both quantities exhibit the expected monotonically increasing behavior. A vehicle enters a backoff state in the event of a communication packet collision and the number of backoffs is thus a measure of the observed contention.



(a) Number of Backoffs vs Rebroadcast Probability (b) Latency vs Rebroadcast Probability

Figure 22: As we increase the rebroadcast probability, both the contention and the latency of message delivery increase.

Having obtained the desired rebroadcast probability values for each of the considered vehicle densities, their relationship is depicted graphically in Fig. 23. We observe an exponential-like, monotonically decreasing behavior of the critical probability as the vehicle density increases. This is expected, as higher vehicular densities suggest that smaller rebroadcast probability values are sufficient to ensure high reachability and low latency of message delivery which are the design objectives.

3.3.2 Phase 2: Development of SAPF algorithm

In this section, we describe the phase 2 of the design approach; we outline the rationale behind our design choices and we present the methodology adopted for the design of the proposed solution. The primary objective of this work has been the design of a decentralized, simple to implement short range multi-hop broadcast scheme which ensures high reachability and low latency of message delivery. The broadcast storm problem poses the most significant challenge to the fulfillment of the above objectives in cases of high vehicular density. The proposed solution, which we refer to as Speed Adaptive Probabilistic Flooding, SAPF, solves the problem by employing probabilistic flooding.

Upon receiving a message for the first time, a vehicle decides to rebroadcast the message with probability p and decides not to rebroadcast the message with probability $1 - p$. A unique feature of the protocol is that the rebroadcast probability p is regulated adaptively based on the vehicle speeds which can be obtained locally. The rationale behind this design choice is that low vehicle speeds in a freeway setting imply large vehicle densities which in turn imply that lower rebroadcast probability values are sufficient to achieve high reachability with low latency.

A major challenge in the design of the SAPF protocol has been the derivation of the rebroadcast probability function which maps the speed of the vehicle to the rebroadcast probability value in case of an emergency warning message being received for the first time. As discussed earlier, in a freeway setting, the speed of the vehicle is sufficient to provide information regarding the vehicle density by means of speed density curves which can be readily obtained from field data [68].

This implies that the problem of deriving a function which maps the speed of the vehicle to the rebroadcast probability can be reduced to the problem of deriving a function which maps the density of the vehicles to the rebroadcast probability. The question that arises is then the following: for a particular vehicle density, what is the rebroadcast probability which achieves the highest possible reachability with the minimum possible latency. In this work, as discussed earlier, for each vehicle density we obtain such rebroadcast probability values by taking advantage of phase transition phenomena [29] observed when relating the reachability with the rebroadcast probability. For a particular vehicle density, there exists a critical rebroadcast probability beyond which all vehicles receive the message with high probability, thus achieving high reachability. This critical probability is the desired rebroadcast probability value for the vehicle density under consideration. So, in order to derive the desired rebroadcast probability function we adopt the following methodology:

- We first choose a suitable set of vehicle density values.
- For each vehicle density we conduct simulation experiments which we use to obtain rebroadcast probability vs reachability curves.
- Using these curves we identify the critical probability value at the onset of the phase transition.
- Using the obtained data we construct the critical probability vs vehicle density curve and finally
- Combine the vehicle speed with the vehicle density curve to obtain the desired vehicle speed vs. rebroadcast probability function.

Below we provide details regarding the adopted procedure and the results obtained.

In the "Phase 1" section, we have demonstrated that transition phenomena exist in VANETs and also have concluded that our design objectives can be achieved by observing an exponential-like, monotonically decreasing behavior of the critical probability as the vehicle density increases. As it has been anticipated higher vehicular densities suggest smaller rebroadcast probability values which are sufficient to ensure high reachability and low latency of message delivery, see Fig. 23.

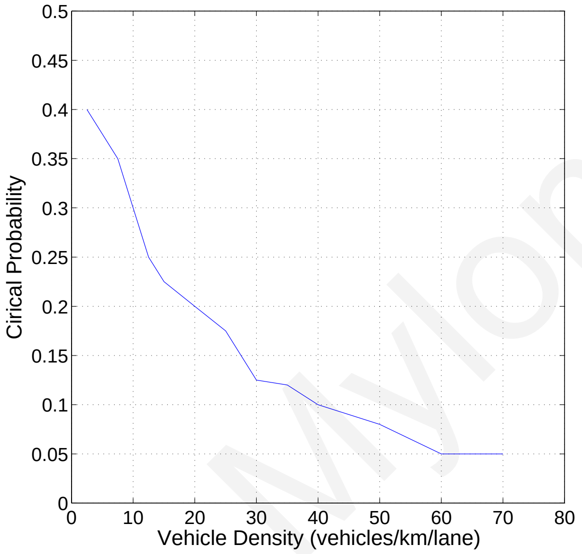


Figure 23: As the vehicular density increases, the desired rebroadcast probability exhibits an exponential-like monotonically decreasing behavior.

The next step is to combine the obtained rebroadcast probability vs density function with the vehicle speed vs vehicle density curve to derive the desired rebroadcast probability vs vehicle speed function, see Fig. 25 for the approach. For the topology under consideration, the vehicle speed vs vehicle density curve is obtained using field data available through the Freeway Performance Measurement System, PEMS [18]. The measurements were taken in the period 12 January 2009 until 10 April 2009. The curve is shown in Fig. 24 and exhibits the well known characteristics of the relationship: a congestion-free regime at low vehicle densities where the vehicles attain a relatively high and almost constant speed value; a phase transition in a relatively narrow density space where the speed suddenly drops indicating the onset of congestion; and a congestion regime at high vehicular densities where the vehicles attain small speed values.

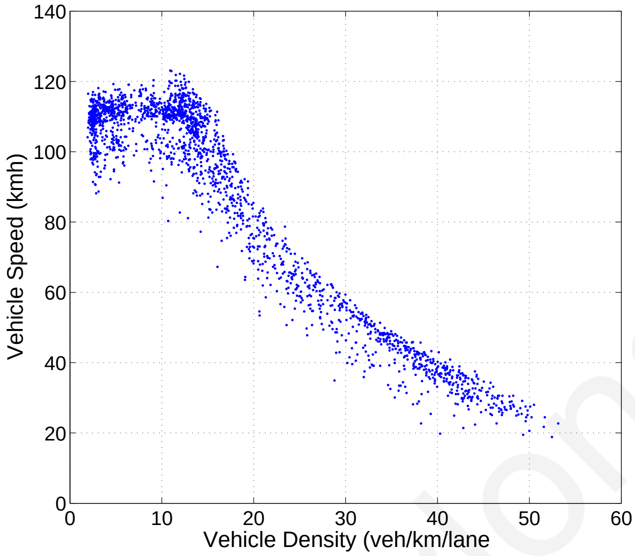


Figure 24: Vehicle Speed vs. Vehicle Density curve for a section of the I-110N freeway between the Slauson and Vernon exits. The graph was generated using real data from PeMS.

The composition of the functions depicted in Fig. 23 and Fig. 24 leads to the desired rebroadcast probability vs. vehicle speed function, which is shown in Fig. 25 and Fig. 26. We observe an almost linear relationship, which is approximated with a linear function whose parameters are obtained through least squares fitting. The function is given by the equation:

$$p = 0.0022 * v + 0.024 \tag{1}$$

where p denotes the rebroadcast probability and v denotes the vehicle speed.

The linear relationship obtained is used to determine the rebroadcast probability for vehicle speeds in the range 15km/h up to 110km/h. For speeds above 110km/h (speed limit) we set the rebroadcast probability equal to 1. The reason is that beyond such speeds it is impossible to estimate the density based on speed information only and so we adopt a rather aggressive

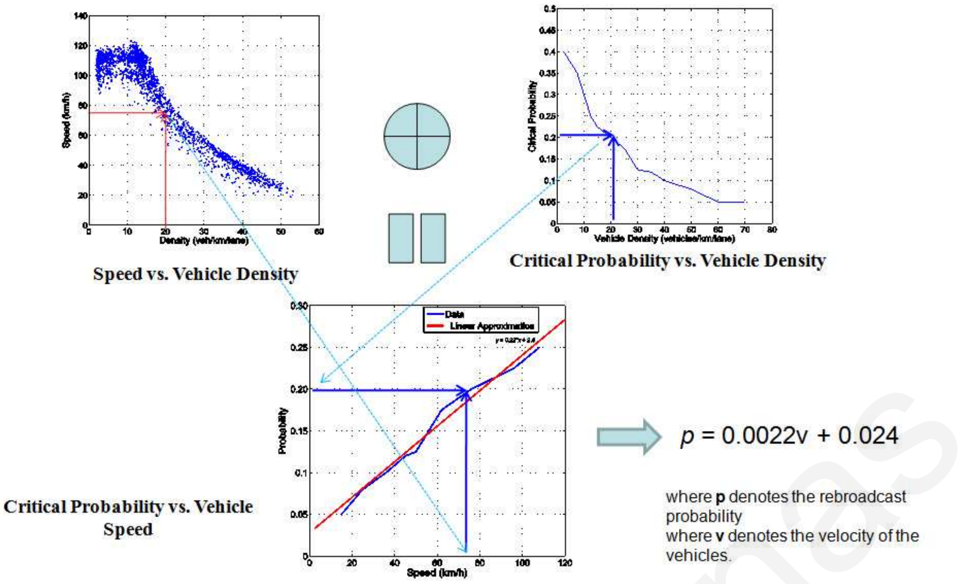


Figure 25: Combining Vehicle Speed vs. Vehicle Density with Critical Probability vs. Vehicle Density to obtain Critical Probability vs. Vehicle Speed

rebroadcast policy in order to ensure message delivery to all vehicles. On the other hand for speed values below 15km/h, we assume that the network has almost reached its capacity and so we consider a constant rebroadcast probability of 0.05 is adequate. The resulting rebroadcast probability vs. vehicle speed function used in the proposed SAPF scheme is shown in Fig. 27.

3.3.2.1 The Speed Adaptive Probabilistic Flooding (SAPF) Scheme

Having derived the rebroadcast probability vs. desired vehicle speed curve, in this section we present implementation details of the proposed Speed Adaptive Probabilistic Flooding scheme. The protocol is implemented above the MAC layer. Each SAPF message has four designated fields in the packet header which store the following: the IP address of the originator , the destination address which is set to broadcast, the time to live (TTL) and the sequence number. All these fields are set by the originator of the message which is the Abnormal Vehicle at the time of the creation of the emergency warning message. The only field that can be modified in transit is the

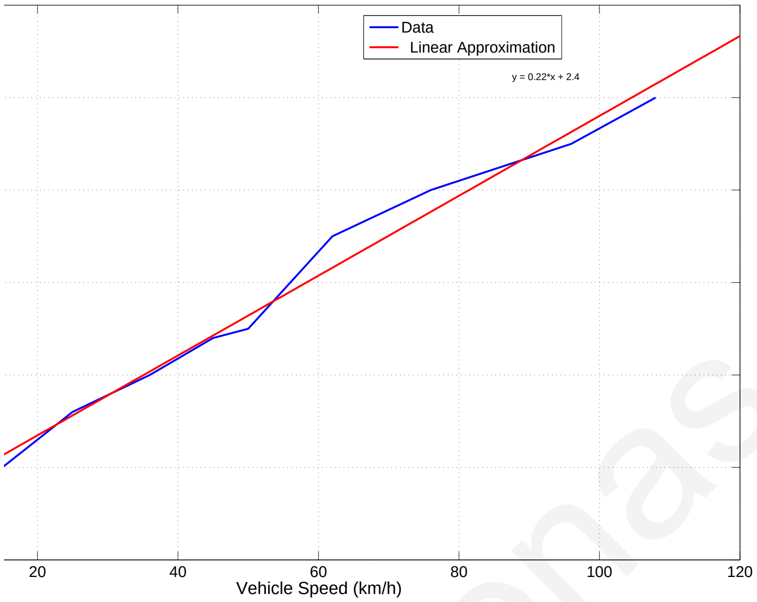


Figure 26: The rebroadcast probability increases linearly as the speed of the vehicle increases.

time to live field, TTL. The TTL field is decreased by one every time the EWM is rebroadcasted. As soon as the TTL reaches a zero value the message is dropped. The TTL depicts the number of hops the EWM can be transmitted in the network. Each vehicle maintains a table of recently received messages. Each message is identified by a combination of the source IP address and the sequence number. Whenever a vehicle receives a new message, it checks whether this message has been recently received through matching of the identifiers in the relevant table. If no matching is found, the message is classified as being received for the first time, its identifier is added to the table of recently received messages and is made available for rebroadcast upon decision of the probabilistic flooding algorithm. Based on the function of Fig. 27, the SAPF algorithm works as follows:

Speed Adaptive Probabilistic Flooding algorithm

```
while (node $n$ receives EWM for a first time and
    it is not the originator of the EWM and TTL $\geq$ 0)
```

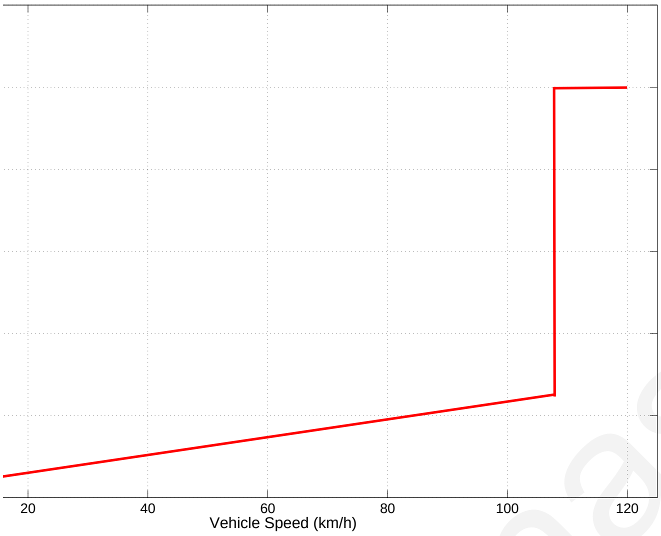


Figure 27: The SAPF rebroadcast probability vs. vehicle speed relationship.

```
    if (veh. speed $\geq$ 15km/h and veh. speed $\leq$ 110km/h)
        broadcast EWM with probability
        $p$ = 0.0022*veh. speed+0.024
    else if (veh. speed $<$ 15km/h)
        broadcast EWM with $p$ = 0.05
    else if (veh. speed $>$ 110km/h)
        broadcast EWM with $p$ = 1
    endif
endwhile
```

3.3.3 Phase 3: Initial Performance Evaluation of SAPF algorithm

In this section, we provide initial results of the performance of the proposed Speed Adaptive Probabilistic Flooding Scheme using simulations. We use as a reference model the same road topology[3] as the one used in the design procedure: a four lane section of the I-110N freeway in the Los Angeles Area spanning a distance of approximately 7km from the Slauson exit until the

Vernon exit. In order to create simulation models which generate realistic representations of the actual traffic conditions, the inflows in the chosen test site are set according to field measurements obtained through the PEMS system. Three sets of data were considered reflecting three different traffic conditions: light, medium and heavy. The classification was based on the location of the corresponding points on the vehicle speed vs. vehicle density curve of the considered freeway section, shown in Fig. 24.

The SAPF scheme was implemented on the OPNET Modeler by making appropriate modifications to the 802.11 WLAN station model which excludes implementations of layers above the MAC. In this model the transmission power was set to 0.0039w to ensure a transmission range of 300m. The vehicles are configured to operate in broadcast mode with no ACK/CTS/RTS mechanisms. The time to live field is set to 2 in order to guarantee a maximum 3-hop transmission; see Table 5. This creates a multi-hop transmission range of approximately 1000m considered to be the given ”safety distance”. The packet size is set to a constant value of 1024 bytes. In all simulation experiments, the accident is assumed to occur 700 seconds after the simulation start time, approximately 1km before the Vernon exit. All simulations run for 1000 seconds simulated time. Our objective has been to investigate the performance and the robustness of the proposed scheme with respect to the chosen performance metrics. Our initial results indicate that the proposed scheme fulfils the posed design objectives as it achieves high reachability, low latency of message delivery, and outperforms blind flooding. More comprehensive results are presented in Chapter 4. Our objective has been to design a short range multi-hop broadcast scheme which can facilitate the fast and reliable transfer of emergency warning messages to all vehicles in the vicinity of an unexpected event, mitigating the effects of the broadcast storm problem typical when using blind flooding. In order to investigate the ability of the proposed protocol to achieve

---

[3] More comprehensive evaluations, using different road topologies, as well as design parameters, thus testing the sensitivity of the design to other conditions not used during the design phase, will be investigated in Chapter 4.

