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Geocasting Solution for BlueWave Services in the Context of Vehicular Communications

by
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Abstract

There is no doubt that an efficient emergency activity saves lives and reduces damages. BlueWave is an emergency activity in which an emergency vehicle (EV) warns vehicles on its trajectory in order to give it a clear way. The conventional BlueWave activity uses siren and flash light as warning signals. The signaling part of BlueWave has limitations which include the dependence of the flash light on line of sight, the effectiveness of the siren being dependent on driver's situation such as loud music, insulated doors and windows. In addition, the system does not differentiate its target vehicles and fails to assist drivers on how to react even if it does. Many of the solutions available extend the signaling part using radio signals directly from the EV to target vehicles. A common limitation of such technologies is their failure to support multihop communication and well established standards such as IEEE 802.11. In this thesis we designed a system that extends the signaling part, which is cooperative (vehicles share information), support multihop communication, and is based on WAVE (WiFi version for vehicular networks).

The PHY and MAC layers of the designed system are based on WAVE standard. In the network, layer a BlueWave protocol is designed to enable vehicles communicate in the BlueWave process. To limit the warning to specific vehicles, a geocasting protocol is designed. In geocasting, vehicles use their geographic location as an address to receive packets. The protocol has basic functionality which is implemented in all involved vehicles. The basic protocol checks if a received message is relevant. A message is said to be relevant if it is not expired, not duplicated and the host is within the ZoR (Zone of Relevance) as defined in the message. Relevant messages are also entitled for dissemination to other vehicles. To disseminate the BlueWave messages within the ZoR, a distance based flooding mechanism called slotted 1-persistent is used. This avoids the broadcast storm problem that may happen if a network is blindly flooded. Moreover, the EV as a source adds extra functionally to enable it broadcast the warning at some rate. To evaluate the performance of the protocol we defined three performance metrics. The first one is Reachability, which measures the number of vehicles that receive at least one message on time. The second metric is Channel utilization, which measures the fraction of time a node uses the medium. The last metric, spam created, which measures the number of unnecessary packets created by the protocol during the BlueWave process.

The protocol is implemented in OMNeT++ simulator and experiments are done in a highway scenario of 10km long. The EV moves at its desired speed (as fast as possible) and other vehicles move according to IDM (Intelligent Driver Model). The protocol when using slotted 1-persistent achieves high level of reachability (90%–94%) irrespective of the network density and broadcast rate of the EV. However, the channel utilization and the number of spam packets created increase with density and broadcast rate. The protocol performs better on slow speed scenarios such as urban cases, but this is in the cost of higher channel utilization and more spam created packets. In all, the protocol performs better at lower rates and fulfills most of the requirements of the application.

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Chapter 1

Introduction

Emergency situations happen every now and then in our daily life. The causes could be manmade such as war, car accident, or natural disasters such as earthquake, storm, and flood. Their worst part is the potential danger they impose on properties and living creatures. Humans have long back experience on how to respond emergency incidents. Historians suggest the use of a cart for emergency services was available as early as 900AD [25]. With the advent of technology, well established units with professional workers and up to date equipments were created throughout the world. These units work to minimize or prevent the consequences of emergency situations. BlueWave (Blue Corridor) is one kind of emergency response activities in which an emergency vehicle (EV)[1] warns road users around to give clear way.

The main objective of the BlueWave warning is to facilitate mobility of the EV, so that it reaches its destination safely and as fast as possible. BlueWave as a system includes emergency vehicles, other vehicles[2] and road users such as pedestrians. The EV is exempted from primary traffic rules such as red traffic light and speed limits as long as it's safe to do so. In order the road users to identify the EV on time, a siren (sound) and flashing light are used as warning signals.

Figure 1.1: The BlueWave system includes Vehicles and signaling with sound and light

The Netherlands traffic rule, article 50, asks road users to cooperate in a safe manner once they know about an emergency situation. Drivers of other vehicles are advised not to panic, reduce speed and give space to the EV as much as possible. However, there is no clear and definite procedural rule which works for all emergency responses. This is easily understandable as it is difficult to regulate each kind of emergency incident that may happen. More often the BlueWave operation is accompanied by common sense rather than strict do that do this rule. EV response guidelines by VFIS[3] clearly indicate that emergency responses are common sense rules and the EV can neither force other vehicles to yield the right way nor can assume the right way.

[1] An Emergency Vehicle is an authorized vehicle dedicated for emergency responses activities such as ambulance, fire fighter, and police cars

[2] throughout the thesis, the term "Other Vehicles" implies to all involved vehicles other than the EV

[3] Vegetation Fire Information System (VFIS) is an American company that provide largest insurance, education and consulting services to Emergency Service Organizations. www.vfis.com

The nature of an EV, high speed and sometimes mobility against traffic flow, exposes them to accidents and consequently extra delays. Research shows that EVs equipped with siren and light are still involved in accidents with high fatality [67]. In the United States for example, every year emergency medical vehicles are involved in accidents which result in high morbidity and mortality [43]. Reports from US National Highway Traffic indicate 301,404 emergency vehicles (ambulance, fire, and police) were involved in nonfatal collisions, and 1,565 in fatal collisions, during the years from 1991 through 2000. In the majority of collisions, the ambulance cannot or does not continue on the call resulting in a significant delay [43]. Caelli et al. in [34] identified the difficulty of drivers in estimating the exact location of the EV from the siren they hear. The research further investigated that drivers actually overestimate the distance of the EV due to slow cycle of the hee-haw siren sound, noise sound from motor and other radio equipments inside the car, and improved sound proof doors and windows. The overall limitations of siren and flash based BlueWave system can be summarized as:

1. Signaling with siren and light is not reliable. The driver situation such as loud music, fully closed window and hearing problems affects the possibility of siren to be heard.
2. The flashing light is greatly dependent on the availability of line of sight. For example a truck in front of a small car can completely block the view of flash from front.
3. The Emergency Warning Message (EWM), siren and light, doesn't differentiate target vehicles. It rather warns everyone it can reach and the decision to take action is solely left to drivers of other vehicles.
4. It also doesn't assist drivers on how to respond i.e. they don't get detailed information about the situation such as which direction to yield.
5. A survey on a group of drivers in the Netherlands also show that drivers act spontaneously when they encounter the EV. This increases the vulnerability to accidents due to sudden headway and speed changes in the traffic [37].

The logical solution is to devise a means to extend the signaling beyond siren and light, so that other vehicles will be warned about the approach of an EV on time[4].

The limitations of conventional siren and light have been the main concern for road and emergency response operators. The implementation of emergency vehicle signal preemption system, a system which changes the traffic lights to favor the EV, was one of the early optimizations which resulted in huge EV accident fall [13]. Systems which include radio signal transmission from the EV were also main solutions to the limitations of siren and light. The Flister system, which is developed in The Netherlands, is one example that is based on a transmitter built into emergency response vehicles. When such a vehicle switches on its siren or emergency light, then an FM signal within a range of 100 to 300 meters is broadcasted. This signal temporarily overrides car radios within that range and may interrupt CD/DVD/MP3 players as well. The radio signal can be used to transmit any sound that you want (a siren, for instance). A text message can also be sent to radio displays, for instance displaying information about the type of emergency response vehicle that is approaching [9]. In the US, many patents have been registered for emergency vehicle warning systems and methods. The system in [7] uses infrared signals to inform vehicles in which direction to yield. Other technologies such as the one in [8], use radio communication to encode an audio warning. The above mentioned solutions lack support of stable established standard. In addition, they are limited to one to one communication

[4]The notion "on time" is defined in chapter 2, Section 2.2 on page 6

between target and the EV. Besides, they don't support multi hop[5] and cooperative communications[6]. A generic solution is to use the already established vehicular ad hoc networks (VANETs), which is based on a variant of the WiFi(Wireless Fidelity) standard.

Vehicular ad hoc networks (VANETs) are a type mobile ad hoc networks (MANETs[7]) which provides communication between nearby vehicles, vehicle to vehicle (V2V), and nearby fixed equipment, vehicle to infrastructure (V2I/I2V), described as roadside equipment [102] [71] [97]. The main goal of VANETs is to provide safety and comfort to drivers. The network operates without infrastructure or legacy client server communication. Vehicles are equipped with a VANET device which act as a node in the ad hoc network, and relay, receive others message in the wireless medium. Main applications of VANETs are safety applications such as emergency warning, lane-changing assistant, intersection coordination, traffic sign/signal violation waning, and road-condition warning; value added applications such as infotainment.