WLAN Parameters	**Values**
Transmission Power	0.00039
Transmission Probability	SAPF AND Blind Flooding
Time to Live	2
Data Rate	12Mbps
Packet Size	1024bytes
Destination address	Broadcast
WLAN Type	802.11a

Table 5: Simulation Parameters

the afore-mentioned objectives, we evaluate its performance in the reference scenario described above and also compare it with the performance of blind flooding when the freeway section under consideration experiences light, medium and heavy congestion. In Fig. 28 we show the reachability values recorded by the SAPF and blind flooding schemes for each of the considered levels of congestion. In Fig. 29 we show the corresponding latency values. It is evident that SAPF manages to maintain high reachability values, comparable to the ones recorded by blind flooding and at the same time achieve significant reductions in the observed latency. It is worth noting that the latency is kept within a few milliseconds. As the transportation network becomes more congested, the negative effects of the broadcast storm problem cause blind flooding to require

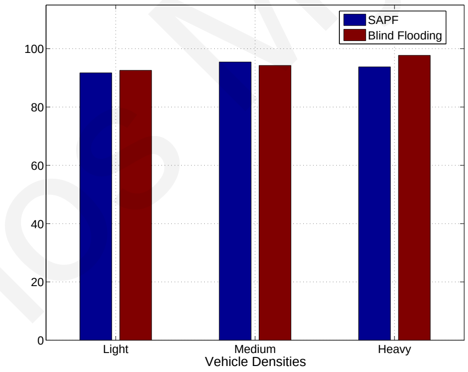


Figure 28: Both the SAPF and Blind Flooding schemes achieve high reachability, close to 100%, at all traffic conditions.

more time to deliver the emergency warning message to all vehicles in the area of interest. Speed Adaptive Probabilistic Flooding, on the other hand, manages to counterbalance the effects of the broadcast storm problem maintaining almost constant latency values as congestion increases. It thus manages to almost decouple the protocol behavior from the level of congestion on the freeway and outperforms blind flooding, especially in cases of heavy congestion, by achieving large reductions in the observed latency.

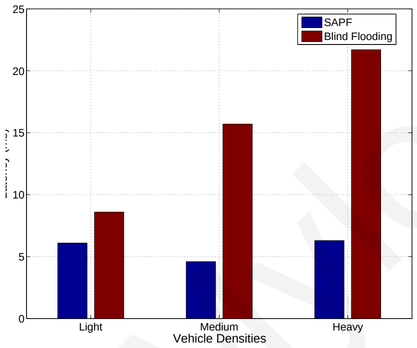


Figure 29: As the transportation network becomes congested, blind flooding reports higher latency values while the SAPF scheme maintains almost constant values thus achieving significant reductions in the observed latency.

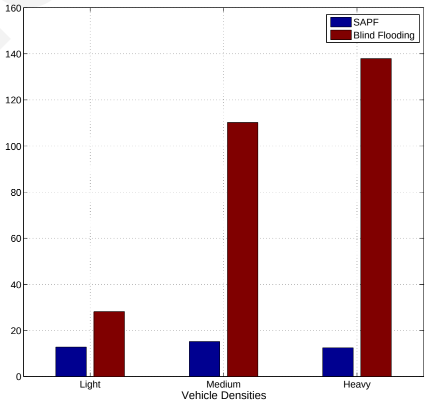


Figure 30: As congestion increases blind flooding rebroadcasts a larger number of messages while SAPF adapts to the varying traffic conditions to maintain an almost constant number of rebroadcasts at all traffic conditions.

The ability of the SAPF scheme to counterbalance the negative effects of the broadcast storm problem is also demonstrated in Figures 30 and 31 which show the number of rebroadcasts and the number of backoffs respectively reported by the two protocols as congestion increases. Increasing levels of congestion cause the vehicular network to become more dense which in turn causes blind flooding to rebroadcast a larger number of messages. These messages lead to increased number of collisions each of which causes nodes to enter a backoff state. So increased contention is reflected in the increased number of backoffs which are shown in Fig. 31. The SAPF scheme, which employs adaptive probabilistic flooding, reduces the number of relays thus achieving significant reductions in the number of exchanged messages. Its ability to adapt to changing traffic conditions is reflected in the number of rebroadcasts remaining almost constant as congestion increases.

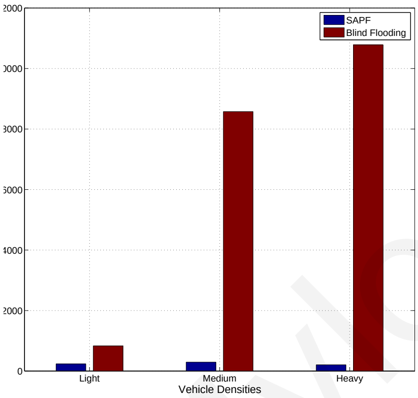


Figure 31: As congestion increases blind flooding experiences increased contention. The SAPF scheme counterbalances the effects of the broadcast storm problem maintaining a small number of backoffs at all traffic conditions.

3.4 Concluding Remarks

The initial investigation shows that Speed Adaptive Probabilistic Flooding is successful in mitigating the effects of the broadcast storm problem by relieving the vehicular network from unnecessary rebroadcasts which consume useful bandwidth and ensuring almost constant levels of contention independent of the traffic conditions. This behavior of SAPF also indicates that it is expected to be scalable and robust in the presence of road traffic changes. In the next chapter we will provide more comprehensive results, as well as investigating the sensitivity of the algorithm to various changing conditions and design parameter settings.

Chapter 4

Performance Evaluation of SAPF

In chapter 3, we provide the motivation and the design of the proposed algorithm, together with an initial investigation. In this chapter we will provide a comprehensive simulation-based evaluation, taking into account both environmental as well as design parameters, which may affect the performance of our algorithm. These include: road structure, road traffic conditions, bi-directional traffic, variation of speed limits of the freeways, transmission range, and number of hops (”safety distance”). We also provide further comparison of SAPF with Blind Flooding, as well as comparison of SAPF with an idealized GPS-based protocol (assuming zero signalling overhead), and with a GPS enabled protocol. For exhaustive evaluation of SAPF algorithm, we used different freeway topologies from Los Angeles area and Cyprus. For each Los Angeles topology we have extracted real time traffic data for a specific section of a freeway using the Freeway Performance Measurement System, PeMS [18]. For all simulations, using the Los Angeles area, the traffic measurements were taken in the period 12 January 2009 until 10 April 2009, and for the Cyprus freeway during the period 15-19 of June, 2009. It is worth noting that for the Cyprus freeway our simulations are obtained in real traffic conditions in a very different environment than the USA freeways, using a different measurement device, thus enhancing our confidence in the robustness of the algorithm. The considered topologies for this section are the following:

- I-105E: a three lane section of the I105E freeway in Los Angeles area spanning a distance of approximately 3.5km.
- I-110N: a four lane section of I110N freeway in Los Angeles area spanning a distance of approximately 7km from the Slauson exit until the Vernon exit.
- I15N: a four lane section of the I15N freeway in Los Angeles area spanning a distance of approximately 2km.
- SR60E: a five lane section of the section of SR60E freeway in Los Angeles area spanning a distance of approximately 4.5km from the S. Mednik until the Ve. Campo entry.
- A1: a two lane section of the A1 Nicosia-Limassol freeway in Cyprus spanning a distance of approximately 6km.

For all the simulation experiments in this section, we are using the same performance metrics that we considered in chapter 3, which are the reachability, latency, and protocol overhead (Number of Backoffs and Number of Rebroadcasts). As we have mentioned in chapter 3, all simulations-based experiments conducted in this thesis use a powerful integrated platform combining two commercial simulators, VISSIM, a road traffic simulator and OPNET Modeler, a communication network simulator. Furthermore, we have used PeMS and RTMS remote road traffic measurement sensors to obtain real time traffic data. In the next section we present the tools and the simulators that we have used in this thesis to evaluate the proposed scheme. Then we present the simulation results, followed by concluding remarks.

4.1 Simulation Tools: Integrated Platform combining VISSIM and OPNET Simulators, PeMS and RTMS sensors

In this section, we present the transportation and communication network simulators that we have used for our simulations, as well as the utilities used to assist us in making the road topologies and road traffic data as realistic as possible. In the area of transportation systems there are many popular traffic simulators, as for example, [4], [19], and [20]. Similarly, in the communication network community there are many network simulators, as for example [3], [21], and [22]. However, there are not many simulators which can combine the two areas. In [50] they provide a thorough comparative review of VANET simulators, but they only review the free publicly available simulators. Based on their findings only four simulators are well known and somehow capable of supporting VANETs. These four simulators are TraNS, GrooveNet, NCTUns and MobiReal. However, each one of these four simulator has some advantages and disadvantages, such as some of them do not fully support network models or transportation driving human behavior, mobility patterns and so on. Based on our experience in the transportation systems and in network communication systems for our simulations we adopted two established commercial simulators: VISSIM [4], a simulator for road traffic simulations, and OPNET Modeler [3] a simulator for communication networks. Both of these simulators are very specialized in their area of expertise and they offer a great number of appealing features, including the possibility to interface together. The combination of these two simulators makes a very powerful simulator for VANETs.

4.1.1 Interfacing VISSIM and OPNET simulators

In this thesis, to interface the two simulators we adopt a serial approach, where we generate the road traffic (vehicle trajectories) using VISSIM first. Then these are imported into OPNET to provide us with the realistic vehicle (communication node) mobility patterns. A more appealing simulation framework is to combine VISSIM and OPNET in a more dynamic way. By dynamic we mean that the vehicles (nodes) respond to the accident information in ”real time”. This would require a tight ”real time” coupling between the two simulators. Within this dynamic simulation one can also show the benefits in terms of accident prevention, and also set the design variables hop-count and power in a more informed way. This is beyond the scope of this thesis. It investigation is high recommended for future work, but it sould be noted that the resulting simulator complexity may render it impractical.

Based on our knowledge, it is the first time that VISSIM, and OPNET simulators are interfaced together to extract topology information from VISSIM simulator, and feed it into OPNET Modeler simulator for further network communication analysis. To interface them, we wrote several unix scripts to convert VISSIM topologies to a compatible xml format that we could use later on in OPNET Modeler to recreate the topology. Fig. 32 shows the workflow diagram that we have created to interface these two simulators together. Below we list the procedure:

- Create and tune road topology in VISSIM simulator using Google map images and PeMS (RTMS) to obtain real time traffic data
- Export the VISSIM topology in a txt file format (name.fzp) containing the following:
    - VehNr: Number of Vehicle
    - t: Simulation Time [s]
    - WorldX: World Coordinate x (Vehicle front end at the end of the simulation step)
    - WorldY: World Coordinate y (Vehicle front end at the end of the simulation step)
    - LCh: Direction of current lane change
    - a: Acceleration [m/s] during the simulation step

  - vMS: Speed [m/s] at the end of the simulation step

- Feed the name.fzp file through several unix scripts to create an xml file and the trajectory files for vehicles. For each vehicle, it requires one trajectory file.

- Use the xml file and the trajectory files to import the vehicle trajectories and network topology in OPNET.

- Configure vehicles (communication nodes) according to the needs of the communication network model and produce the appropriate simulation results.

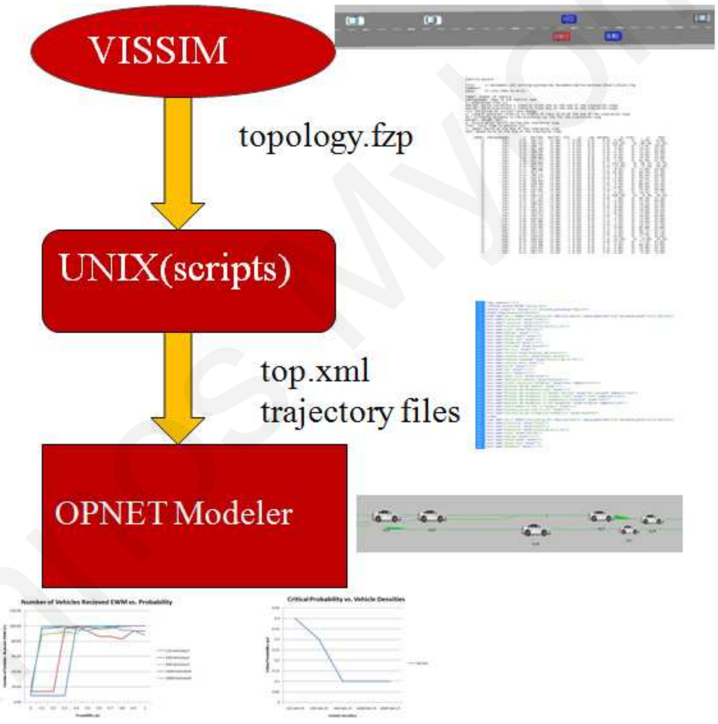


Figure 32: A workflow diagram converting VISSIM topologies to OPNET compatible format.

Fig. 33 and Fig. 34 show a snapshot of a VANET topology generated in VISSIM and OPNET Modeler simulator, respectively. In VISSIM the vehicle behavior is captured in a ”realistic fashion”, whilst in OPNET Modeler the vehicle represents the communication nodes; whose mobility patterns are the ones captured in VISSIM. OPNET and VISSIM are briefly described in the next sections.

Figure 33: A snapshot of the reference model generated in the VISSIM Simulator.

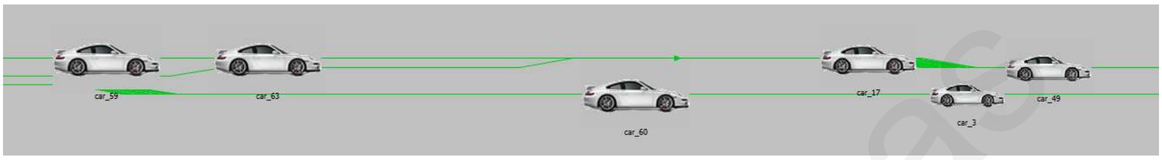


Figure 34: A snapshot of the reference model generated in the OPNET Simulator.

4.1.1.1 VISSIM Simulator

VISSIM is considered as the industry leading commercial microscopic simulation program for multi-modal traffic flow modeling. With its unique high level of detail, it accurately simulates urban and freeway traffic, including pedestrians, cyclists and motorized vehicles. For all the road topologies we have used in this thesis, we used VISSIM simulator to create the topology and to simulate the behavior of the human driver. Towards this end, we have obtained the structure of the road topologies using Google Maps. Then we use the image map as a background transparency, to build on top of the map the real structure of the road. All the road topologies that we have built in VISSIM are based on real measurements. This was achieved with the help of the Google map, see Fig. 35 and the Google Earth tools, where we could see in detail the structure of the road, (see figures 36 and 37).

Having completed the road structure in VISSIM, the next step was to configure the mobility of the vehicles in the freeway using, realistic traffic extracted through the PeMS system, which we discuss later. To tune the mobility of the vehicles in VISSIM simulator, we had to create the

Figure 35: A snapshot from the Google maps for the I110N freeway

Figure 36: A snapshot from the Google Earth for the I110N freeway

routes for the vehicles including; which vehicles will take an exit or continue their path on the main lanes. This requires knowledge of the percentage of vehicles that will take an exit or not. This information was obtained from PeMS system.

4.1.1.2 OPNET Modeler System Implementation

OPNET Modeler is the industry's leading commercial software for network modeling and simulation, used by universities and research and development organizations to develop new protocols for fixed and wireless communication technologies. For our proposed algorithm, we used OPNET Modeler to implement VANETs by making appropriate modifications to an 802.11 WLAN station model, which excludes implementations of layers above the MAC layers such as TCP/IP. The model is implemented in the Wlan_station_adv mobile node module which emulates layers above the MAC by appropriate source and sinks modules. The structure of the Wlan_station_adv mobile node is shown in Fig. 38, and its sub-modules and their functionalities are as follows:

- **Source module**: it generates the packets in the event of an accident.

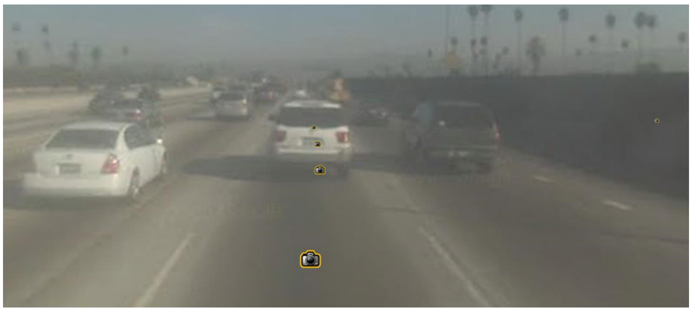


Figure 37: Using Google Earth to obtain information regarding the structure of the freeway I110N

- **Sink module**: it destroys the packet when the TTL field is equal to zero.