The V2V communication paradigm of VANETs could be used for BlueWave services. This kind of solution is proposed in the EC (European Commission) supported GST (Global System for Telamatics) subproject RESCUE [17]. RESCUE focuses on post accident rescue activities. Its main objective is to optimize the post accident emergency services so that the damages and casualties are reduced. The communication chain includes, an eCall[8] from accident site to a central station through public service access points, these are the back end infrastructure of service providers, and an optimal route information from route guidance system to Emergency vehicle. BlueWave is one of the services required in such scenarios to create a clear way for the emergency vehicle. However, GST doesn't specify the details of their V2V solution for BlueWave.

1.1 Research Objectives and Scope

The overall emergency services include communication between accident point and central units, which in turn feeds the emergency unit with details. To function smoothly the system incorporates service providers, through which emergency calls may be forwarded; data validation and computational units, to validate the information, locate the place and route; virtual cone, to deliver accident notification to vehicles approaching the incident point; and BlueWave services. This research focuses on design of a communication system for BlueWave services as an extension to the siren and light. Objectives of this research can be summarized as follows:

O1. Investigate the methods of information dissemination and data routing in VANETs and their relevance for emergency activities, especially BlueWave services.

O2. Design a specific data dissemination system for BlueWave services.

O3. Research the feasibility and performance of the designed system in real application scenarios.

[5]Multi hop communication in a wireless networks is the use of two or more hosts to convey information from source to destination.

[6]Cooperative communication is a type of communication in which hosts share information between each other for a common purpose.

[7]MANETs are wireless networks in which nodes communicate without central coordinator in a distributed fashion [83].

[8]eCall is a European project which aims to employ a hardware black box installed in vehicles that will wirelessly send airbag deployment and impact sensor information, as well as GPS coordinates to local emergency agencies. http://en.wikipedia.org/wiki/ECall

1.2 Research Approach

The research approach is divided in three parts: 1) Literature and background study, 2) Design of the BlueWave system, and 3) Validation and analysis of designed system using simulation model. The literature review is meant to grasp the theoretical solutions and current research levels in the area. Based on the background study a communication system for a specific application, the BlueWave in this case, will be designed. Finally the performance of the system will be tested using simulation techniques. The research questions to be tackled are summarized as follows:

Q1. What are the requirements of BlueWave services from communication and application point of view? To obtain a clear picture of the system it is important to identify its requirement from normal users perspective and the translation of these to technical system requirements.

Q2. How to disseminate BlueWave messages in vehicular networks? Somehow, the information need to be distributed to the intended receivers. There are many ways of disseminating information in wireless networks. The method chosen greatly affects the performance of the network as a whole and the needs of the application in particular.

Q3. How to measure the performance of the designed method? Knowing the effectiveness of the system is an important aspect of communication systems design. For this reason some metrics derived from the application requirements of the system will be needed.

Q4. Does the dissemination method fulfill the requirements of the BlueWave services? The requirements are meant to give a standard to the application. Therefore, the first concern during testing is if the primary needs of the application are met. In practical applications users do not care how complicated and difficult the system is, it is the job of the designer to make sure basic requirements are met.

1.3 Outline of the Paper

The rest of the thesis is organized as follows:
Chapter 2 focuses on setting the requirements of the BlueWave system. These requirements will be based on practical traffic rules and safety recommendations for transportation systems.
Chapter 3 is dedicated to introduce the technologies and standards related to VANETs. These technologies are the basis of the BlueWave system to be designed
Chapter 4 describes the data dissemination techniques and routing mechanisms commonly used in VANETs.
Chapter 5 presents the main work of this thesis, the design of BlueWave protocol. The design is based on the requirements set in chapter 2 and standards and technologies described in chapter 3.
Chapter 6 includes the implementation details of designed protocol in OMNeT++ and definition of specific scenarios for experimentation.
Chapter 7 defines the specific performance metrics used to evaluate the BlueWave protocol and presents the results obtained from simulations.
Chapter 8 is the concluding chapter of this thesis. It includes answers to research questions and recommendations for extension of this further research.

Chapter 2

BlueWave Requirements

In the introduction, the importance of extending the signaling part, siren and light, of BlueWave services was discussed. One of the research objectives of this thesis is to design a communication protocol between vehicles for BlueWave services. This chapter is meant to set clear requirements of the protocol to be designed. Having clear requirements will make the design goal oriented and the evaluation part quantifiable.

The first section of this chapter describes the operation principle of the proposed BlueWave system. It explains the application on an abstract level. The second section will focus on setting the requirements of the proposed BlueWave system from communication and application perspectives. This section also includes the assumptions needed for the system to operate and the quantitative derivation the requirements.

2.1 Description of BlueWave System

As mentioned above, the main objective of this chapter is to set requirements for the protocol to be designed. It is important to describe the constituents and operation of the system in order to get clear implications of these requirements on it. Therefore, this section focuses on description of the BlueWave system as whole and the extension of the signaling part with wireless technology in particular.

In Chapter 1, the current BlueWave system was described. It is mentioned that the signaling part of the BlueWave system, siren and light, has limitations. The available solutions for these limitations do not support cooperative communications. Therefore, a new approach using V2V communication is proposed in this thesis. The main change in the BlueWave system will be the addition of a wireless technology to the signaling part. This technology, software and hardware, is expected to be available in all involved vehicles in the BlueWave process. The proposed BlueWave process from application perspective can be explained as follows:

The EV's driver launches the wireless emergency warning, typically presses a button, in response to a true emergency situation[1]*. This will launch the signals of the BlueWave warning, in addition to the current signals (sound and light). The warning propagates in the air to reach other vehicles in the vicinity of the EV. On the receiver side, the embedded technology will interpret the messages and an alarm will pop-up. The warning could be a simple sound device inside the driver cabinet, like beep sound, or a*

[1] According to American fire administration definition, a true emergency is a situation in which there is a high probability of death or serious injury to an individual or significant property loss, and actions by an emergency vehicle driver may reduce the seriousness of the situation.

flash lights to just bring the attention of the driver to the situation. In other case, it could also be a sophisticated multimedia application with complete information of the emergency situation and map traces.

2.2 BlueWave requirements

In Section 2.1 on the previous page, we described the operation of the proposed BlueWave system. In practice, implementing such a system should meet the demands of the user, rules(such as traffic), and standards. Therefore, this section will introduce the requirements of BlueWave protocol from application and communication perspectives.

2.2.1 Application requirements

1. The warning messages need to arrive on time[2], so that other vehicles will have enough time to take action before the EV is close to them. The notion "on time" also means warning message shouldn't reach neither *too early*[3] nor *too late*[4] at the targeted vehicles. The *"too early"* case may result in unnecessary traffic disturbances due to early attempts to clear way. The *"too late"* case may result in blockage of EV due to late reactions.

2. The warning messages should only be valid for vehicles within the ZoR (Zone of Relevance). A ZoR is a specific geographic area in which only vehicles inside are entitled to hear the BlueWave warning. The size of ZoR and the parameters which influences it are described in Section 2.2.4 on page 8. An example shown in Figure 2.1 magnifies the importance of this requirement. The BlueWave messages reach vehicles which are both inside and outside the ZoR, but only those within the ZoR take action.

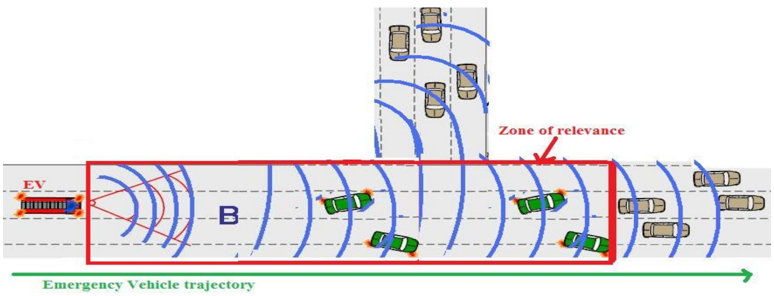

Figure 2.1: BlueWave communication target differentiation, an example

3. The warning should have a limited age. Since the EV is dynamic, the information contained in a message, such as location of the EV, should have limited age.

[2]The notion "on time" is quantified in Section 2.2.4.2 on page 12.

[3]"too early" means other vehicles receive the message when the EV is very far away. It is quantified in Section 2.2.4.2 on page 12.

[4]The notion "too late" implies to the situations in which other vehicles will not have enough time to react by the time they receive the BlueWave message. It's value is quantified in Section 2.2.4.2 on page 12.

2.2.2 Communication requirements

The application level requirements are the needs of the user of the BlueWave system. From communication perspective these requirements are interpreted differently based on the technologies and standards used. This section introduces the communication level requirements in which the designed protocol need to comply with.

1. ***Zone of Relevance (ZoR):***The communication protocol is required to specify a zone of relevance as defined in Section 2.2.4 on the following page and limit the validity of the warning within it as described in item 2 of the application requirements in previous section.

2. ***Limited Time to Live:*** The protocol need to limit the time to live of messages on air. One of the reasons for these requirements is the nature of BlueWave application. The source (EV) is moving and consequently the ZoR is changing every time. Therefore, the warning messages broadcasted by the EV will have different contents (such as location of ZoR). Consequently, the protocol needs to differentiate the new information from old ones.

3. ***Bandwidth:*** According to European ITS, which is based on IEEE 802.11p, the 30 MHz at 5875-5905 MHz are for now divided into 3 sub-channels of 10 MHz each, where the first one, SCH1, is the main service channel for safety and efficiency messages (optimized for high throughput). Most likely a low rate (e.g. 3 Mbps) will be chosen since traffic safety applications require a high reliability [4]. Lower rates have lower coding rates which makes them robust to channel errors. The BlueWave warning messages are not expected to occupy the medium alone. Perhaps, there will be other applications which want to share the channel at the same time. Therefore, the BlueWave application need to consider:-

   - use of the minimum rate from the IEEE 802.11p specifications ($3Mb/s$) at its maximum channel access demand. This makes sense both from reliability point of view in which low rates are more reliable, and the fact that Bluewave messages probably are small sized control packets.

   - not to use the total bandwidth alone. There are no clear bases to set a numeric value of the bandwidth usage but leaving a space for other applications is a preferable characteristics. Therefore, bandwidth usage should be as low as possible.

4. ***Scalability, Fragmentation, Security :*** The protocol need to be scalable, immune to fragmentation and secure. Vehicular networks in general can have extreme network density conditions. On dense network scenarios the protocol needs to be robust enough to maintain its functionality. Sparse networks are good for the BlueWave application as the EV will get clear way easily. However, sparse networks also mean there will be a possibility of network fragmentation. Hence, It should also have a means to challenge partitioned networks. Security is a generic problem of VANET applications. The trustworthiness of the warning message is an important issue as false warning could expose road users to accidents.

2.2.3 Assumptions

In Sections 2.2.1 on the previous page and 2.2.2, the requirements of the BlueWave system are set from application and communication perspectives. It is clear that these requirements cannot be attained in every possible scenario that may happen. This subsection will describe the assumptions that were made during the design of the system to meet these requirements.

1. All involved vehicles are assumed to operate under normal traffic rules such as obeying the speed limit. However, the EV is expected to have slightly higher speed than the speed limit during

emergency responses, as long as it doesn't endanger its own safety and that of road users. The VFIS recommend an EV in an emergency situation not to exceed $10 miles/hr$ or $16 km/hr$ above the speed limit. Other vehicles are not always expected to obey the speed limits as well. However, it is not deterministic how high a reckless driver will drive above the speed limit. For the design purposes we assume a safe margin of $10 km/hr$ above the speed limit for other vehicles.

2. The traffic rules are different in different countries. In our case, The Netherlands traffic rule is used as a reference. For example, the speed limit in an expressway (a divided highway)in The Netherlands is $120 km/hr$ i.e. $33.3 m/s$[5]. According to the assumption drawn in item 1 above, the maximum speed of EV (V_{EV_max}) in a highway will be $136 km/hr$ or $37.7 m/s$. Other vehicles will have a maximum speed of $120 km/hr + 10 km/hr = 130 km/hr$ or $36.1 m/s$ in a highway scenario.

3. The wireless technology is not a standalone part in the BlueWave system. It needs several supplementary elements in order to function properly. These elements include sensors, actuators, and processing units involved in data communication of the BlueWave system. The overall BlueWave system[6] to work as intended is assumed to have the following entities:

   (a) A wireless technology for all vehicles in the system. This of course is the main basis of this thesis. It is not difficult to expect a stable wireless technology for vehicular communications in the near future. The IEEE has already drafted the vehicular version of the 802.11 standard, i.e. IEEE 802.11p, which is expected to be released by November 2010 [11].

   (b) Different sensors inside the vehicle to supply required information to the BlueWave wireless technology. These include speed sensor, headway detector, lane detector, and location devices (such as GPS).

   (c) BlueWave application

   (d) User interfaces.

2.2.4 Quantifying the BlueWave requirements

One of the important aspects of setting requirements is to make sure they are measurable. This subsection is dedicated to quantify the requirements set in Sections 2.2.2 and 2.2.1 based on the assumptions made in Section 2.2.3. The following parameters of the requirements are derived in this section: 1) The size of ZoR.2) The time to live (age of one message). 3)The notions *message on time, message too late, and message too early.*

Let us first see how a successful[7] BlueWave process is operated in a time line. Later we will derive the requirements based on this time line process. The following terms are used to describe the the time line of the BlueWave process:

$t_{overtake}$ is the total time elapsed from the moment the EV send a warning message to a targeted vehicle until it overtakes it.
$t_{reaction}$ is a reaction time needed by a driver to notice the warning signals inside his/her vehicle (provided the warning reached the vehicle and some application device gives an indication).
t_{clear} is clearing time needed by a driver to give a space to the EV.
t_{wait} is the amount of time a driver has to wait for the EV to overtake him/her after clearing a way.

[5]http://en.wikipedia.org/wiki/Speed_limits_by_country
[6] it includes EV, other vehicles and communication in between
[7]A BlueWave process is said to be successful if the EV manages to overtake a targeted vehicle after sending a wireless warning message. Successful processes don't necessarily mean message has reached on time.

1. First, the EV send a BlueWave message through the wireless medium as shown in the top part of Figure 2.2. There will be propagation and processing delay before the driver is notified. However, these values are very small compared to the time needed by the EV to overtake the vehicle (which is in order of 10's of seconds as will be estimated later in this section). Hence, they are ignored in our analysis. Once the message reaches a targeted vehicle and it pops up on the vehicles display, the driver will need some time to react ($t_{reaction}$).

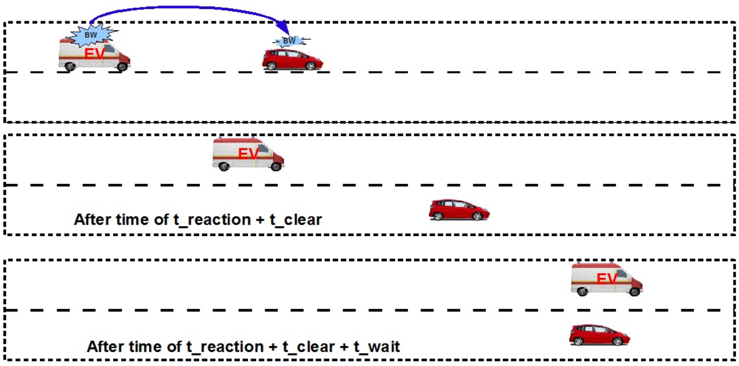

Figure 2.2: an example of a successful BlueWave process

2. After knowing the emergency situation it is time to take action. The decision and action are taken by the driver. For a successful BlueWave process, the driver will need an amount of time equal to t_{clear}.

3. After $t_{reaction} + t_{clear}$ the EV is free to overtake as shown in the middle part of Figure 2.2. Once the targeted vehicle clears the way there could be some moment it has to wait until the EV overtakes it, the waiting time (t_{wait}). Its only after $t_{clear} + t_{reaction} + t_{wait}$ the BlueWave is said to be successfully completed. This process is shown at the bottom part of Figure 2.2.

$$t_{overtake} = t_{reaction} + t_{clear} + t_{wait} \tag{2.1}$$

The value the reaction time, $t_{reaction}$, varies from driver to driver and the worst case as studied in [49] is taken in our design. Therefore, $t_{reaction} = 1.5s$. The clearing time (t_{clear}) is non-deterministic and greatly depends on driver decision and traffic situation. Heavy traffic may hinder the mobility and lane change process. The waiting time (t_{wait}) is also non-deterministic, it depends on the users of the BlueWave application to decide which value is tolerable by driver's of other vehicles. Since we are dealing with vehicles, it is not realistic to assume 0 waiting time i.e. all movements are not perfectly deterministic but rather depend on driver actions and mechanical operations of vehicles. For the sake of simplicity the total non deterministic values in the time line, ($t_{wait} + t_{clear}$), are taken to vary between $5s$ and $12s$ [8].

$$t_{ovetake} = 1.5s + [5s, 12s] \tag{2.2}$$
$$t_{overtake\_max} = 13.5s \tag{2.3}$$
$$t_{overtake\_min} = 6.5s \tag{2.4}$$

[8] Note that, the writer discussed these issue with people in transport engineering field, one of them is Kasper van Zuilekom (CTW-UT), who consulted the "Unit vakinstructie rijopleiding" on his behalf, and suggested the mentioned order of time, though modeling exact human behavior is difficult.