- **Wlan_mac_intf**: checks whether the packet has been received from the source module or from the MAC layer.

- **Wireless_lan_mac**: it includes the MAC layer implementation.

- **Wlan_port_rx0 and wlan_port_tx0**: they are responsible to receive and transmit packets respectively.

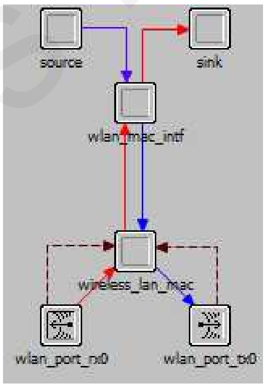


Figure 38: WLAN Node Model.

The most significant changes were made to the wlan_mac_intf and wireless_lan_mac modules whose structure is shown in figures 39 and 40, respectively.

As mentioned above, the Wlan_mac_intf module checks whether the packet was received from the source or the MAC layer and responds accordingly. If the packet is received from the source

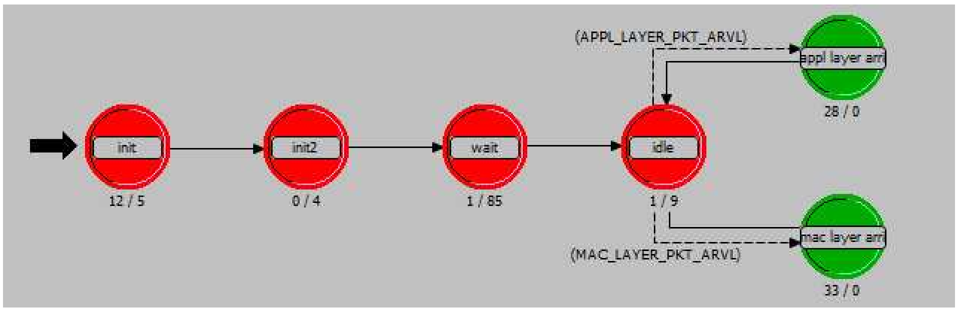


Figure 39: Process Diagram of Wlan_mac_intf.

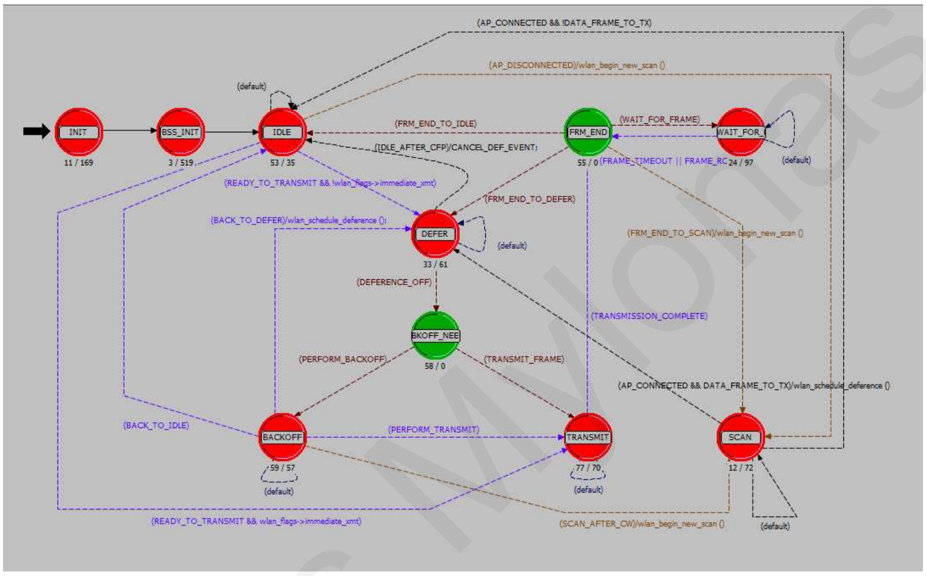


Figure 40: Process Diagram of WLAN MAC layer.

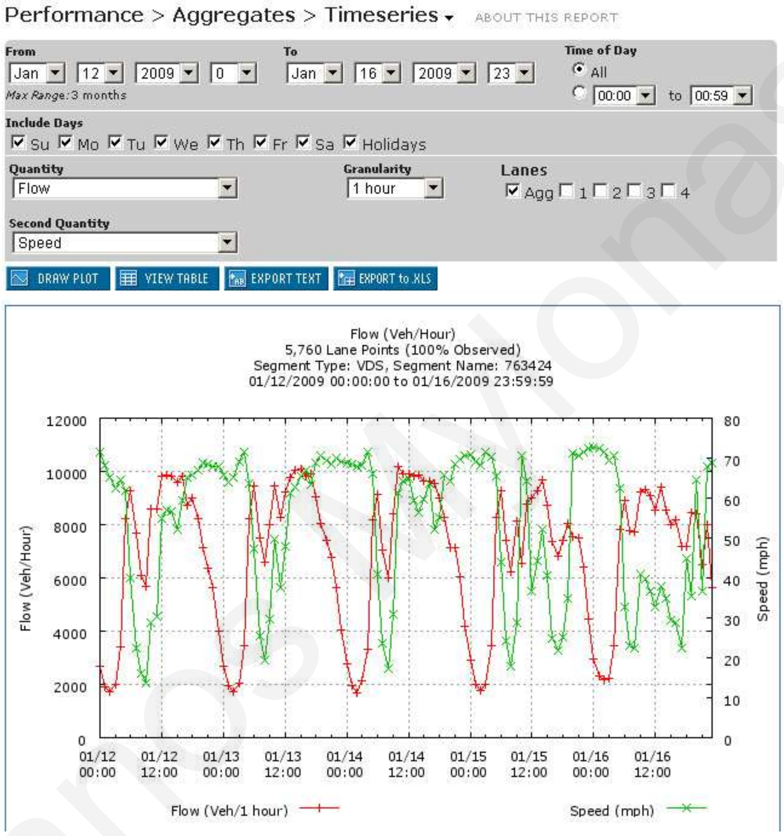
it is handed to the MAC layer. This function is left unchanged. If, however, the packet is received from the MAC layer the standard response is for the packet to be forwarded to the sink. We have modified this process redirecting the message back to the MAC layer to allow rebroadcast of the received message based on the chosen dissemination algorithm (e.g. SAPF, BF, GPS, etc.). The latter is implemented in the wireless_lan_mac module. The major modifications made to the wireless_lan_mac module are summarized below. A time to live field has been added to the header of the transmitted packets. Upon receiving a packet from the source, the MAC layer sets the TTL value equal to a predefined TTL_max value. Whenever a packet is rerouted back to the MAC layer by the wlan_mac_intf module, the TTL field is decreased by one. In addition, the IP address of the source of the packet is maintained in the packet header and is not updated with the IP address of the node receiving the message as was the original implementation. This is done in order to create appropriate identifiers for each packet which will allow each node to infer whether it has received the warning message for the first time. These unique identifiers are created by combining the IP address of the packet source with the source sequence number which is also included in the packet header. A table of recently received messages is also created in the module. When receiving a message, a node checks whether the identifier of the message is included in the table. If it is included, then the packet is destroyed. If it is not, then a new entry is added in the table and the packet is made available for retransmission. In the case of SAPF, the packet is retransmitted with probability p. The op_dist_uniform function is used to generate a random number in the range 0 to 100 according to a uniform distribution. The packet is then transmitted when the generated number is smaller than p times 100. The TTL_max and transmission probability parameters could be set separately for each vehicle. Table 6 shows the WLAN parameters chosen for all nodes. Other dissemination algorithms are added in a similar fashion.

WLAN Parameters	**Values**
Transmission Power	0.00039W
Transmission Probability	0-1 (steps:0.1)
Time to Live	2
Data Rate	12Mbps
Packet Size	1024bytes
Destination address	Broadcast
WLAN Type	802.11a

Table 6: Simulation Parameters

4.1.2 Performance Measurement System, PeMS.

The Performance Measurement System, PeMS, provides historical and real-time data from freeways in the State of California in order to compute freeway performance measures. For our simulations we have used PeMS to obtain average speeds and flow measurements at different locations on the freeway where appropriate sensing equipment is installed, see Fig. 41. Fig. 41 shows the vehicle flows and the average vehicle speed for an hour for the period 12 January 2009 until 16 January 2009. It is interesting to note the reverse relationship between vehicle speeds and vehicle flows.



From Jan 12 2009 0
Max Range: 3 months
To Jan 16 2009 23
Time of Day
● All
○ 00:00 to 00:59
Include Days
☑ Su ☑ Mo ☑ Tu ☑ We ☑ Th ☑ Fr ☑ Sa ☑ Holidays
Quantity Flow
Granularity 1 hour
Lanes ☑ Agg ☐ 1 ☐ 2 ☐ 3 ☐ 4
Second Quantity Speed

Flow (Veh/Hour)
5,760 Lane Points (100% Observed)
Segment Type: VDS, Segment Name: 763424
01/12/2009 00:00:00 to 01/16/2009 23:59:59

Figure 41: A screen shot from PeMS that shows the flows and speed of the vehicles for I110N

For better interpretation of the congestion status and for protocol design which will be described later in this section, average vehicle speed and vehicle density values are required at the corresponding locations. However to derive vehicle speed vs. vehicle density curves we need to transform the vehicle flow measurements into vehicle density measurements. This has been achieved by using the following well known formula from the area of the transportation systems:

$$q = k * v \tag{2}$$

where

q denotes the vehicle flow (vehicles/hour)

k denotes the vehicle density (vehicles/kilometer)

v denotes the vehicle speed (km/h)

Using the above formula we compute the vehicle density of the road topology and we plot the graph vehicle speed vs. vehicle density; e.g. see Fig. 42.

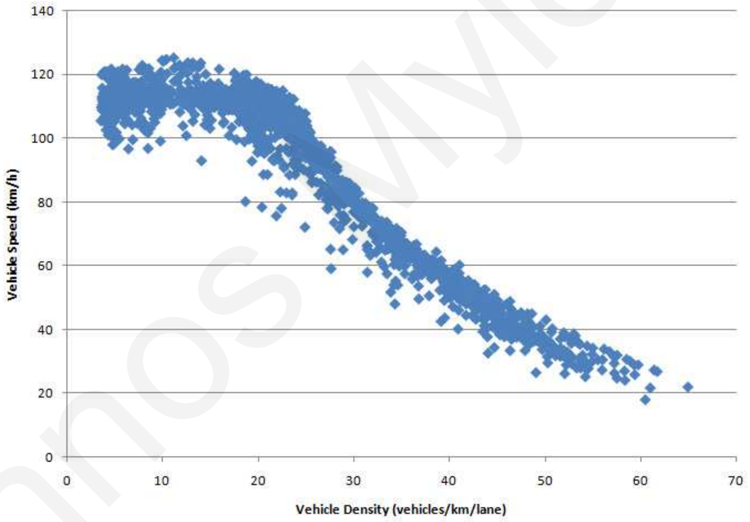


Figure 42: Vehicle Speed vs. Vehicle Density for the I110N freeway.

For all our simulations, we have identified three different traffic conditions, light, medium and heavy which have been extracted from the vehicle speed vs. vehicle density curve. For each topology we have created a different vehicle speed vs. vehicle density curve and a different set of traffic conditions. These traffic conditions were used to tune the VISSIM simulator and thus render our simulations more realistic. Below we describe the procedure we followed to create these traffic conditions for the heavy traffic condition for the freeway I110N; the procedure is the same for all traffic conditions and topologies.

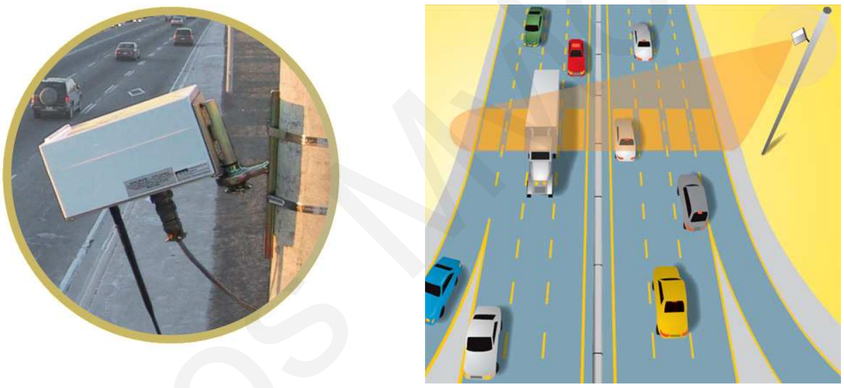
Procedure for creating heavy traffic condition:

1) Extract the vehicle speed and vehicle density values from the vehicle speed vs. vehicle density curve which corresponds to a heavy traffic condition. Usually this is the case where the vehicle density is over 40 vehicles per kilometers per lane, therefore we pick a point above that range.
2) Use the two values that we have obtained above to find the time and date that have been recorded. For the I110N freeway a date which meet this condition was 3/10/2009 at 8:00am.
3) Knowing the exact date and time that the vehicle speed and the vehicle density values have been recorded, obtain from PeMS systems more detailed information for that specific date and time. We use an interval of 5 minutes from 7:00am-8:00am on 3/20/2009.
4) Having obtained the speed of the vehicles in intervals of 5 minutes, we choose the minimum and the maximum speed that have been recorded and assign these speeds into the VISSIM simulator. VISSIM creates different speeds values between these two limits.
5) Apply this process for each entry/exit and main lanes of the freeway for tuning the VISSIM simulator correctly.

This process is used each time, we create a specific traffic condition (light, medium, heavy) for a certain location of a freeway. Each traffic condition is valid only for the section that has been created.

4.1.3 RTMS sensor for collecting Real Time Traffic Data

In the previous section, we show how we obtained real time traffic data using the PeMS website in California. In this section, we describe how we have collected real time traffic measurements using a different remote traffic sensor in a freeway in Cyprus. We utilize an RTMS remote traffic sensor made by EIS Traffic Solutions, which is capable of collecting traffic information from the freeways [23]. This remote sensor can be easily installed at the side of the road, see Fig. 43. This traffic sensor has the ability to collect significant traffic information such as traffic flows, vehicle speeds, and also categorizes vehicles based on their length whether they are vehicles or trucks. Fig. 44 shows the vehicle flows vs. time in each direction for the Nicosia-Limassol freeway that we have obtained using the RTMS traffic sensor for a specific time period. From these graphs, we have extracted the vehicle flows for the three traffic conditions that we have used in VISSIM simulator to tune it for the A1 road topology.

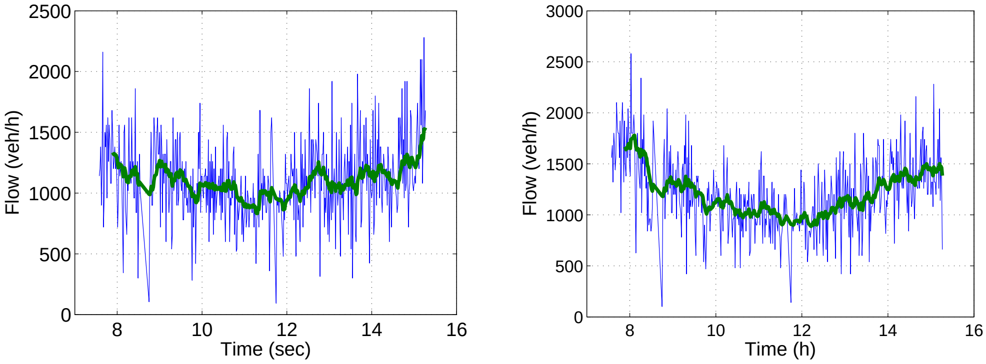


(a) RTMS Remote Traffic Sensor (b) RTMS collecting data from 8 lanes

Figure 43: RTMS Remote Traffic Sensor

4.2 Effect of Highway Topology and Traffic Conditions

The design parameters of the proposed SAPF scheme were tuned using field data from a specific section of the I110N freeway. This raises concerns regarding the ability of the protocol



(a) Vehicle Flows vs. Time (h) for Nicosia-Limassol Highway

(b) Vehicle Flows vs. Time (h) for Limassol-Nicosia Highway

Figure 44: Vehicle traffic flows captured by the RTMS remote sensor at Nicosia-Limassol Freeway

to maintain good performance as the topology changes, e.g. to different lane freeways, when the parameter values are kept constant. Of course, for each section, one may choose to ensure good performance by adopting the same design procedure off-line to tune the desired design parameter values of the protocol specifically for each topology type, and then communicate these values to all vehicles entering the section either through the vehicular ad hoc network or via fixed infrastructure on the roadside. However, this significantly increases the implementation complexity and so our approach has been to keep the parameter values constant to the ones suggested in section 3.3.3, and investigate the robustness of the protocol with respect to changing freeway topologies and traffic conditions, using simulations. Towards this end, we have evaluated the performance of the proposed protocol at two other sections of the freeway network in Los Angeles area. These sections were chosen to have different number of lanes in order to also investigate the effect of the number of lanes on the performance of the proposed scheme. Furthermore, we evaluate the proposed scheme by applying SAPF on a bidirectional freeway, the I110N freeway in Los Angeles to evaluate the effect of the traffic on the opposite direction on SAPF algorithm.

4.2.1 Effect of different number of Lanes

In this section, we evaluate the performance of the proposed protocol at two other sections of the freeway network in Los Angeles area. These two sections differ in the number of lanes of their road topology. The first road topology is a three lane section of the I105E freeway in Los Angeles area from the S. Main St. until the S. Wilmington entry spanning a distance of approximately 3.5km. The topology of the I105E is shown schematically in Fig. 45.

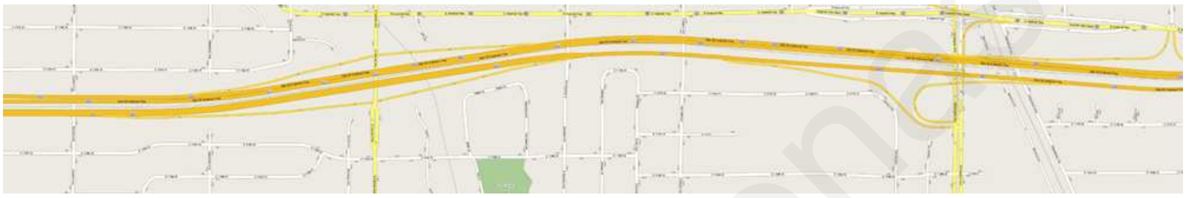


Figure 45: The section of the I105E freeway in the Los Angeles area from S. Main St. entry until the S. Wilmington entry.

The second road topology is a five lane section of the SR60E freeway in Los Angeles area from the S. Mednik until the Ve. Campo entry spanning a distance of approximately 4.5km. The topology of the SR60E is shown schematically in Fig. 46.

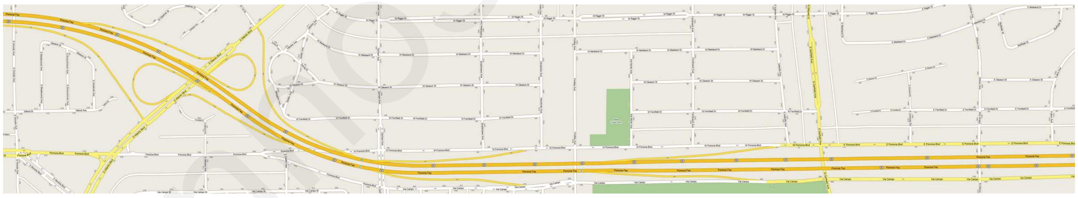
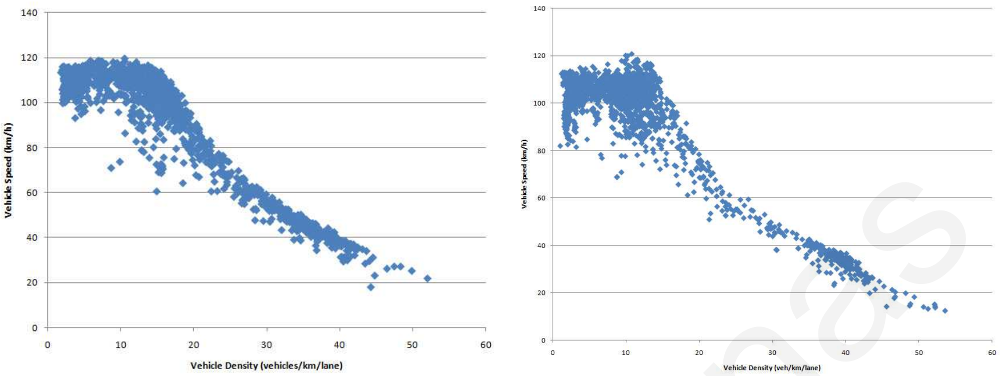


Figure 46: The section of the SR60E freeway in the Los Angeles Area spanning a distance of approximately 4.5km from the S. Mednik until the Ve. Campo entry.

As in the case of the I110N test site, the inflows were obtained from field data available through the PeMS system. For the I105E freeway vehicle speeds and density measurements were considered at Wilmington area, using the Vehicle Detector Station (VDS) 760196, in the period of 12 January 2009 until 10 April 2009. The resulting speed vs density curve, see Fig. 47a, is obtained using the procedure that we have described in section 4.1.2. Using the same procedure, we have obtained vehicle speeds and density measurements for the SR60E freeway as well, at Montebello area, using VDS 768444, in the period of 12 January 2009 until 10 April 2009. The resulting speed vs density curve is shown in Fig. 47b.



(a) Vehicle Speed vs. Vehicle Density for the I105E fwy.

(b) Vehicle Speed vs. Vehicle Density for the SR60E fwy.

Figure 47: Vehicle Speed vs. Vehicle Density for the 3 lane freeway I105E and the 5 lane freeway SR60E.

For each road topology, using the speed vs. densities curves we generate two sets of three traffic conditions: light, medium, and heavy. We have applied these two sets of traffic conditions to the two road topologies, the I105E and the SR60E, to evaluate the effects of the different number of lanes on SAPF algorithm. The network simulation parameters that were applied for both of the scenarios are shown in Table 7.

WLAN Parameters	**Values**
Transmission Power	0.00039W
Transmission Probability	SAPF and Blind Flooding
Time to Live	2
Data Rate	12Mbps
Packet Size	1024bytes
Destination address	Broadcast
WLAN Type	802.11a

Table 7: Simulation Parameters

In Fig. 48, we show the reachability achieved by blind flooding and the proposed SAPF scheme in all three considered test sites, as congestion increases. In Fig. 49 we show the corresponding latency values. It is evident, that in all cases, the SAPF scheme achieves high reachability values comparable to the ones achieved by blind flooding and at the same time manages to achieve significant reductions in the observed latency. It is noteworthy that the SAPF scheme achieves almost constant latency values, independent of the specific freeway topology and thus the number of lanes, and it is also independent of the level of congestion on the freeway. This demonstrates the robustness of the protocol and its ability to bring major improvements to the achieved performance independent of the road location and road conditions, it is applied.

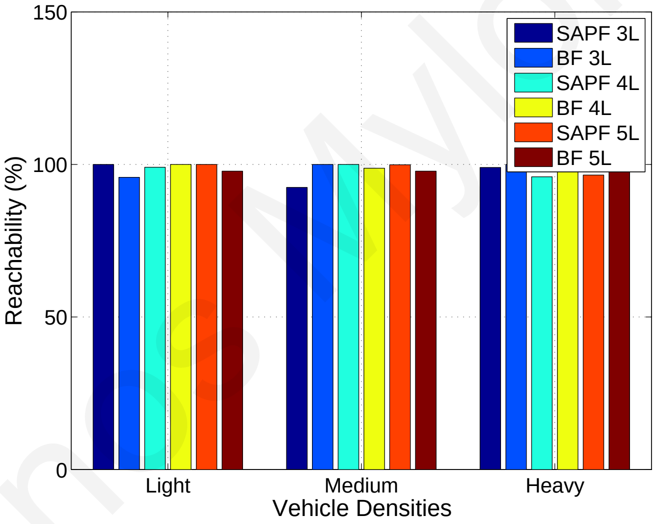


Figure 48: The SAPF scheme achieves high reachability comparable to the one achieved by blind flooding, in all three test sites and at all levels of congestion on the freeway.

4.2.2 Comparing custom designs of SAPF algorithm with the proposed scheme

A question that may arise is the following: how does the proposed SAPF algorithm compare with a SAPF version specifically designed for each freeway topology under consideration. Towards this end, we have designed two new versions of the SAPF algorithm, one for I105E and

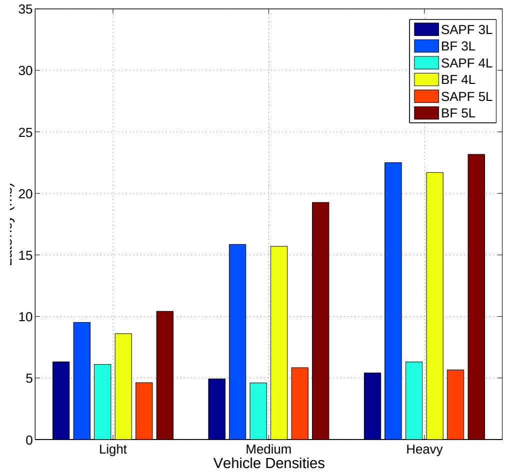


Figure 49: SAPF maintains constant latency values independent of the test site under consideration and independent of the level of congestion on the freeway. It outperforms blind flooding achieving much lower latency values, especially in cases of heavy congestion.

one for SR60E, and compare them with SAPF algorithm. We have repeated the procedure we described in section 3.3 for designing the new SAPF algorithms specifically for freeways, I105E and SR60E. The simulation models are the same as the ones described in section 3.3. The first step in this design procedure is to choose a set of vehicle density values. The values chosen were 2.5, 5, 7.5, 10, 12.5, 15, 20, 25 30, 35, 40, 50, 60, and 70 measured in vehicles per kilometer per lane. In the simulation experiments that we conducted, the vehicle density was set by appropriately setting the vehicle penetration rate in the test site under consideration. For each vehicle density value, a reachability vs rebroadcast probability graph was obtained. Rebroadcast probabilities in the range 0 to 1 in steps of 0.05 were considered. Fig. 50 and Fig. 51 show the reachability values obtained as we varied the rebroadcast probability for a subset of the vehicle density values under consideration. Both graphs exhibit similar behavior as in the section 3.3 and we reconfirm that there exists a critical threshold probability beyond which almost all vehicles receive the emergency warning message with high probability.

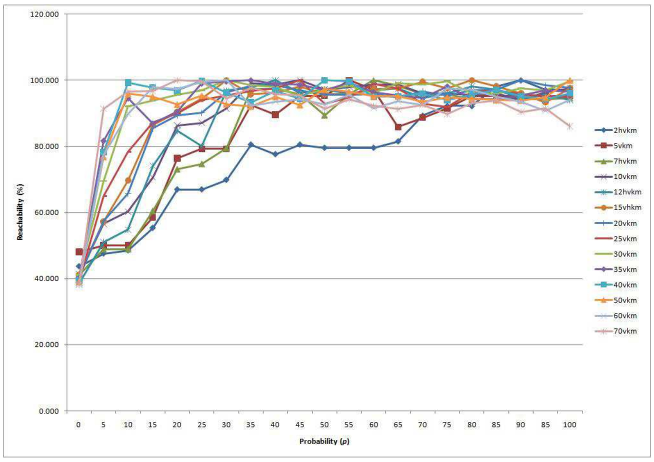


Figure 50: Reachability achieved as a function of the rebroadcast probability for different vehicular densities in a section of the I105E freeway

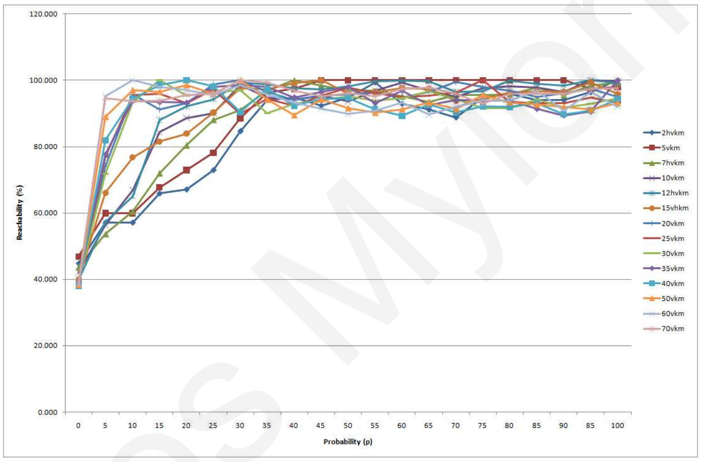
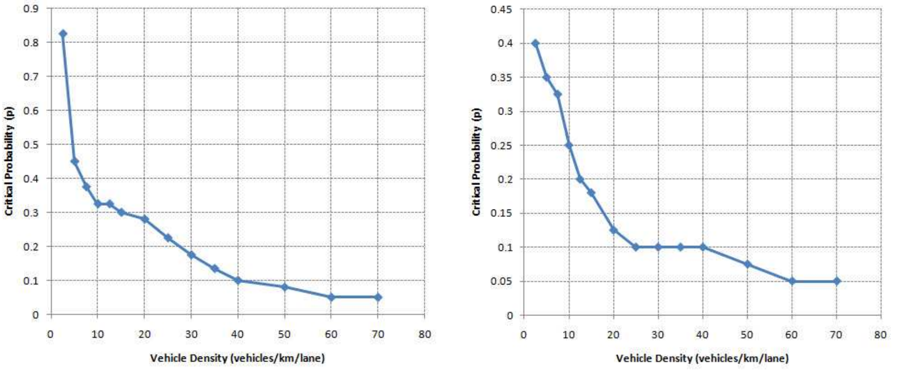


Figure 51: Reachability achieved as a function of the rebroadcast probability for different vehicular densities in a section of the SR60E freeway.

The next step is to create the critical probability vs. vehicle density curve for I105E and SR60E freeways. Fig. 52 shows the critical probability vs. vehicle density curve for the I105E and SR60E; as in the critical probability vs. vehicle density curve of freeway I110N, higher vehicular densities suggest smaller rebroadcast probability values which are sufficient to ensure high reachability and low latency of message delivery.

The next step is to combine the obtained rebroadcast probability vs. vehicle density function with the vehicle speed vs. vehicle density curve to derive the desired rebroadcast probability vs.



(a) Critical Prob. vs. Vehicle Density for I105E fwy.

(b) Critical Prob. vs. Vehicle Density for SR60E fwy.

Figure 52: As the vehicular density increases, the desired rebroadcast probability exhibits an exponential-like monotonically decreasing behavior

vehicle speed function, (see Fig. 25 for the approach). The composition of the functions depicted in Fig. 52 and Fig. 47 leads to the desired rebroadcast probability vs. vehicle speed function graph from where we extract the following rebroadcast probability equations:

For the I105E 3 lane freeway:

$$P_{I105E} = 0.003 * v + 0.00554 \tag{3}$$

For the SR60E 5 lane freeway:

$$P_{SR60E} = 0.0013 * v + 0.0475 \tag{4}$$

Recall for SAPF as from eq. (1) designed in chapter 3, we have:

$$P_{sapf} = 0.0022 * v + 0.024 \tag{5}$$

where p denotes the rebroadcast probability and v denotes the vehicle speed.

To avoid confusion among these versions of the SAPF algorithm, we labeled the two new algorithms as SAPF:3L and SAPF:5L for the freeways I105E and SR60E, respectively. Furthermore, in this section we name the original SAPF algorithm as SAPF:4L. In Fig. 53 we provide a visual comparison between the 3 algorithms between speeds of 15km/h to 110km/h, i.e. the linear part of the probability curve. The SAPF (4-lane) algorithm as expected lies between the 3 lane and 5 lane ones.