The value of the overtake time, $t_{overtake}$, determines when the EV has to announce the emergency warning or in other words, how far from the target vehicle it should be when sending the first message. Hereafter, the overtake time is used to quantify the requirements of BlueWave system.

2.2.4.1 Zone of Relevance (ZoR)

In practical applications the size of ZoR may depend on several factors such as relative speed of EV, vehicular density and topology of road. It means the actual dimension of ZoR is dynamic as the values change non-determinically. Since designing such a complicated ZoR needs special expertise and extensive studies, we limit the scope in this thesis to static ZoR. In the sequel, the maximum size of ZoR is derived from the overtake time and broadcast rate of the EV. However, the sensitivity of size of ZoR is studied in testing phase of the protocol (Chapter 7).

Suppose the relative distance of the EV to a targeted vehicle at the moment a BlueWave warning is launched is denoted by $d_{relative}$ as shown in Figure 2.3. If the speed of the EV is V_{EV} and that of

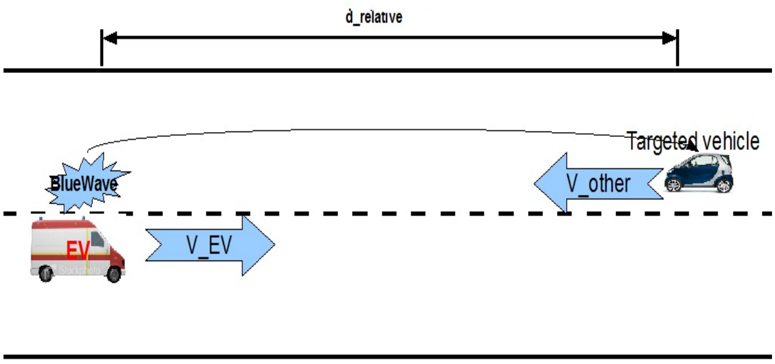

Figure 2.3: The relative distance of the EV to an approaching targeted vehicle at the moment BlueWave warning is launched

targeted vehicle is V_{other}, then the relative speed will be:

$$V_{relative} = V_{EV} - V_{other} \tag{2.5}$$

The sign of V_{other} is negative if the other vehicle is moving in opposite direction to the EV, and positive if it is moving in the same direction as the EV. The relative distance of the EV to the targeted vehicle at time of launching the warning, $d_{relative}$, can be calculated as follows:

$$d_{relative} = t_{overtake} \times V_{relative} \tag{2.6}$$

Note: This equation is true under a simplistic assumption that the relative speed, $V_{relative}$, is constant for the amount of time $t_{overtake}$.

To derive the size of ZoR, let us further consider the worst case scenario that may happen in the BlueWave process. The possible maximum relative speed happens when an EV moving at its maximum speed targets a vehicle approaching at its maximum speed too.

$$V_{relative\_max} = V_{EV\_max} - (-V_{other\_max}) \tag{2.7}$$

Taking the values in Section 2.2.3 on page 7 $V_{relative\_max} = 37.7m/s + 36.1 = 73.88m/s$.
The maximum value of $d_{relative}$ is obtained if we assume the worst case of overtake time ,$t_{overtake\_max}$.

Therefore, the maximum relative distance between EV and target vehicle that could happen is:

$$d_{relative\_max} = V_{relative\_max} \times t_{overtak\_max} \tag{2.8}$$

$$\begin{aligned} d_{relative\_max} &= 73.88m/s \times 13.5s \\ &= 997.38m \end{aligned}$$

This $d_{relative\_max}$ is the benchmark: receiving a warning at a distance less than that may not give the targeted vehicle enough time to react to the EVs warning. The system needs to make sure that at least one message is received before a targeted vehicle crosses the $d_{relative\_max}$. The EV is responsible for generating and directing messages towards target vehicles. Besides, the EV is assumed as moving towards a destination. Therefore, it has to update its warning with a certain rate. Let us assume for simplicity a static broadcast rate of B_{Rate} $messages/second$, the actual value could be dynamic depending on the speed of the EV and car density though. This concept of broadcast rate is further discussed in the protocol design phase of this research (Chapter 5, Section 5.4.1 on page 47). Therefore, we need to define an area beyond $d_{relative\_max}$ in which targeted vehicles can be announced about the emergency situation. This is the basic concept behind the ZoR. Literally, the ZoR should begin at $d_{relative\_max}$ and end at $d_{relative\_max} + size\ of\ ZoR$ as shown in Figure 2.4. Where $size\ of\ ZoR$ is sufficient distance for the targeted vehicle to at least receive one BlueWave message successfully.

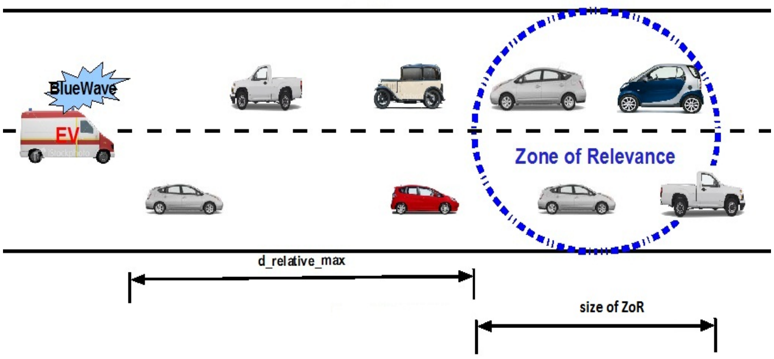

Figure 2.4: The dimensions of Zone of relevance for BlueWave

The ideal possible size of ZoR exists if we assume every packet sent by the EV arrives at a targeted vehicle successfully. Therefore,

$$size\ of\ ZoR\ =\ distance\ covered\ by\ a\ targeted\ vehicle\ at\ broadcast\ interval\ of\ one\ message.$$

However, our targeted vehicle may not receive all the packets sent to it due to channel errors and collisions. Suppose our targeted vehicle could receive at least one warning successfully after N successive broadcast by the EV. Then, the size of ZoR is given by:
$size\ of\ ZoR = distance\ covered\ by\ target\ vehicle\ at\ broadcast\ interval\ of\ N\ message$

$$size\ of\ ZoR\ =\ \frac{N \times V_{relative}}{B_{Rate}} \tag{2.9}$$

$$size\ of\ ZoR[worst\ case\ vehicle] = distance\ covered\ by\ worst\ case\ vehicle\ at\ broadcast\ interval\ of\ N\ messag$$

$$size\ of\ ZoR[worst\ case\ vehicle] \ = \ \frac{N \times V_{relative\_max}}{B_{Rate}} \tag{2.10}$$

where B_{Rate} is the broadcast rate of the EV. The above equation is represented pictorially in Figure 2.4 on the previous page. An important point to consider is the optimum value of N. It depends on the probability that our targeted vehicle will receive at least one message generated by the EV. A further and detailed discussion on value of N is presented in Section 5.4.1 on page 47.

In practice, the case of an approaching vehicle discussed above is not the only possible scenario. Vehicles could have different speed and direction than the worst case studied above. This implies that the size of ZoR and $d_{relative}$ suitable for each involved vehicle in the BlueWave process depends on its speed and direction. Therefore, the practical ZoR should include all possible scenarios that may happen. Hence, the practical ZoR in our research is defined as an area which covers a distance of $d_{relative\_max} + size\ of\ ZoR[worst\ case\ vehicle]$ from current position of the EV. Figure 2.5 represents the idea of practical ZoR.

$$practical\ size\ of\ ZoR = d_{relative\_max} + size\ of\ ZoR[worst\ case\ vehicle] \tag{2.11}$$

Clearly the scenario *"message too late"* may happen especially at the beginning of the EV trajectory, where close vehicles receive BlueWave message for the first time. Still, it is advantageous to start the ZoR from EV's location because telling late is better than not telling at all.

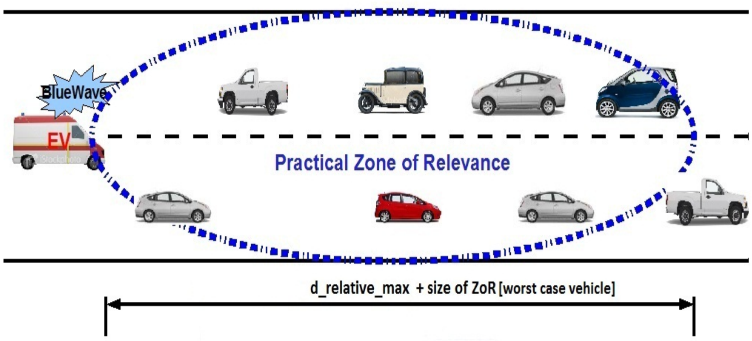

Figure 2.5: Practical Zone of relevance for BlueWave

2.2.4.2 Message (on time, too early & too late)

In Section 2.2.4.1 on page 10, we derived the concept of ZoR based on the overtake time and EV's broadcast rate. The actual size of ZoR is different for different vehicles, but based on the worst case scenario we created a practical ZoR which can be used for all possible scenarios, i.e. vehicles moving in any direction and at any speed less than the maximum limit. Each vehicle can evaluate the received message based on its relative speed and estimated time it needs to take action. This subsection will quantify the concepts of *message on time, message too early, and message too late.*

Let us take a case of a single arbitrary vehicle, $vehicle[other]$, moving at speed of V_{other} and is targeted by an EV moving at speed of V_{EV}. If the time needed by the EV to overtake $vehicle[other]$ is $t_{overtake}[other]$, then the actual ZoR for this vehicle can be constructed in similar way we deed for the worst case scenario analysis in Section 2.2.4.1 on page 10, i.e. $d_{relative\_max}[other] = t_{overtake\_max}[other] \times$

$V_{realtive}[other]$, where $V_{relative}[other] = V_{EV} - V_{other}$ and size of ZoR corrosponds to $vehicle[other]$ based on Equation 2.10 on the preceding page. Based on this idea we can define the arrival of a message as follows:

1. **Message on time**: a message is said to have reached targeted vehicle on time, if the targeted vehicle receive it within the ZoR as shown Figure 2.6.

   $d_{relative\_max}[other] < d_{relative}[other] < (d_{relative\_max}[other] + size\ of\ ZoR[other]).$

   It is important to note that different vehicles will have different values of message on time depending on their relative speed to EV.

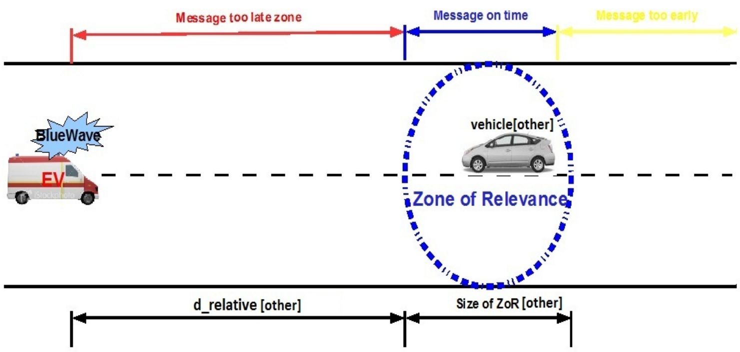

Figure 2.6: Actual ZoR and message arrival evaluation cases for a single vehicle, an example

2. **Message too early**: It describes a situation in which a vehicle receives a warning message too early(when it is very far away from the EV) and has to wait unnecessarily long time to be overtaken by the EV. It can be expressed quantitatively as:

   $d_{relative}[other] > (d_{relative\_max}[other] + size\ of\ ZoR[other]$

3. **Message too late**: The message is said to be late when other vehicles have no enough time to clear way before the EV overtakes them. i.e $d_{relative}[other] < d_{relative\_max}[other]$.

2.2.4.3 Time to live

As mentioned in Sections 2.2.1 and 2.2.2 the BlueWave message need to have limited age. The main purpose of the BlueWave messages is to assists EV on overtaking other vehicles on its way. Once the BlueWave process is complete these messages should be invalid. The worst case for the age of one message is the estimated maximum overtake time.

$$Time\ to\ live \ = \ t_{overtake\_max}[worst\ case\ vehicle]$$

Chapter 3

Related standards and Technologies

In the previous chapter, the proposed BlueWave system and its communication and application level requirements were described. The main intention was to identify and quantify the respective requirements. It is mentioned that this proposal is based on wireless technology related to vehicular communications. The objective of this chapter is to introduce the technologies and related standards available for vehicular communication purposes.

A wide range of technologies is used for vehicular communication purposes. The COMeSafety[4] classified these access technologies as:-

1. Short range and Ad hoc systems
   - CEN DSRC: Dedicated Short Range communication by the European Commission for standardization; European ITS at 5.9GHz; WLAN(Wireless Local Area Network) at 5GHz; IR (InfraRed); WiFi
2. Cellular Systems
   - WiMax; GSM/GPSR; UMTS
3. Digital Broadband Systems
   - DAB (Digital Audio Broadcasting) and DMB (Digital Multimedia Broadcasting) ; DVB (Digital Video Broadcasting) and DVB-H (Digital Video Broadcasting-Handheld); GPS (Global Position System)

In this chapter we limit our discussion to most relevant access technologies. By most relevant we mean widely used technologies and related standards in VANETs. The first section of this chapter will focus on the history and working principle of WAVE(Wireless Access for Vehicular Environment), an upcoming wireless standard for VANETs. It will describe the components of WAVE and its compliment standards (IEEE 1609.x). The second section will take a look at the DSRC technology. The diversity and architecture of DSRC will be part of this section. In section 4 the CALM (Communications, Air-interface, Long and Medium range) architecture is described. CALM provides a set of interfaces so that different services may interoperate. Finally, the chapter will be closed with discussion on the presented different technologies and motivation on selecting specific one for BlueWave.

3.1 Wireless Access for Vehicular Environment(WAVE)

WAVE is a complete protocol stack which is designed for vehicular communications. The history and evolution of WAVE is given in the Appendix, Part A.1 on page 84. The main objective of WAVE is to support wireless communication in highly mobile environment (typically >60Mph) [23]. The radio block view of WAVE system consists of 2 categories as shown in Figure 3.1, the management (control) plane and data plane [30] [87]. The main purpose of control plane is to run maintenance functions

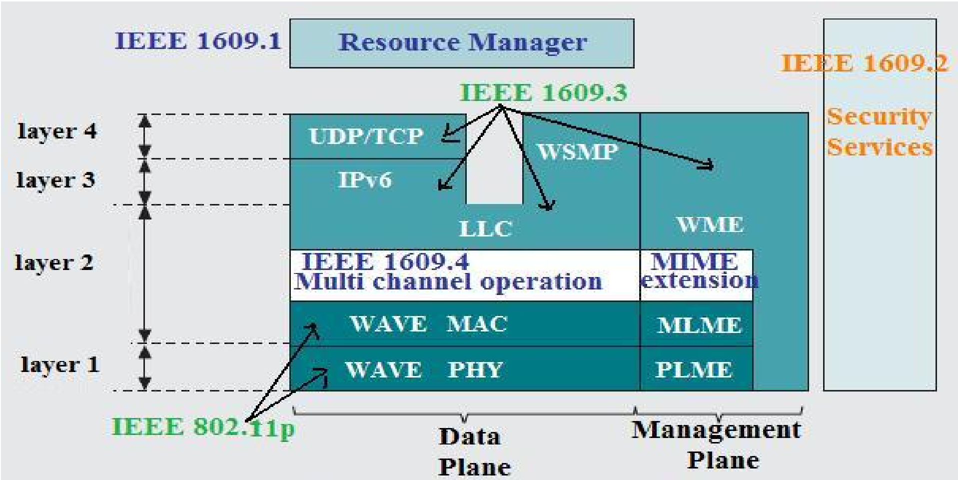

Figure 3.1: The WAVE protocol stack

and perform system configurations [20]. Management traffic between WAVE devices is monitored by management functions using data plan services. Each layer has its own relevant management entity such as physical layer management entity(PLME), and MAC layer management entity (MLME). The WAVE management entity (WME) is a more general collection of management services providing interface to all data plane entities. On the other hand, the data plane comprises communication protocols and hardware used for data delivery. It is responsible for transportation of traffic between applications and/or control plane entities and applications.