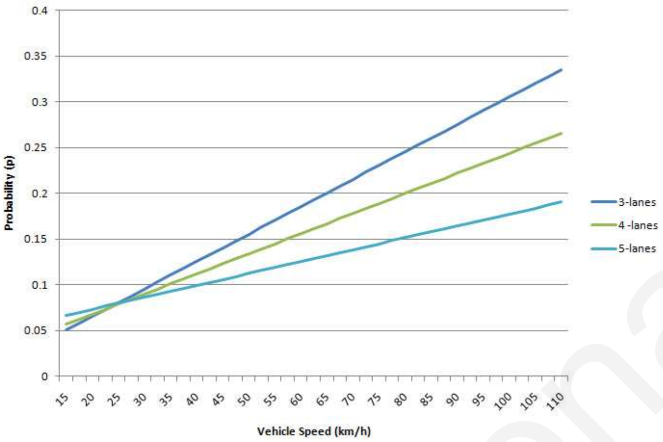
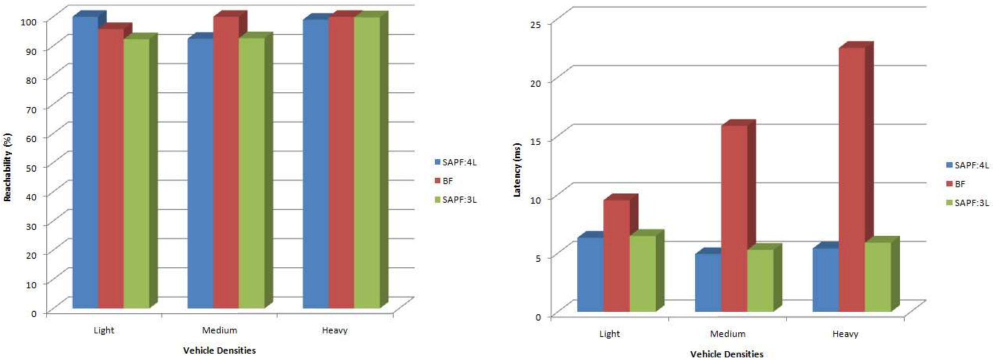


Figure 53: Probability (p) vs. Vehicle Speed (km/h)

We have implemented the two algorithms, SAPF:3L and SAPF:5L, in OPNET and run several simulations to evaluate their performance comparing to the SAPF:4L algorithm. The question we are trying to address here is how the SAPF:4L performs on a 3-lane (or 5-lane) freeway comparing to a SAPF:3L (or SAPF:5L) which was designed specifically for this freeway. Fig. 54 shows the reachability and latency values recorded by the SAPF:3L, SAPF:4L, and BF algorithms for each of the considered levels of traffic congestion.

It is worth noting that SAPF:4L has shown good performance, with only a very small degradation performance in terms of reachability, in the order of 2% at medium and heavy traffic conditions (Fig. 54a), however it shows slightly better performance in terms of delay (Fig. 54b). This is as expected by comparing the probabilities curve in Fig. 53

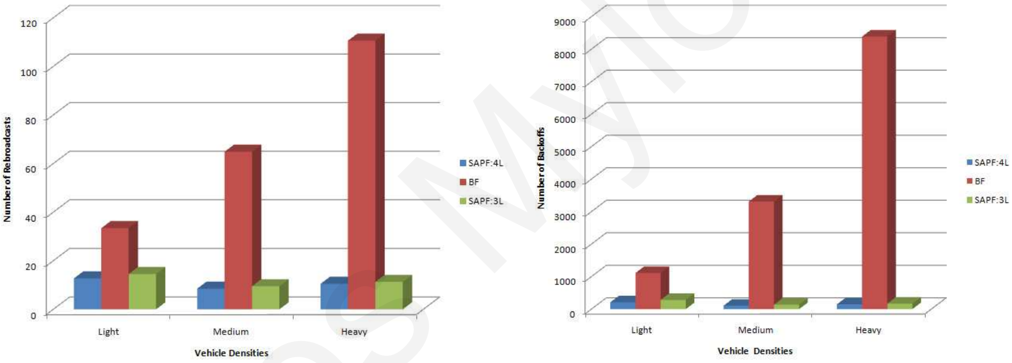
From Fig. 55 we observe the performance of the three algorithms with respect to the number of backoffs and the number of rebroadcasts occurring in the network. In both graphs SAPF:4L shows similar performance with SAPF:3L and both SAPF algorithms outperform BF algorithm.



(a) Reachability (%) vs. Vehicle Densities (b) Latency (ms) vs. Vehicle Densities

Figure 54: SAPF:3L and SAPF:4L demonstrate good performance by achieving high reachability and latency values in comparison to BF algorithm.

For a better understanding and justification of the results, we plot critical probability vs. vehicle density of the SAPF:3L and SAPF:4L algorithms, in Fig. 56. It is obvious from the graph that at heavy traffic conditions (values over 40 vehicles per kilometer per lane) the critical probabilities of the two algorithms are almost identical. However, at low and medium vehicle densities (lower than 40 vehicles per kilometer per lane) SAPF:4L has lower probability values than SAPF:3L.



(a) Number of Rebroadcasts vs. Vehicle Densities (b) Number of Backoffs vs. Vehicle Densities

Figure 55: SAPF:3L and SAPF:4L demonstrate good performance outperforming BF by recording lower values for the Re-Broadcasts and Backoffs metrics.

Next we complete our performance evaluation regarding the effect of the number of lanes on the SAPF algorithm, by applying SAPF:4L algorithm on five lane freeway, SR60E freeway and

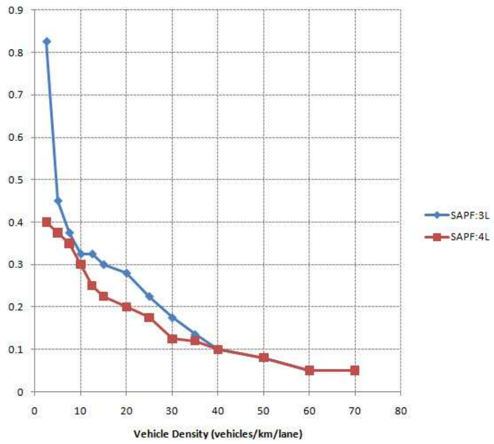
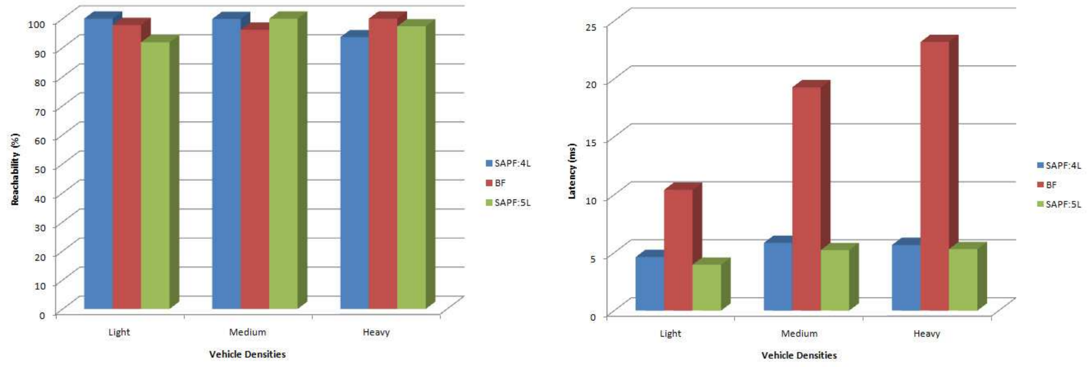


Figure 56: The Critical Probabilities vs. Vehicle Densities of the I105E and i110N freeways

compare it with performance of SAPF:5L, specifically designed for a 5-lane freeway. Fig. 57a shows the reachability values recorded by the SAPF:4L, SAPF:5L and BF schemes for each of the considered levels of congestion. It can be observed that at low traffic densities the SAPF:4L outperforms SAPF:5L and BF algorithm. At the medium traffic condition, SAPF:4L performs equally well as SAPF:5L and much better than BF algorithm. However, in heavy traffic condition BF performs better than the two SAPFs algorithms. Furthermore, SAPF:5L performs slightly better than SAPF:4L, in the order of 4%. With respect to the latency metric, we see in Fig. 57b that SAPF:4L algorithms performs comparably well in all traffic conditions as compared to SAPF:5L, with a difference of 0.5ms at worst case. Thus both outperform BF.

Fig. 58 shows the performance of the three algorithms with respect to the number of back-offs and the number of rebroadcasts that occurred in the network. Both graphs SAPF:4L and SAPF:5L perform very well (with SAPF:5L doing slightly better than the SAPF:4L), with both SAPF algorithms outperforming by a lot BF.

Fig. 59 shows the critical probabilities vs. vehicle densities of the SAPF:4L and SAPF:5L. We observe a similar behavior as in Fig. 56, that both of the algorithm have similar probabilities



(a) Reachability (%) vs. Vehicle Densities (b) Latency (ms) vs. Vehicle Densities

Figure 57: SAPF:5L and SAPF:4L demonstrates good performance. SAPF:4L manages to achieve very high reachability values in all traffic conditions while maintaining comparably low latency values with SAPF:5L. They both outperform BF.

(a) Number of Rebroadcasts vs. Vehicle Densities (b) Number of Backoffs vs. Vehicle Densities

Figure 58: The SAPF:4L and SAPF:5L perform comparably well and much better than BF for Rebroadcasts and Backoffs

in heavy traffic densities over 40 vehicles per kilometer per lane and at densities lower than 40 vehicles per kilometer per lane the SAPF:5L has lower probability values than SAPF:4L.

Based on the results that we have obtained in this section, it is evident that SAPF manages to maintain high reachability and low latency values regardless of the number of lanes and gives similar values as the SAPF:3L and SAPF:5L algorithms that have been specifically designed for the freeways I105E and SR60E (at worst 4% for reachability, and at times better than the others in terms of delay). These are encouraging results as with respect to using the proposed SAPF in all

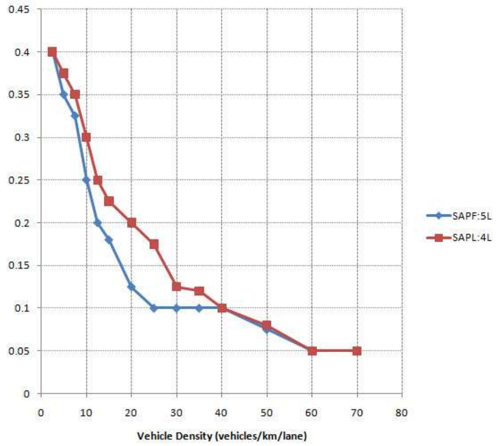


Figure 59: The Critical Probabilities vs. Vehicle Densities of the I110N and SR60E freeways

freeway topologies and traffic conditions. To increase our confidence in this conclusion we next consider a very different measurement device in a very different freeway, in Cyprus.

4.2.3 Applying SAPF algorithm in Cyprus freeways using real time traffic data

In this section, we show a comparison of the SAPF algorithm with BF algorithm in a two lane road topology. The topology of the simulation model used in our study is based on a section of the A1 freeway in Cyprus. The chosen test site is a two lane freeway which spans a distance of 6Km. It has been taken from a particular section of the freeway where high congestion and traffic accidents have been observed frequently even with low penetration rates. Fig. 60 shows the entry and exit lanes in the freeway that has been chosen for our study. It is apparent from Fig. 60 that the 3rd vehicle has collided with the 4th vehicle between the exit lane and the main lane of the freeway.

Our objective has been to evaluate the performance of the SAPF algorithm with respect to the chosen performance metrics and compare it with the BF algorithm using real time measurements obtained via a different measuring device to generate the different traffic condition. We conducted a number of experiments, in order to evaluate the performance of the SAPF scheme in scenarios

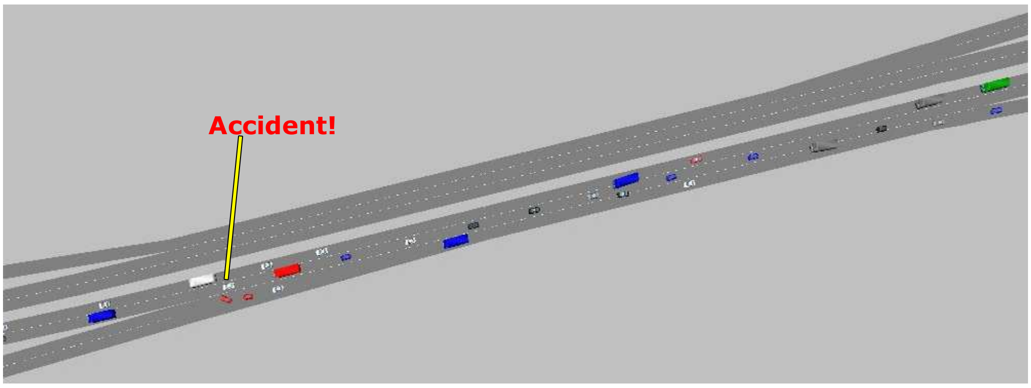
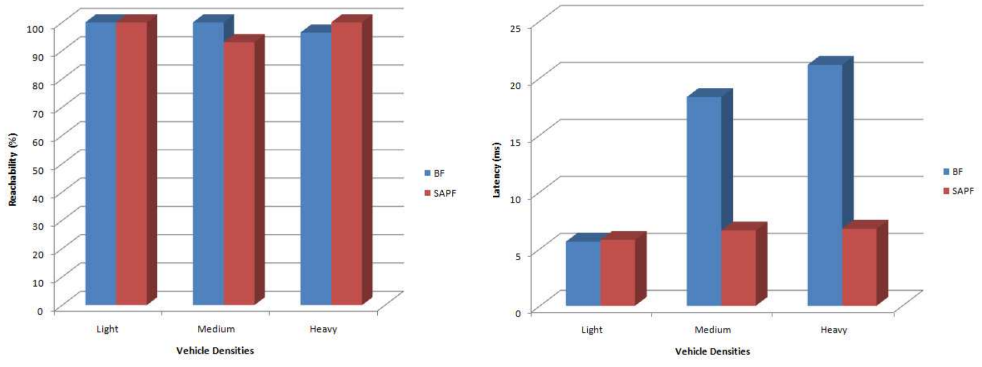


Figure 60: Snapshot of the section of Nicosia-Limasol freeway.

reflecting three types of congestion: light congestion, medium congestion and heavy congestion. The three traffic conditions were extracted from a real time data that have been collected using the RTMS remote traffic sensor discussed in section 4.1.3. Fig. 44 shows the vehicle flows vs. time in both directions for the Nicosia-Limassol freeway. From these graphs, we have extracted the flows of the three traffic conditions and have tuned the VISSIM simulator for the considered scenario.

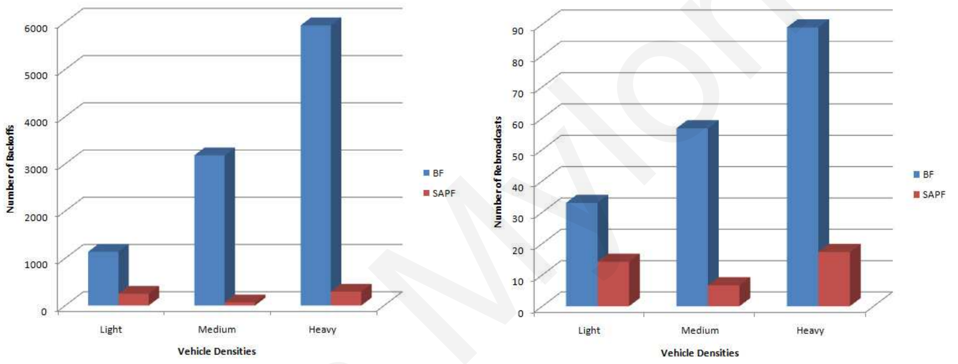
Fig. 61a depicts the reachability for the three penetration rates under consideration. Both algorithms, SAPF and BF exhibit high reachability in all vehicle densities. SAPF algorithm outperforms the BF algorithm in almost all vehicle densities, except at the medium congestion where the BF algorithm performs much better. Considering the latency, see Fig. 61b, the SAPF algorithm outperforms BF algorithm in all traffic conditions by recording latency values in the range of 7ms in comparison with the BF algorithm where its latency varies from 11ms to 30ms. Fig. 62 shows the number of backoffs and the number of rebroadcasts that occurred in the network; SAPF algorithm outperforms BF algorithm significantly. Based on Fig. 62 which represents the protocol overhead, it is obvious that SAPF algorithm generates much less contention in the network in all vehicle densities.

Thus, we may conclude that SAPF has performed adequately in reachability and has outperformed BF in terms of latency in all traffic conditions showing its robustness in performing well in



(a) Reachability (%) vs. Vehicle Densities (b) Latency (ms) vs. Vehicle Densities

Figure 61: SAPF algorithm demonstrates acceptable performance in comparison with BF algorithm in Cyprus freeway.



(a) Number of Backoffs vs. Vehicle Densities (b) Number or Re-Broadcasts vs. Vehicle Densities

Figure 62: SAPF algorithm achieves lower overhead in comparison with BF algorithm in Cyprus freeway.