If the WAVE is seen from protocol stack point of view, it is built of IEEE802.11p (WAVE PHY), IEEE1609.4 (WAVE MAC), IEEE1609.3 (WAVE network), IEEE1609.2 (security, which actually doesn't fit the stack), IEEE1609.1 (resource manager, this also doesn't fit the stack), IEEE802.2 (LLC), IETF RFC2460 (IPv6), IETF RFC768 (UDP) [87] [30]. The protocol stack as shown in figure 3.1 has the same PHY, MAC and LLC(Logical Link Control) layers but divides in to two on Network and Application Layers. One part supports IPv6 and TCP/UDP to give service to less prioritized traditional internet applications. The second part is built by WAVE Short Message Protocol (WSMP) to handle highly crucial safety applications. The WAVE Short Message (WSM) is highly prioritized signal and uses a reserved control channel to avoid channel access delays [87] [52].

In the sequel the main standards, IEEE 802.11p and IEEE 1609.x, which together build the WAVE system, are described in detail.

3.1.1 IEEE 802.11p

The IEEE802.11p is a draft standard which is not finalized (to the time this paper was written) [23]. Its basic architecture is mostly adapted from the legacy 802.11 standard and related amendments. There is high expectation that this inheritance will enable 802.11p to become inter-operable between different vehicles and highly accepted by industry and academia [87]. The draft also need to consider special features of vehicular networks such as long transmission range, highly mobile nodes, extreme multipath environment, need of QoS, and special beacon frame [87]. The IEEE802.11p is the core basis of WAVE and it decides how other standards have to operate [23]. Therefore, it is worth to describe the special features and differences it has from the legacy IEEE802.11 standard.

PHY Layer

The basic techniques used in PHY(physical) layer are taken from IEEE802.11a. OFDM(Orthogonal Frequency division Multiplexing) is used as a multiplexing technique in a new licensed channel with 75MHz bandwidth at around 5.9 GHz of the radio spectrum. This avoids the interference with ISM band in 2.4GHz and 5GHz used in IEEE802.11b and IEEE802.11a respectively. The bandwidth of each channel is 10MHz which is half of the legacy standard (20MHz) and this implies halved data rate (3–27 Mbps unlike 6–54Mbps in IEEE802.11a). It means symbols will have more spread in time which reduces the inter symbol interference. Due to the high mobility feature of vehicles, reaching a destination could be difficult within the 802.11 legacy transmission range. To increase the transmission range, four levels of isotropic radiated power are defined. A maximum value of $44dBm$ ERIP is defined for emergency applications and $33dBm$ is reserved for safety applications [15] [23] [30].

MAC Layer

The first change from legacy MAC is the BSS (Basic Serivce Set) operation [54]. The topology form will be a loose form of IBSS (Independent Basic Service set) called WBSS (WAVE Basic Service Set). IBSS in 802.11 is an Ad Hoc mode where all nodes are peers. Nodes need to make authentication before joining an IBSS and get synchronized through beacon frames. In 802.11p, however, authentication is not needed to join WBSS in order to avoid delays in such highly mobile nodes. To make this happen, the WAVE beacons contain all the details needed by a host to join a service. The absence of authentication at this level doesn't mean there is no security, in fact security is handled by higher layers. Nodes synchronization is done by tuning to a common control channel at the beginning of global time reference used by all nodes such as universal coordinated time (UTC) [23].

The legacy 802.11 uses CSMA/CA (Carrier Multiple Access Collision Avoidance) as main mechanism to govern the wireless medium. DCF (Distributed Coordinator function) is employed to maintain one sender at a time in the medium. If a station want to send data it first sense the channel, which is called physical carrier sense. If the channel is busy it has to differ its transmission by random amount of back-off time which is drawn from certain window called the contention window (CW). The contention window is divided in time slots and has a size between 0 and CW, where CW is current contention window size. It multiplies the CW with the slot time (which depends on physical layer in use and propagation delays) and set it as back-off time. The back-off timer decrements every time the channel is free and when it is zero transmission starts immediately. The CW size doubles up to a maximum value of CWmax every time transmission fails. Once the CW reaches maximum or transmission attempt exceeds the maximum number of trails, packet will be dropped and CW will be set back to minimum.

Even if the channel is idle, a station has to wait for an amount of time equal to DIFS(Distributed Inter-Frame Space) before start sending as shown in Figure. DIFS is the minimum waiting time to access an idle channel. If the channel is occupied while it is in the DIFS waiting period, it has to go to the random back-off mechanism again. This basic functionality of 802.11 CSMA/CA is not fair as stations which lost the last contention have to contend again from scratch regardless the amount of time they waited in the last back-off. To introduce a sense of fairness the back-off timer is made to resume from last counting instead of drawing new value. This gives stations which had failed in the last contention a priority on the new contending nodes. If the transmission mode is not broadcast, it has to wait for ACK (acknowledgement) from recipient. ACK may not be received due to packet loss, packet error, or ACK from receiver lost. In that case a back-off procedure is invoked as described above [14].

It may happen that two stations which are not within the transmission of each other want to com-

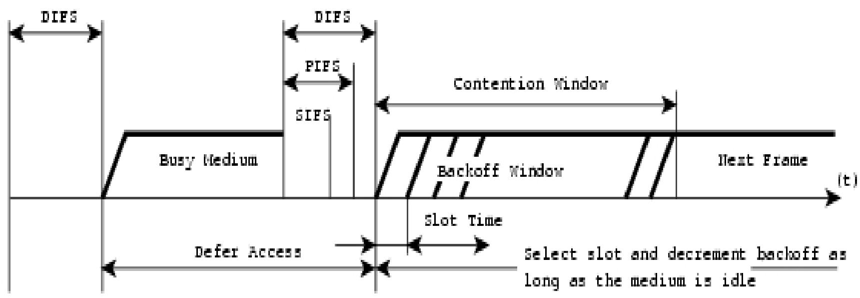

Figure 3.2: IEEE 802.11 DCF channel access

municate with another station which is somewhere within the transmission range of both. Such specific case as seen in figure 3.3 will lead to a problem called hidden terminal problem. One of the external

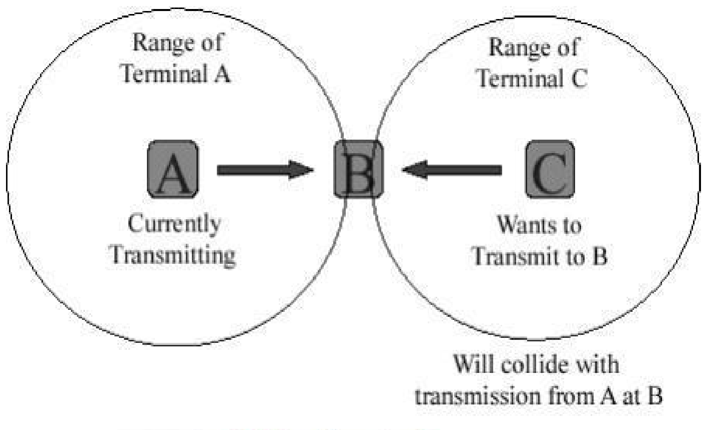

Figure 3.3: The hidden terminal problem

stations may send data while the other is already sending, which result in a collision. Hidden Nodes are solved by the use of a RTS/CTS (request to send/clear to send) protocol prior to packet transmission. In our three node network in 3.3 Node A sends a small RTS packet which is heard by Node B which send a small CTS packet which is heard by both Nodes A and Node C. Node C will not transmit in this case. To avoid unnecessary channel sensing and compel stations go to sleep mode in order to save power, a virtual carrier sense called NAV (Net Allocation Vector) is also used. Each packet contains the estimated time the present transmission will take and other stations set their NAV to avoid collision.

The CSMA/CA uncertainty, nodes have to contend, is not convenient for time critical VANET applications. Hence, in IEEE 802.11p the basic method still works but uses EDCA (Enhanced dedicated Channel Access) as in IEEE 802.11e. Applications are categorized in priority level in order to introduce a sense of QoS. Instead of constant DIFS, Arbitrary Inter-Frame Space (AIFS) which has different value for different classes is used [23]. As shown in table 3.1 on the next page, four kind of access categories are defined with four different AIFS, voice traffic (AC_VO) , video services (AC_VI), best effort (AC_BE), and background (AC_BK) [16] [44]. Traffics form four queues, each work on FIFO (First In First Out), as shown in fig. 3.4 on the following page and contend to access the common channel according to their back-off time which depends on current CW and slot time. In addition, the 802.11p MAC supports

Access Category Type	AC(Access category)	AIFS	CWmin	CWmax
Voice	AC_VO (Pr(0))	9	15	1023
Video	AC_VI (Pr(1))	6	7	15
Best effort	AC_BE (Pr(2))	3	3	7
Background	AC_BK (Pr(3))	2	3	7

Table 3.1: Default Access category values in IEEE 802.11p

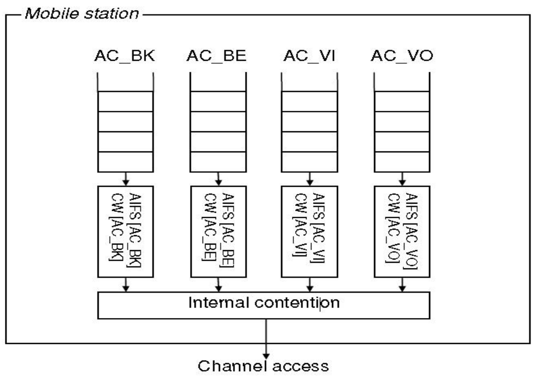

Figure 3.4: Internal queueing method in IEEE 802.11p

multichannel operation as specified in [52]. The new spectrum will have 6 service channels (SCHs) and one control channel (CCH). The detail operation of multichannel operation is discussed below in section 3.1.2.

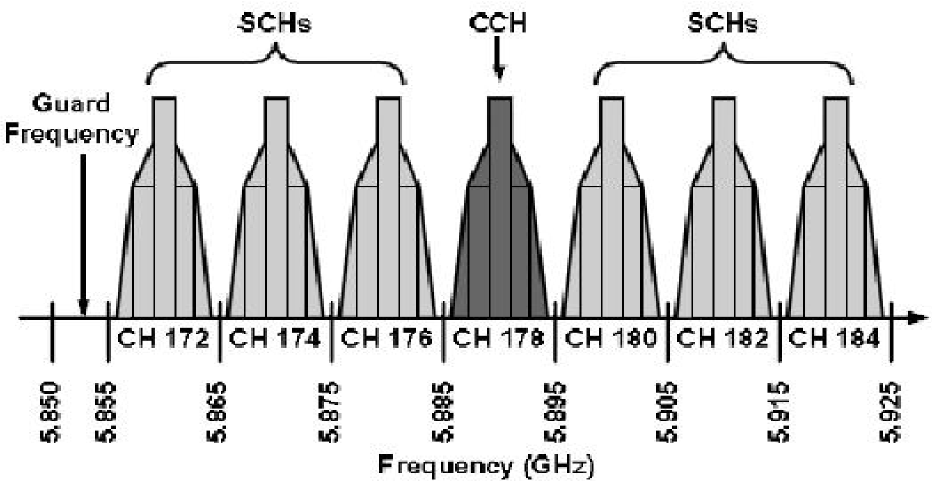

Figure 3.5: The WAVE frequency spectrum

3.1.2 IEEE 1609 series

The IEEE1609.x are trail standards, it means they will be revised after 24 months from their first release to public use and get published as a final standard [30]. They are complements of the WAVE standards for vehicular communication and defines the architecture, communications model, management structure, security mechanisms and physical access for the wireless medium. They also determine how a WAVE environment should operate and how WAVE applications should function based on the management activities defined in IEEE P1609.1, the security protocols defined in IEEE P1609.2, the network-layer protocol defined in IEEE P1609.3, and IEEE P1609.4. which provides multi channel operation. A detailed description of the IEEE 1609 family is given in the Appendix, Part A.2 on page 84.

The WAVE system doesn't emerge suddenly. In fact many of its parts are based on previous technologies which tried to address mobility of nodes. Even infrastructure based networks support communication at speed comparable to vehicular speeds. In the next section the DSRC (Dedicated Short Range Communications), a plethora of applications and technologies for vehicular communications, will be discussed.

3.2 Dedicated Short Range Communications (DSRC)

DSRC is a short to medium range communications service, like bluetooth and WiFi, that supports both Public Safety and Private operations in roadside to vehicle and vehicle to vehicle communication environments [6][30]. The current application of DSRC includes electronic toll collection, and electronic credentialing and monitoring of commercial vehicle operations (CVO). Different parts of the world adopted their own DSRC standards. In Japan the ARIB STD-T55 specifies physical, data link and application layer on 5.8GHz with rate not more than 1Mbps [30]. It was initially application specific

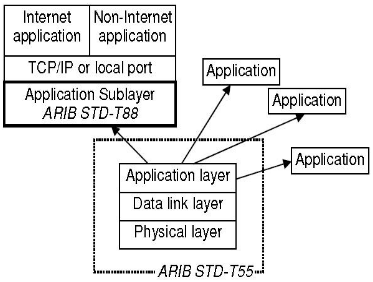

Figure 3.6: Japanese version of DSRC

but later they developed application layer extensions to support TCP/IP, i.e ARIB STD-T88[30].

In Europe, the DSRC protocol stack is also divided in to three, physical, data link and application layers [30]. All European counties reserved a dedicated band for DSRC between 5.795 and 5.805 GHz of the radio spectrum. The channel has 500kbps bit rate in the downlink with two level amplitude modulations and 250kbps uplink bit rate with binary phase shift keying modulation. The data link

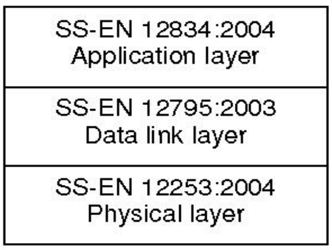

Figure 3.7: European version of DSRC

layer comprises MAC and LLC(logical link Control) sub layers. The MAC sub layer adopts the IEEE 802.2 standard and TDMA based beaconing used for channel access mechanism [30] [5]. Similar to the Japanese counterpart, the application layer is application specific.

The American DSRC is built on the basis of IEEE 802.11. It contains the PHY, MAC and application layers. The PHY and MAC are standardized by ASTM (American Society for Testing and Materials)[1] where as the application layer is standardized by IEEE. The ASTMs' PHY layer uses a modified version of IEEE 802.11a on 5.9GHz band to support highly mobile nodes. The MAC strategy

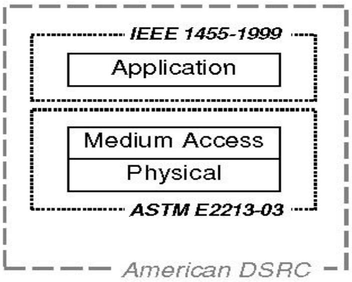

Figure 3.8: American version of DSRC

is similar to IEEE 802.11p, there is one control channel and two service channels. It uses a dynamic addressing mechanism and avoids the beaconing concept for synchronization [30] [5].

The over all components of DSRC systems are similar to WAVE. They have RSU and OBU to facilitate the Vehicle to Vehicle and Vehicle to Infrastructure communications. Some of the specific applications of DSRC are emergency warning system for vehicles, Cooperative Adaptive Cruise Control(CACC), Cooperative Forward Collision Warning , Intersection collision avoidance, Approaching emergency vehicle warning (BlueWave), Vehicle safety inspection, Transit or emergency vehicle signal priority, Electronic parking payments, Commercial vehicle clearance and safety inspections, In-vehicle signing, Rollover warning, probe data collection, highway-rail intersection warning, Electronic toll collection [18] [5]. Actually the WAVE, protocol stack explained in section 3.1 on page 14, is meant to replace DSRC to built an inter-operable and robust framework.

3.3 CALM

In the introduction of this chapter, we have mentioned a variety of technologies which are relevant to VANETs. Having a variety of technologies gives the flexibility on choosing the most suitable one for specific application. However, inter-operability and seamless handovers from one technology to another are major problems on availability of diversified access technologies. This section introduces a new framework, CALM (Communications, Air-interface, Long and Medium range), dedicated to tackle the problem of having diversified technologies.

CALM is a framework by ISO TC 204 WG 16 for Intelligent Transport Systems (ITS)[4]. It defines a set of protocols and interfaces for wireless communications under different scenarios based on convergence of IPv6. It supports inter-operability between present and coming standards in the wireless technology. The idea is to build a system which uses resources efficiently in short, medium and

[1] ASTM International, originally known as the American Society for Testing and Materials, is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services. http://www.astm.org

long range communications using any of the available media (WiMax, 3G, Bluetooth). The main ideas behind CALM can be summarized as:

- seamless communication
- support of multiple media
- future proof (adaptable to latest communication technologies)
- applications are independent of communications

More or less CALM is considered as the 4G vision of vehicular communications.