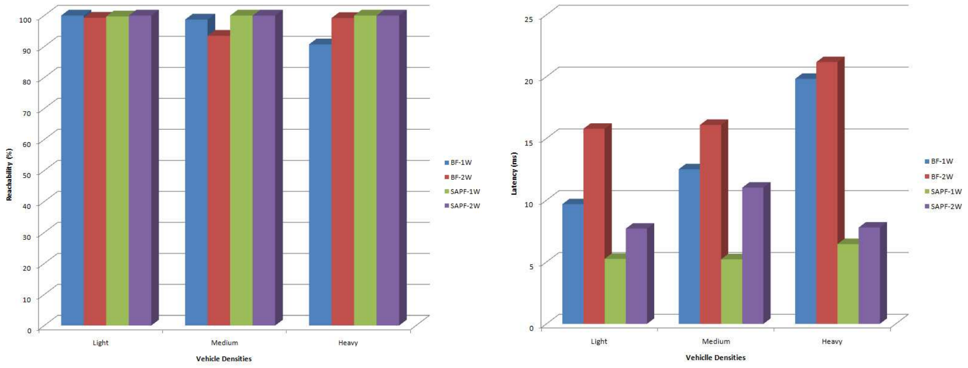
different topologies and traffic data, even when considering a design derived from using a 4 lane freeway data.

4.2.4 Effect of a Bi-Directional Freeway topology

SAPF algorithm was designed and evaluated on one way traffic. One might question how SAPF performs if the opposite traffic was also taken into consideration. Earlier we have shown that SAPF has not been significantly affected by the number of lanes. It is interesting to observe whether vehicles moving into the opposite direction have any (positive or negative) effect on the performance of SAPF algorithm. One might expect that the vehicle speed will not always be representative of the density of the vehicles, since there will be additional vehicles in the opposite direction. It is anticipated that the worse simulations is when the opposite stream is congested. We evaluated the performance of SAPF algorithm using a bidirectional traffic topology of the freeway I110SN in Los Angeles. The reference model and the simulation parameters are exactly the same as in the section 3.3.3. As in the case of the I110N test site, the inflows were obtained from field data available through the PeMS system. The only difference in this scenario is that we have taken measurements in both directions at certain times and dates. To avoid confusion between the one way traffic and the bi-directional traffic of the freeway I110SN, we have named SAPF algorithm as SAPF:1W and SAPF:2W. SAPF:1W represents the SAPF algorithm applied on one way direction on the I110N freeway (North direction), and SAPF:2W represents the SAPF algorithm applied when considering traffic on both directions on the I110SN freeway, (South and North directions).

Fig. 63 shows the reachability and the latency curves of the SAPF and BF algorithms in the considered topology. It is evident from these two graphs that SAPF:1W and SAPF:2W perform very well under all traffic conditions, achieving high reachability and maintaining low latency. SAPF:2W performs better than BF:2W algorithm in all traffic conditions, by achieving higher reachability values and lower latency values in the range of 7ms to 11ms in contrast to 15ms to 21ms that BF:2W achieves.

The question here is whether SAPF:2W performs comparably to SAPF:1W which takes does not account for the traffic in the opposite direction. Before any assessment can be made, we analyzed the state of the two traffic streams. We will focus on the ”medium” traffic scenario using the vehicle speeds and densities that exist in both directions. In the ”medium” traffic condition for the freeway I110N (as defined for the one way scenario), we have 423 vehicles with vehicle speeds in the range of 41-98km/h, in contrast to the opposite traffic of the freeway, I110S for



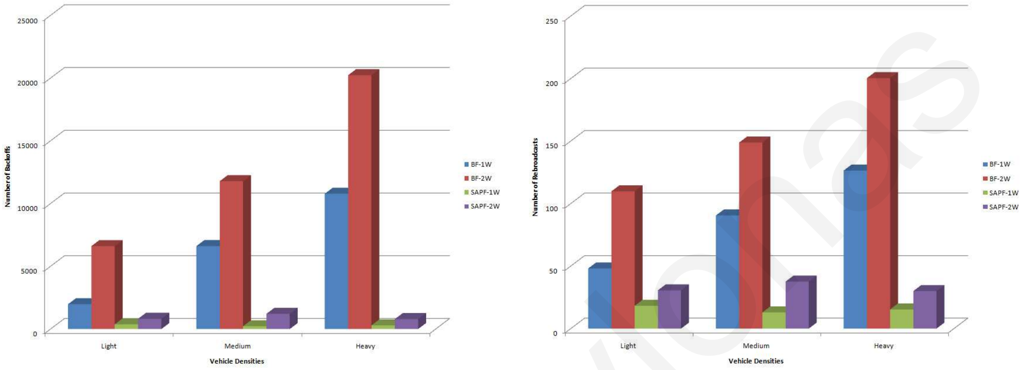
(a) Reachability (%) vs. Vehicle Densities (b) Latency (ms) vs. Vehicle Densities

Figure 63: SAPF performance evaluation in bidirectional traffic

the same time of period, when we have an extra 276 vehicles with vehicles speeds 100-108km/h. Therefore, SAPF operating in the direction of the accident broadcasts with low probabilities since vehicle speeds are in the range of 41 to 98km/h, while at the same instant on the opposite traffic direction, I110S, SAPF broadcasts with higher probabilities since vehicles speeds are in the range of the 100 to 108km/h. Fig. 64 shows an instant of the bi-directional traffic where on the I110N direction there is a medium traffic and on the I110S direction there is not much traffic.

Figure 64: Snapshot of the section of I110SN freeway for bi-directional traffic.

This has an effect on SAPF:2W causing a degradation of performance in comparison to SAPF:1W as we have an increased number of vehicles on the road beyond what the vehicle speed information can ascertain. In this case considering the direction of the accident SAPF selects a lower rebroadcast probability as, based on the speed reading the vehicle density is less as it does not account for the vehicles in the other lane. In case of the opposite lane, the vehicle speed is high. The vehicles assume a very low density and set the rebroadcast probability to 1. We can verify this by observing an increased number of backoffs, increased number of rebroadcast vehicles and higher latency values in contrast to SAPF:1W; see figures 65 and 63b.



(a) Number of Backoffs vs. Vehicle Densities (b) Number of Re-Broadcasts vs. Vehicle Densities

Figure 65: SAPF performance evaluation in bidirectional traffic

Considering above results it can be concluded that SAPF can perform reasonably, when both directions are considered, however its performance can be improved if we can inform vehicles in the opposite direction not to rebroadcast. This can be achieved by using a GPS system to provide the direction of the abnormal vehicle and include this information in the EWM. As the EWM is received by all approaching vehicles, in both directions, they will compare their direction with the direction of the EWM and if they match they will use SAPF to disseminate the EWM, otherwise the message will not rebroadcasted. Some discussions with practical considerations, including the use of GPS maps is included in section 4.5.

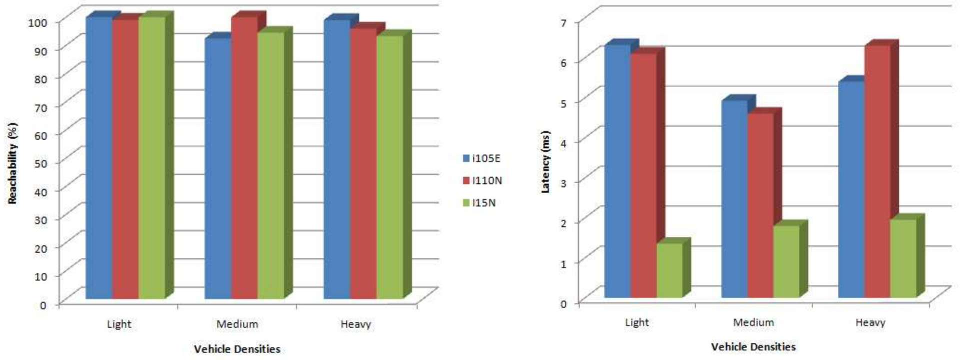
4.2.5 Effect of the Speed Limit of the freeways

The SAPF algorithm was designed for a specific road topology, the I110N a four lane freeway, with a speed limit of 105km/h. The question that may arise is how does SAPF perform on freeway sections with different speed limits. One might argue that since we rebroadcast with probability 1 when the speed is above 110 km/h the algorithm might observe slight degradation in performance, when the speed limit exceeds this value. To investigate the effect of speed limits, we consider the application of the SAPF algorithm in the following three freeway sections with different speed limits.

- I105E a three lane freeway with a speed limit of 90km/h see Fig. 45.
- I110N a four lane freeway with a speed limit of 105km/h, see Fig. 20.
- I15N a four lane freeway with a speed limit of 112km/h, see Fig. 66.

Figure 66: The section of the I15N freeway in California.

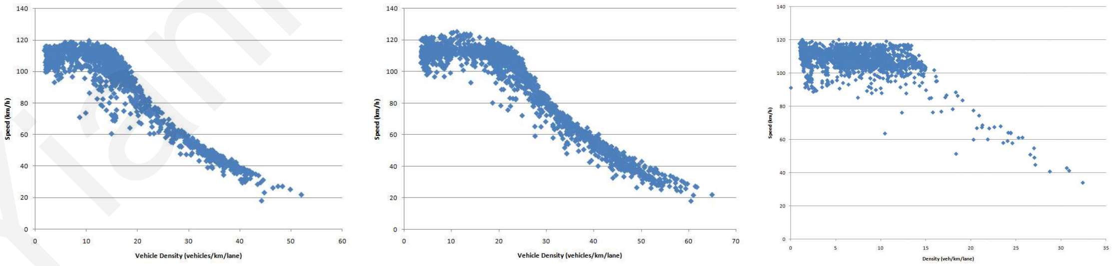
The reference models, the simulation parameters and the performance metrics that were used for the above three road topologies are the same as in the section 4.2. Fig. 67 shows the reachability and latency values, recorded by SAPF algorithm for the three freeways I105E, I110N and I15N for the considered levels of congestion. It is evident that SAPF manages to maintain high reachability values over 90% regardless of the different speed limits of each freeway, and also maintains good latency; 6ms at worst case.



(a) Reachability (%) vs. Vehicle Densities (b) Latency (ms) vs. Vehicle Densities

Figure 67: SAPF algorithm still achieving very high reachability values and low latency values even at different speed limits

Fig. 68 shows the three speed density curves for the three considered scenarios. It is apparent that the speed density curve of the I105E freeway exhibits similar behavior as the speed density curve of I110N freeway with slightly increased values of the I105E freeway. Freeway I15N is a four lane freeway in Los Angeles area with a speed limit 112Km/h. As shown from the speed density curves there is not much observed medium and heavy traffic conditions as observed in the other two freeways. This one may argue that is is expected since the transportation authorities do not set high speed limits at road sections where there is heavy traffic. The latency for this freeway is much less than the other 2 freeways.



(a) Vehicle Speed vs. Vehicle Density for I105E fwy. (b) Speed vs Density for I110N fwy. (c) Vehicle Speed vs Vehicle Density for I15N fwy.

Figure 68: Vehicle Speed vs. Vehicle Density curves for the freeways I105E, I110N and I15N, respectively.

4.3 Effects of Design Parameters

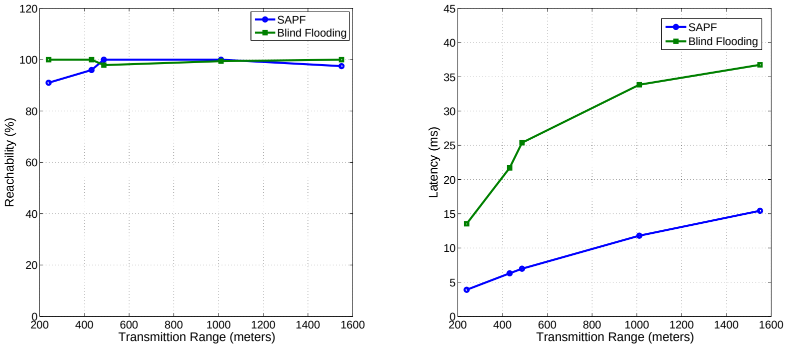
In this section, we evaluate the effects of two design parameters, the distance of transmission range and the number of hops. Both of these parameters extends the coverage area of the emergency warming message which can be related to the driver ”reaction time ” and ”safety distance”, discussed in Chapter 3. Therefore it is essential to evaluate the impact that these two parameters may have on the performance metrics.

4.3.1 Effect of the Transmission Range

Despite the fact that the 802.11p standard has a maximum transmission range of 1000m, vehicles may choose to vary their transmission range during their operation. Power control in vehicular ad hoc networks is a major issue, as varying transmission range values may bring significant improvements in the achieved end to end performance due to the dynamic nature of the vehicular density. It is thus important to ensure that the SAPF scheme continues to perform well as the transmission range changes. We again consider the reference scenario under heavy congestion and we compare the performance of blind flooding with the SAPF scheme for transmission range values in the range 200m to 1000m in steps of 100m. Fig. 69 shows the recorded reachability and latency values as the transmission range changes. We observe that in all cases the SAPF scheme outperforms blind flooding as it achieves high reachability values and significantly reduces the observed latency. Also, as the transmission range increases we observe an increase in the latency, however this increase is at an acceptable rate and it is still within acceptable values.

4.3.2 Effect of the number of hops

The number of hops that emergency warning messages travel before they are dropped is a design parameter of the protocol, whose value can be changed based on the transmission range of



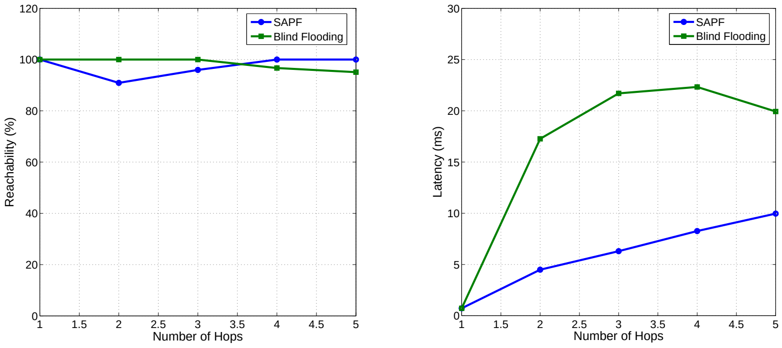
(a) Reachability (%) vs. Transmission Range (meters)

(b) Latency (ms) vs. Transmittion Range (meters)

Figure 69: SAPF achieves very high reachability values and records very low latency values compare to BF as the transmission range changes

the vehicles engaged in the vehicular ad hoc network and the desired area within which all vehicles should receive the emergency warning message ("safety distance"). It is thus important for the SAPF scheme to continue to perform well as the value of this parameter changes. In this section we investigate the ability of the SAPF scheme to achieve the latter using simulations. We consider the reference scenario on the I110N freeway section and we set the inflows to values which cause the considered freeway to become heavily congested. The number of hops was changed by making appropriate modifications to the time to live field in the packet header. Values in the range 1 to 5 were considered. Fig. 70a compares the reachability values recorded by blind flooding and the SAPF scheme as the number of hops increases. Fig. 70b shows the corresponding latency values.

We observe high reachability values as the number of hops increases for both blind flooding and the SAPF scheme, recording high reachability values close to 100%. However, the SAPF scheme outperforms blind flooding as it consistently achieves smaller latency of message delivery values. Note that as the number of hops increases the latency of both the SAPF scheme and blind flooding increase, which is expected, as the message traverses a larger distance over a larger number of nodes.



(a) Reachability (%) vs. Number of Hops (b) Latency (ms) vs. Number of Hops

Figure 70: SAPF achieves very high reachability values and records very low latency values outperforming BF as the number of hops increased

4.4 Comparative Performance evaluation of SAPF with GPS enabled protocols

In previous sections, we have compared SAPF against BF for several road topologies and traffic conditions. In this section, we compare SAPF algorithm with two GPS algorithms that have been implemented in OPNET Modeler. As pointed out in Chapters 2 and 3, the most popular and effective approach to mitigate the effects of the broadcast storm problem in VANETs and design a protocol which can facilitate the fast and reliable transfer of emergency warning messages to the vicinity of an unexpected event has been to choose vehicles on the boundary of the transmission range to rebroadcast the emergency warning message. However, this approach relies on the existence of a positioning system, such as GPS, with an added overhead which allows for the exchange of the positions data between high speed moving vehicles and which may not always be available or functioning. The availability of a positioning system enlarges the allowable design space. We consider two GPS algorithms. The first algorithm represents an idealized GPS algorithm, which does not take into account the protocol overhead (GPS with zero overhead; GPSzo) whilst the second one is a GPS algorithm (GPSwo), which takes into consideration the protocol signalling overhead, which includes all the necessary signalling information for exchanging positioning information between high speed moving vehicles and hence implements a more realistic scenario. Note that in both cases we assume a 100% accurate positioning device. If positioning error are present, and how accumulate with time is beyond the scope of the thesis. In any case if we take positioning error into account the GPS based scheme performs can only degrade. Also note that for SAPF any error in the speed measurement are in one direction (overestimating true speed), which can be somewhat compensated. It is worth stating again that in this work, we proposed an alternative which does not rely on the existence of such a positioning system. It thus reduces the implementation complexity at a potential cost on achievable performance. This section investigates this tradeoff.

4.4.1 SAPF vs. GPS Idealized Protocol with zero overhead, GPSzo

In this section we investigate the degree to which the proposed SAPF scheme deviates from the idealized GPSzo algorithm. This comparison will allow us to compare how far we may be from an ”idealized” protocol. We consider the reference scenario on the I110N freeway section in light, medium and heavy traffic conditions and we compare the performance of blind flooding and the proposed SAPF scheme with that of the GPSzo protocol which utilizes a GPS system which ensures that only one vehicle on the boundary of the transmission range of each vehicle retransmits the emergency warning message. In the simulation the positioning information is made available globally to all vehicles, without the need to provide any signalling or delay as it would be the case in a real system and further we assume that the positioning accuracy of the GPS is error free.

In case of the GPSzo protocol used in a VANET, at the instance of an accident, the AV (abnormal vehicle) will broadcast the emergency warning message to its neighbors and select a vehicle that lies at the outermost of its transmission boundary to be the rebroadcasting vehicle of the

EWM. This process is repeated each time a vehicle receives a message and the TTL value of the message is higher than 0.

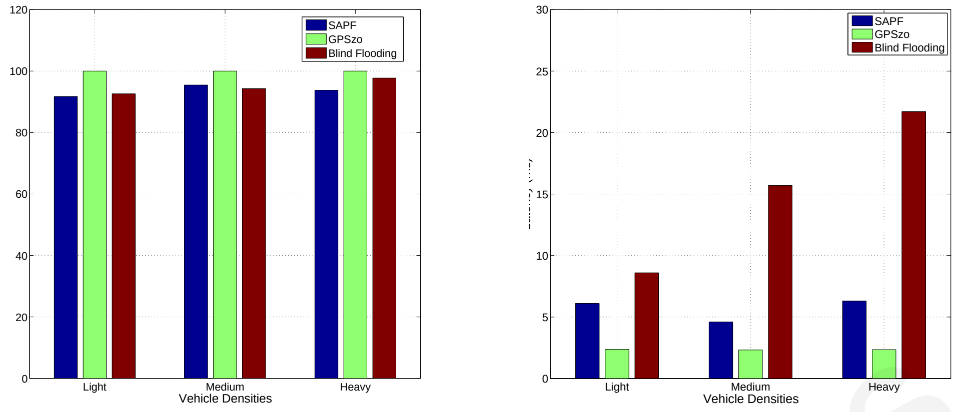
GPSzo algorithm pseudocode:

```
while (node $n$ receives EWM for a first time and it is not the originator of the EWM and TTL $\geq 0$)
    find the vehicle which is the furthest away but within its transmission range
    decrement the TTL value of the EWM
    (re)-broadcast EWM including in the EWM the MAC ID of the next rebroadcasting vehicle
endwhile
```

Fig. 71a shows the reachability values achieved by the three protocols as congestion increases and fig. 71b shows the corresponding latency values. It is evident that all three protocols achieve high reachability values. In addition, we observe that despite the fact that blind flooding reports increasing latency values as congestion increases, both the SAPF scheme and the GPSzo protocol manage to maintain almost constant values. As expected, the GPSzo protocol reports smaller latency values than SAPF, with the difference being approximately 3ms which is within an acceptable range for a design that relies only in vehicle speed. This demonstrates the effectiveness of SAPF scheme to significantly reduce the implementation complexity, at the cost of acceptable reductions in the achieved performance relative to the GPSzo solution thus making it attractive for deployment in real situations, given it only uses a local variable and does not require any exchange of data with neighboring vehicles. This will be contrasted in the next section with a GPS based algorithm which includes all the necessary signalling positioning overhead.

4.4.2 SAPF vs. GPS with signaling overhead included, GPSwo

In the previous section 4.4.1, we have shown that the SAPF algorithm performs almost equally well as the idealized GPSzo protocol by achieving high reachability values and maintaining acceptable latency values in the order of a few milliseconds. However, the GPSzo protocol has been



(a) Reachability (%) vs. Vehicle Densities

(b) Latency (ms) vs. Vehicle Densities

Figure 71: As congestion increases, the three protocols exhibit comparable performance in terms of the reachability achieved. In terms of the latency metric BF reports increasing latency values whilst SAPF and the "idealized" GPSzo protocol manage to maintain almost constant latency values with SAPF exhibiting higher values than GPSzo but lying within acceptable bounds.

implemented in OPNET Modeler without the necessary signalling overhead. In this section, we compare SAPF algorithm with the GPSwo protocol that has been fully implemented in OPNET Modeler to include all the necessary signalling information to represent a more realistic scenario and evaluate its performance with respect to its overhead included. Again, it is assumed that the positioning device is 100% accurate.

In case of the GPSwo protocol used in a VANET, at the instance of an accident, the AV (abnormal vehicle) will broadcast the emergency warning message to its neighbors and select a vehicle that lies at the outermost of its transmission boundary to be the rebroadcasting vehicle of the EWM. This process will be repeated each time a vehicle receives a message and the TTL value of the message is higher than 0. This necessitates that all vehicles in the network are aware of the location of their neighbors. The location of each vehicle is most commonly obtained locally within each vehicle, from a GPS device. Thus to locate the furthermost vehicle in their transmission range, each vehicle must exchange small hello messages periodically including its identity (MAC address or IP address) and its location in the hello packet. A vehicle receiving a hello packet extracts the identity and location from the appropriate fields of the packet and computes the distance between the creator of the hello packet and itself. Furthermore, it updates its neighborhood table recording MAC vehicle's ID, the distance, and the time it was received. It is evident that the frequency of message exchange (hello interval time) will influence the accuracy (and staleness) of the vehicle position information.

GPSwo algorithm:

```
while ((node's $hellointervaltime$ == expires) or (node $n$ receives a message))
    if (hello interval == expired )
        broadcasts a hello message including: MAC ID, Location
    elseif (message=hello message received)
        extract the MAC ID and the location, calculate the distance and process it
    elseif node $n$ receives EWM for a first time and it is not the originator of the EWM and TTL $\geq$ 0)
        find the vehicle which is the furthest away within its transmission range
        decrement the TTL value of the EWM
        (re)-broadcast EWM including in the EWM the MAC ID of the next rebroadcasting vehicle
    endif
endwhile
```

The GPS scheme described above was implemented in OPNET Modeler by applying all necessary modifications to the 802.11 WLAN station model. The supported features of the GPSwo protocol are listed below:

- **GPS Hello Interval**: Defines the time interval between the hello packets.
- **GPS Hello Variance**: Defines the range of the randomness of the transmitted hello packets (picks a random number from 0 to variance number). After the Hello Interval has expired, the hello message will be generated in the range of the variance randomly.

- **GPS Hello Initial Time**: The first hello packet that will be created will be transmitted based on a random time between the GPS Start time and the Hello Initial time.
- **GPS Hello Start Time**: Defines the startup time of the hello packets.
- **GPS Hello Stop Time**: No hello messages will be transmitted after hello stop time.
- **GPS Hello Distance**: Hello messages which are further away from this distance will not be processed by the receiving vehicle.
- **GPS Hello Garbage Collector**: How often to remove stale vehicles from the neighborhood table.

In this model the transmission power was set to 0.0039W to ensure a transmission range around 300m. The vehicles are configured to operate in broadcast mode with no ACK/CTS/RTS mechanisms. The time to live field is set to 2 in order to guarantee a maximum 3-hop transmission; see Table 8. This creates a multi-hop transmission range of approximately 1000m considered to be the given ”safety distance”. The packet size is set to a constant value of 1024 bytes. In all simulation experiments, the accident is assumed to occur 700 seconds after the simulation start time, approximately 1km before the Vernon exit. All simulations run for 1000 seconds simulated time. Our objective has been to investigate the performance and the robustness of the proposed scheme with respect to the chosen performance metrics.

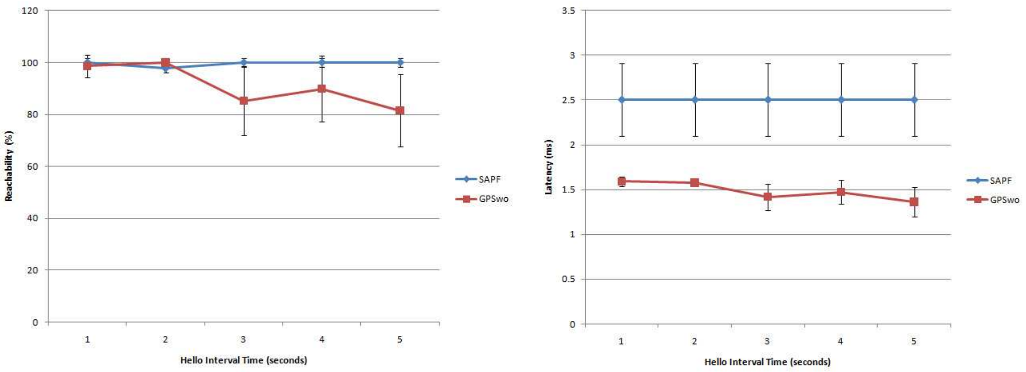
We consider the reference scenario on the I110N freeway section in light, medium and heavy traffic conditions and we compare the performance of the SAPF algorithm with GPSwo algorithm. In all figures for this scenario, we also show the 80% confidence intervals. Fig. 72 shows the reachability and latency vs. hello interval time under a heavy traffic condition. The hello interval time shows the periodicity of the hello packets which has been set from 1s to 5s in steps of 1s.

WLAN Parameters	**Values**
Transmission Power	0.00039W
Transmission Probability	SAPF and GPS Alg.
Time to Live	2
Data Rate	12Mbps
Packet Size	1024bytes
GPS Hello Interval	0.95s, 1.95s, 2.95s, 3.95s, 4.95s
GPS Hello Variance	0.1s
GPS Hello Initial Time	4s
GPS Hello Distance	315m
Destination address	Broadcast
WLAN Type	802.11a

Table 8: Simulation Parameters

On average, each vehicle moves approximately 15 meters per second for the considered scenario, so by transmitting every second a hello packet, we have more accuracy for the position of the vehicles, and higher reachability values. However, it also creates large overhead. If we increase the hello interval time, we have less accuracy for the position of the vehicles but less overhead and lower reachability values. Therefore, since on average the vehicle in this scenario moves 15m/s, we have set the hello time interval from 1s to 5s, so we have updates in the range of 15 to 75 meters at most. These values are adequate for our simulation purposes since in a heavy traffic condition covering an area of 75m may contain a large number of vehicles. The same values have been considered for the medium and light traffic conditions, since the vehicles in these scenarios have higher velocities but less traffic as compared to the heavy traffic scenario.

It is evident from Fig. 72a that the SAPF algorithm achieves almost the same values of reachability as the GPSwo algorithm with a hello time interval 1s and 2s . However, in hello time interval over 3s SAPF outperforms GPSwo algorithm, reaching 100% reachability. The reason that GPSwo algorithm suffers some performance degradation is due to the stale positions of the vehicles at these time intervals. We discuss this in more detail later in this section. Fig. 72b shows the latency achieved by the two algorithms and in particular shows SAPF to be 1ms slower than



(a) Reachability (%) vs. Hello Interval Time (s) (b) Latency (ms) vs. Hello Interval Time(s)

Figure 72: SAPF performs equally well as a GPSwo algorithm in low hello intervals, and in some instances even better in heavy traffic conditions with hello intervals greater than 1. With respect to the latency SAPF is 1ms only slower which can be considered negligible.

GPSwo algorithm, which can be considered negligible, considering the overhead that the GPSwo algorithm generates. In Fig. 72, we can also see the confidence intervals of the SAPF and GPS algorithms. We can see that for reachability the GPS-based algorithm has very high variance, even dropping by about 15% (especially for high hello interval values). SAPF shows a very much smaller deviation regarding reachability, however it increases when considering the latency, but still remaining within acceptable limits. Overall, the SAPF performance can be considered good. Similar conclusions can be drawn for the rest of the results when considering confidence intervals, so we will not discuss further.

Fig. 73a shows the number of backoffs that occurred in the network by the two algorithms. It is obvious that GPSwo algorithm creates a large overhead under all traffic conditions and in particular with hello interval times in the range of 1s and 2s generating many collisions and backoffs. It is obvious that SAPF outperforms GPSwo algorithm considerably, recording a number of backoffs values in the range of 300 as compare to GPSwo which records 1100 to 5600. It is worth noting that there is an exponential increase of the protocol overhead, as we decrease the hello interval time. In Fig. 73b we show the number of hello messages that have been sent to the network by the GPSwo algorithm in a time frame of 12 seconds which is in the region of 1000’s. This can be contrasted with the number of messages that are created by SAPF algorithm which is only 12 messages, since it only broadcasts a message at the instance of the accident. Fig. 74 shows how many vehicles have rebroadcasted the emergency warning message. As it is expected GPSwo algorithm rebroadcasts the message 3 times only and SAPF 12 times. Overall, the signalling needs of SAPF remains much less that the GPSwo algorithm.

(a) Number of Backoffs vs. Hello Interval Time (s) (b) GPS Hello Messages vs. Hello Interval Time (s)

Figure 73: SAPF outperforms GPS algorithm by achieving low protocol overhead in heavy traffic conditions.

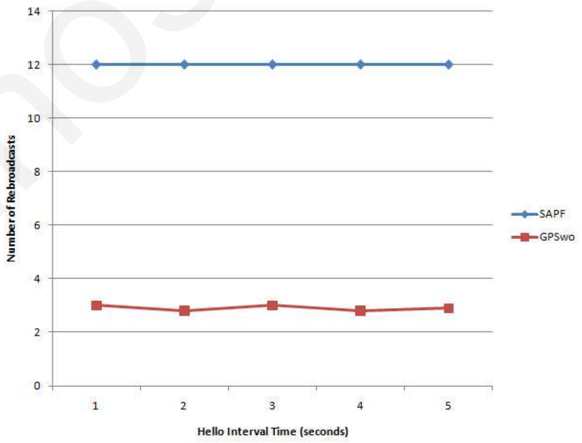
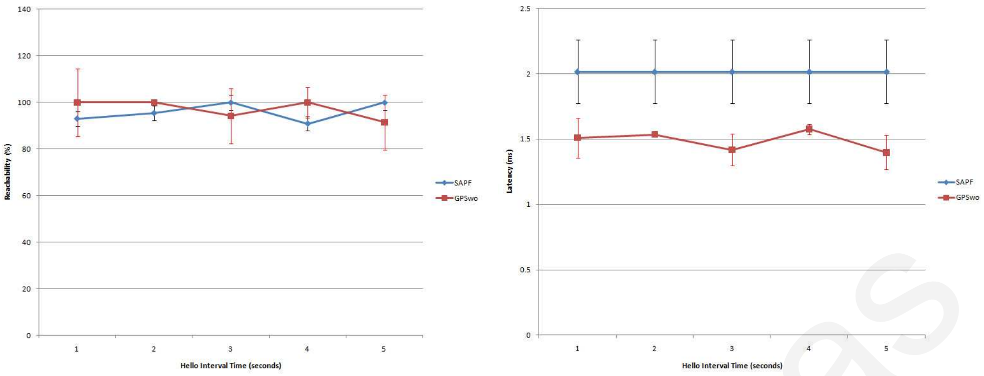


Figure 74: Number of Vehicles that Re-Broadcasts the message vs. Hello Interval Time (s)

For the medium and light traffic conditions we only show the reachability and latency curves since the results are similar to the ones we have discussed in the heavy traffic condition. Fig.

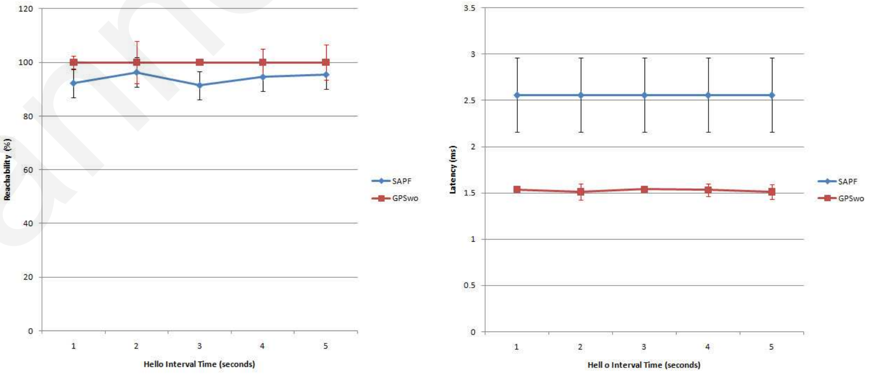
75 shows the reachability and latency values for the medium traffic condition. Both algorithms achieve high reachability values over 95% and very low latency.



(a) Reachability (%) vs. Hello Time Interval (s) (b) Latency (ms) vs. Hello Time Interval (s)

Figure 75: In medium traffic condition both algorithms maintain high reachability and low latency values

For the light traffic condition it is clear that GPSwo performs better than SAPF with respect to reachability and latency. However, SAPF still maintains high reachability values in the range of 95% and above, and with respect to latency it is only 1ms slower than GPS algorithm, see Fig 76. These figures are again very acceptable, given the simplicity and considerably less overhead required by SAPF.



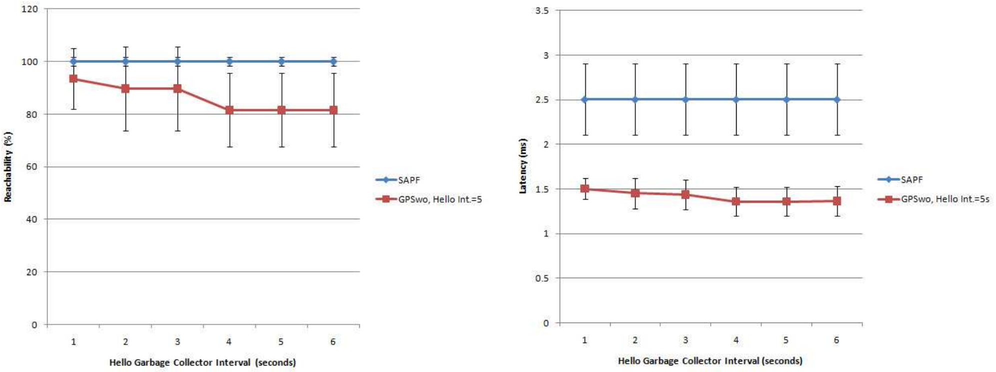
(a) Reachability (%) vs. Hello Time Interval (s) (b) Latency (ms) vs. Hello Time Interval (s)

Figure 76: In light traffic condition SAPF maintains high reachability in the range of 95% and low latency values

In Fig. 72 we observed that at hello time intervals equal to five seconds, the reachability of the GPS algorithm has dropped to 80% due to the stale positions of the vehicles. Therefore to investigate this problem further we have implemented a hello garbage collector and simulate the same scenario by keeping the hello interval time constant at 5s and vary the hello garbage collector interval from 1s to 6s. The garbage collector removes all the stales vehicles from the neighborhood table. Fig. 77 shows that we can improve the performance of the GPSwo algorithm by removing the vehicles with stale positions from the neighborhood table. It is evident from the graph that at heavy traffic condition it requires more frequent garbage collection. At low time intervals we obtain higher reachability values in the range of 93%, much higher in contrast to a percentage of 80% obtained at garbage collection interval equal to 6s. However, these findings are only valid for this specific traffic condition. One factor that we have not considered for the GPS-based protocols is that the GPS systems positioning accuracy can be 10-30 meters off, something that might cause further degradation of performance at all traffic conditions. Consider the scenario where an abnormal vehicle rebroadcasts the EWM and on its neighbor table shows vehicle X to be at the outermost of its range but actually it is not. Then the EWM will not be received and an acknowledgment mechanism must be in place so that the message is rebroadcast again, or by another vehicle in the range. This process increases the delay and the overhead of the overall system. For the other traffic conditions a different value may apply and this can be a matter to be investigated further in the future for an adaptive garbage collection.

4.5 Practical Considerations

This section addresses some practical aspects of our proposed scheme. One of them is how SAPF performance will be affected if a percentage of vehicles on the freeway do not participate in VANET since they are not ITS enabled. In this case the vehicle speed vs. vehicle density curves



(a) Reachability (%) vs. Hello Garbage Collector Interval (s)

(b) Latency (ms) vs. Hello Garbage Collector Interval (s)

Figure 77: Varying the hello garbage collector interval we can obtain higher reachability values for the GPS algorithm. However, SAPF algorithm still achieves higher values with respect to reachability, in heavy traffic conditions.

are misleading, causing causing a degradation of performance, as SAPF will set the rebroadcast probability lower than the actual vehicle density of active vehicles will dictate. However, this could be resolved by taking a more aggressive approach in implementing SAPF, that is for given vehicle speed to rebroadcast the information with higher probabilities that in the original SAPF. Of course, this may have as an effect a slight increase in the latency, but it will also increase the reachability in cases where a certain percentage of vehicles are not equipped with VANETs. This tradeoff needs to be considered under more realistic test conditions.

As we have discussed in the section 4.2.4 (when considering two way traffic), we could use a GPS system to exclude the opposite traffic from rebroadcasting the information. In addition to that, we could make use of the maps available locally in a GPS system for more enhancements with regard to considering structural information conditions, such as number of lanes, speed limits, etc. One of these enhancements is to use the maps of the GPS to identify the number of lanes of the freeway and use this information to select one of the SAPF versions specially designed and tuned for the given number of lanes and stored locally. For instance if the accident takes place on a 3-lane road topology then all the vehicles select the SAPF:3L to rebroadcast the EWM. As we have shown in section 4.2.2, using a SAPF version that was specifically designed for a given road topology performs slightly better than the SAPF which was designed for a 4 -lane road topology. Furthermore, if GPS maps were to include vehicle speed vs. vehicle density curves for each road topology then we could fine tune our algorithm, and hence potentially obtain higher reachability and lower latency values for each topology.

Another practical aspect is how we may prevent someone from creating malicious alarms (fake accidents) and causing confusion on the freeway. This need to be investigated further, and since security is a large research area it is beyond the scope of this thesis and will remain a future research item.

4.6 Concluding Remarks

In this section, we have discussed how we interfaced the VISSIM and OPNET simulators to provide us with a powerful integrated road transportation and communications network simulation platform for simulating VANETs. Then, we have evaluated and shown that SAPF algorithm performance remains very good, independently of the freeway topologies, the number of lanes and also on the level of congestion on the freeway. Thereafter, we evaluated the SAPF algorithm with custom designed SAPF algorithms on a 3-lane and 5-lane road topology and have shown that SAPF performs almost as well as the custom designed SAPF algorithms. Furthermore, we evaluated the effects of the design parameters on the SAPF algorithm performance by varying the number of hops and the transmission range. The results attest that the SAPF performance is not significantly affected by these two parameters, and it has also outperformed BF by recording high reachability values and low latency values. Likewise, in the evaluation of SAPF algorithm in bidirectional road topology, SAPF has shown acceptable performance, and again outperforms BF by large. Furthermore, the results that we have obtained using the RTMS sensor, for the A1 freeway in Cyprus transportation network have also shown that SAPF performs very well. Furthermore, SAPF has performed well, when compared with the idealized GPS-based algorithm (assuming zero signalling overhead) and sometimes even better, when compared with a GPS enabled protocol with associated signalling included. It achieved high reachability values over 90% and low latency values in the range of 6ms. Considering its simplicity of operation and no overhead requirements for exchanging any positioning information, this is a remarkable result.

Lastly, we also provide a discussion on practical considerations such as: not all vehicles are equipped with VANET, and that the use of GPS maps allows us to extract structural information, such as number of lanes, freeway structure and direction of vehicle flow, and hence select the SAPF designed specifically for that setting.

Summarizing, SAPF algorithm has shown that its performance is independent of road topology (its performance remains within acceptable bounds in all traffic conditions); is unaffected by the design parameters in any significant fashion, and can even perform equally well as the idealized zero overhead GPS-based protocols and at times better than the GPS-based protocol when considering its signalling overhead. This makes it a good candidate for use in effective dissemination a EWM in VANETs. In the next chapter, we will discuss in more detail our conclusions and future work.

Chapter 5

Conclusions & Future Work

In this chapter we discuss our conclusions and future research directions.

5.1 Conclusions

Information dissemination in VANETs is currently of great interest due to its promised potential to assist drivers in reducing road accidents, by providing timely information about impending dangerous situations and hence increasing the available time to the vehicle driver to respond. It is however a challenging task due to high speed mobility, network topology rigidity, unpredictable vehicle density, and high vehicles speeds.

The thesis addresses this problem in a freeway setting in an elegant manner by employing speed adaptive probabilistic flooding, based on the vehicle speed alone (a locally measurable variable). The scheme is expected to adapt to road traffic density conditions by means of a suitable rebroadcast probability function whose input variable is the vehicle speed. The protocol enjoys a number of benefits relative to other approaches:

- It is simple to implement.

- It is totally distributed.
- It does not introduce additional communication burden, as it relies on local information only (the vehicle speed).
- It does not rely on the existence of a positioning system which requires significant additional exchange of beacon messages for mutual awareness. Furthermore, a GPS device may not always be available and functioning.
- It mitigates the effect of the broadcast storm problem, typical when utilizing blind flooding, or similar approaches, in a freeway setting.

Next we provide our main findings and contributions, and thereafter our suggestions for future work.

5.1.1 Main findings and contributions

Below, we summarize our main contributions and findings:

- We have observed and verified through simulations the existence of phase transition phenomena when probabilistic flooding is employed in VANETs in a freeway setting, and we have utilized these phenomena in the design of the proposed SAPF algorithm:
  - For a specific vehicle density we show that as we increase the rebroadcast probability there exists a threshold value beyond which the desired reachability is achieved. This threshold value is the desired rebroadcast probability for the proposed probabilistic flooding scheme, as it achieves the desired reachability with a minimum number of EWM messages exchanged.

  - We identified that for a specific road topology, we can use real time measurements to obtain speed density curves which can then be used to map the speed of each vehicle to the traffic density.
  - It is worth noting that all road traffic data was obtained from measurements in a number of different freeways.

- Using above findings we have developed a new multi-hop information dissemination scheme for VANETs in a freeway setting. This design effectively mitigates the broadcast storm problem:
  - It employs a novel technique which decides on the density of neighbors rebroadcasting the critical message, taking into account the current traffic state, as dictated by the vehicle speed, and using the specific characteristics of the freeway topology where the dissemination process takes place. The speed-density curves are obtained from past data (see above).
  - It is totally distributed and besides the dissemination of the critical message, it does not require any exchange of messages (zero overhead).
  - Each vehicle upon receiving the critical message decides to rebroadcast the message with probability p and not to rebroadcast the message with probability 1-p. As stated above, a unique feature of the proposed scheme is that the probability p is determined solely from the speed of each vehicle. The reasoning behind this design choice is the existence of phase phenomena, and that low vehicle speeds in a freeway setting imply large vehicle densities and thus low rebroadcast probabilities suffice to achieve high reachability. We refer to the proposed scheme as SAPF (Speed Adaptive Probabilistic Flooding).

- We have shown through simulations that the proposed SAPF scheme performs very well, with reachability approaching 100% and delay bounds in the milliseconds range of values, whilst keeping overheads at a minimum. We have also demonstrated its insensitivity and robustness with regard to a number of changes in the environment and in the design parameters, as for example:
    - Different number of lanes in a freeway, e.g. 2, 3, 4 and 5 lane topologies have been evaluated.
    - Different freeway system found in Cyprus, as compared to the ones in the state of California, and also a different measuring sensor.
    - Different levels of road traffic congestion (low, medium and high).
    - Bi-directional traffic.
    - Different speed limits (considered 3 different speed limits).
    - Transmission range.
    - Number of hops.
- To reaffirm above conclusion we have shown through simulations that the SAPF algorithm:
    - Outperforms Blind Flooding in all tested scenarios in terms of delay behavior and compares favorably with regard to reachability. In terms of latency, SAPF manages to disseminate the EWM faster than the BF (in the order of 20ms).
    - Performs comparatively well as compared to custom design SAPF versions for each specific freeway.
    - Achieves comparably high reachability and latency values as an idealized GPS and a realistic GPS algorithm (with the required signalling overhead included). The slightly

lower of performance that SAPF has shown is negligible, considering the very high protocol overhead that a GPS algorithm generates.

- We have combined a road transportation simulator with a communication network simulator to enable us to create more realistic simulation scenarios, taking into account both realistic road conditions and vehicle/driver traffic behavior, as well as communication networking behavior. The two simulators are interfaced in such a way as to extract the realistic mobility behavior of the vehicles using the road transportation simulator and then import these into the networking simulator. The adopted simulators are OPNET and VISSIM, which can be considered industry leading in their area of expertise.

5.2 Future Work

Below we discuss suggested future work. Some suggestions relate to the improvement of the proposed algorithm, as for example to investigate city behavior and possible (re)design, or the adoption of the phase like phenomena to address problems in other algorithms (such as GPS enabled techniques) or in other areas (such as routing). Also, we suggest that a more dynamic real-time coupling between the two simulators may allow us to investigate more real life scenarios, and also assist in the setting of design parameters, such as number of hops and power levels, related to driver reactions times.

SAPF has demonstrated that in freeway settings it performs very well in comparison with other algorithms. The question that arises is what happens in the case of the city environment. It is known that the speed density curves in city differ, perhaps significantly, from the ones in the freeway setting. So we plan to investigate how we could alter our algorithm to obtain speed-density curves for city settings, or find a way to obtain just the density of the road and alter our algorithm to work based on density only. Also, we plan to attempt a mathematical analysis of the sensitivity of the algorithm and its properties, using percolation theory. A hovering algorithm using SAPF algorithm is also suggested for future work.

In this thesis, we have demonstrated that using our proposed scheme we can mitigate the effects of the broadcast storm problem in VANETs by reducing the number of rebroadcasting vehicles while maintaining high percentage of reachability and low latency values. However, our initial investigations suggest that we can obtain even better results by adding some additional (adaptive) features to the proposed scheme. Therefore, one of our future plans is to use the receive signal strength (RSSI) measurements to estimate the distance between the receiver and the (re)broadcasting vehicle. Knowing the distance between the two, SAPF could take this into its consideration and give higher probabilities values to the vehicles that reside at the outermost of the transmission range of the (re)-broadcasting vehicle, as seen through the locally measured RSSI. Note that by using this approach there is no necessity for GPS-based support and the associated excessive signalling with the update of other vehicle positions in comparison to our vehicle.

Enhancements of SAPF algorithm such as using GPS system to include direction in the EWM and exclude the traffic from the opposite direction are enhancements that we will be investigating further. Also by extracting structural information, such as number of lanes, speed limits, etc...from the maps that are included in a GPS system, the vehicle could select a more 'customized' SAPF algorithm, that has been designed for that road topology.

The idea of estimating the density of the freeway based on the speed of the vehicles and the existence of the phase transition in VANETs opens the door for many new ideas. For instance, the interval time for the hello messages on a GPS-based protocol can be adaptively set by a speed-density driven algorithm. This will allow us to reduce the number of hello messages in a heavy traffic condition. Along the same lines, using the speed-density curve we could try and investigate the idea of the Speed-Power Adaptive broadcasting scheme. The idea is to increase the power at low densities and reduce the power at high densities while the number of hops is varied accordingly in order to transmit the emergency warming message to the desired distance.

It is well known that many routing algorithms use broadcasting methods to dissimilate control information like ”route discovery” to obtain a path from source to destination. It would be interesting to adopt SAPF in routing algorithms that use these broadcasting methods and evaluate its performance.

Using our integrated platform for our simulations we have realized that a more dynamic simulator will be very useful in the setting of the design parameters, in that it will include the ability to signal drivers to change routes, slow down, or even stop in case of congestion or an accident. Hence a more realistic testing environment can be adopted for evaluating SAPF. Therefore we plan to integrate VISSIM and OPNET in such a way that they will interact between them in real time, and allow for evaluations in a more realistic setting.

SAPF algorithm has been designed to inform the approaching drivers of an imminent danger but not to be used maliciously so there is a need of investigating further how to make SAPF more secure and not used maliciously to cause confusing on freeways.

Finally, we plan to implement SAPF algorithm on embedded systems such as mobile phones, PDAs, or an ARM PXA320 kit to verify the simulation results with a real testbed system.

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