CALM Architecture

The architecture of CALM is shown in Figure 3.9. The CALM layers are associated with respective OSI model layers. The CALM architecture comprises four blocks and service access points (SAPs)[4], in which their functionality is described below:

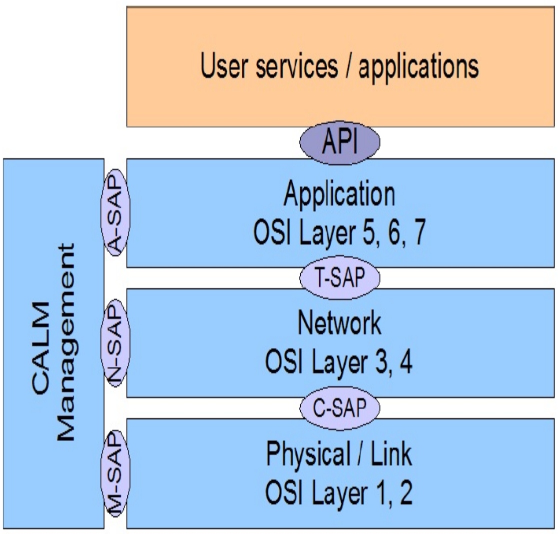

Figure 3.9: Architecture of CALM

1. The Application block provides a common API (Application Program Interface) to applications that want to communicate using CALM.
2. The Network block creates a relation between applications and communication media, isolating the upper OSI layers from the different technologies which actually perform communication. It is connected to the Application block through T-SAP (Transport Service Access Point) and C-SAP (Core Service Access Point)to the Physical/Link layer.
3. The Physical/Link block contains the different physical interfaces. It can contain several native CALM interfaces (CALM-IR, CALM-M5) or physical interfaces which have not been specifically been developed for CALM.
4. The CALM management stack doesn't fit the communication stack and hence placed out side. It provides management functionality to the CALM system. It is connected through the A-SAP (Application Service Access Point) interface with the application block, N-SAP (Network

Service Access Point) interface with Network Block, and M-SAP (MAC Service Access Point) to thePhysical/Link block.

SAPs define the interfaces between the individual blocks of the CALM architecture. Within the communication stack the T-SAP (Transport Service Access Point) connects the Application layer with the Network layer. The T-SAP provides the Application layer with a unified interface which allows a CALM service to address a specific CALM service at a remote node. Using the T-SAP the following operations are supported:

- creation of a socket
- deletion of a socket
- transmission of a packet
- confirmation for a transmitted packet
- reception of a packet

3.4 Discussion

In the introductory part of this chapter, we have listed a wide range of technologies that can be used in vehicular networks. The WAVE, DSRC, and CALM are discussed in detail. In addition, some of the related broadband technologies are described in the Appendix, Part A.4 on page 87. A summary of the comparison between different technologies is presented in Table 3.2 on the following page. Which technology to use depends on the kind of application. For example, very short range applications may use infrared technology, where as long range applications may chose WiFi technology or cellular system. In our case the WAVE is chosen as basic technology behind BlueWave application for the following reasons:

1. Unlike DSRC and broadband technologies, the WAVE supports cooperative and multi hop communications.
2. The WAVE supports ad hoc communication which literally extends communication any where as long as two or more vehicles are within their transmission range. Clearly this is not possible in wireless broadband technologies and DSRC in which communication depends on infrastructures.
3. Communication without central station reduces delay in case of WAVE. The absence of peer to peer communication introduces extra delay in case of broadband technologies. In addition, the coverage is limited to interference range of base stations.

	WAVE/DSRC	WiFi	Cellular	WiMax
Data rate	$3 - 27Mbps$	$6 - 54Mbps$	$< 2Mbps$	$1 - 32Mbps$
Mobility	$> 60Miles/hr$	$< 5Miles/hr$	$> 60Miles/hr$	$> 60Miles/hr$
Nominal Bandwidth	$10MHz$	$20MHz$	$< 3MHz$	$< 10MHz$
operating band	$5.86 - 5.925GHz$ (ITS-RS)	$2.4GHz, 5.2GHz$ (ISM)	$800MHz, 1.9GHz$ (GSM)	$2.5GHz$
related standard	$IEEE802.11p$ $IEEE1609.x$	$IEEE802.1a/b/g$	GSM	$IEEE802.16e$

Table 3.2: comparison of access technologies related to VANETs

Chapter 4

Related Data Dissemination & Routing Mechanisms

In the last chapter, we have seen a wide range of technologies which are used in vehicular communications. The main purpose of these technologies is to maintain data communications within the vehicular network (V2V/V2I) one way or another. Therefore, this chapter will investigate the various data communication mechanisms as presented in the literature.

The first section describes the general overview of the ongoing research on VANETs. In section 2, the focus will be on data dissemination mechanisms. Three mechanisms will be addressed namely, flooding based, relaying based and opportunistic forwarding. The third section will discuss routing mechanism for VANETs. This section will narrow down the topic to a type of routing which is more related to BlueWave application called Geocasting.

4.1 VANETs Research Overview

In recent years Vehicular networks has got a considerable attention from government and academic institutions. The FCC (Federal Communications Commission)[1] has allocated a dedicated robust spectrum band around 75GHz for DSRC applications in the US. Similarly, in August 2008 the European commission has decided to reserve 75MHz spectrum for vehicular communications [1]. The dream of having connected cars has induced high curiosity and interest from industries too. NOW (Network On Wheel) is one of the actively participating parties which has a collaborative project between several car companies to solve technical questions on communication protocols and data security in car to car communication [12]. GeoNet is another European project focusing on extension of C2C CC manifesto to achieve the European road safety plan of 2010 [10]. It basically focus on implementing and formally test networking mechanisms as stand alone software module. GST (Global System for Telematics) is also an EU funded project with the objective of creating end to end architecture for automatic telematic services [19]. The C2C-CC manifesto, funded by 6 European companies, works on drafting basic architecture of car to car communicating [18]. The COMeSafety is a more general project which tries to harmonize different projects and propose a support for realization and possible deployment of cooperative, communication based safety systems [4]. The overall research on vehicular networking can be seen in four big blocks:

1. MAC and PHY layers related
2. Data dissemination in VANETs
3. Mobility & Simulation packages

[1] The Federal Communications Commission (FCC) is an independent agency of the United States government, created, directed, and empowered by Congressional statute. http://en.wikipedia.org/wiki/Federal_Communications_Commission

4. Security & privacy issues

The scope of this research is limited on design of network layer protocol for BlueWave application. Hence, the rest of the chapter will focus on network layer mechanisms such as data dissemination and geo-routing. Short description of the other three research areas is presented in the Appendix, part A.3 on page 86.

4.2 Data Dissemination in VANETs

The VANET system architecture includes: 1) Direct communication between vehicles using IEEE 802.11p, V2V(Vehicle to vehicle); 2) Communication with roadside unit[2] using IEEE 802.11p, V2I/I2V (Vehicle to Infrastructure/Infrastructure to Vehicle); and 3) Communication with other types of infrastructure such as UMTS, GSM and WiFi hot spots [100]. VANETs have special features which result in a general challenges of data dissemination mechanisms [99]. The following factors are recommended for consideration in design of data dissemination protocol for VANETs[100][89]:

1. Mobility and dynamic topology:
   Due to high mobility of nodes, dynamic topology and absence of global view, it is difficult to use MANET routing protocols as they are[83]. Proactive protocols such as DSDV (Destination-Sequenced Distance Vector routing) fail to maintain their routing tables in a reasonable time and bandwidth usage[71]. Similarly, reactive protocols such as AODV are not fast enough to create route before the link breaks[76][95]. In all, the addressing model and routing protocol for VANETs should overcome these difficulties.

2. Scalability:
   VANETs in principle can extend their size up to the end of the road. This results to possible existence of large networks. In special scenarios and topologies, for example in rush hour on a highway, the network could be extremely dense. The protocol to be used need to be robust enough to work on such situations. The scalability of a protocol is related to the choice of addressing model and routing mechanism, for example IP based addressing may not be scalable in such large network as the routing table could be difficult to manage [89] [57] [26] [103].

3. Fragmentation:
   Network fragmentation may happen if a node is unable to reach next hop. This could be due to sparse node density or the gradual market penetration of the technology which will create mixture of equipped and non-equipped(dump) vehicles.

VANET dissemination related protocols can be classified based on variety of criteria such as type of application (safety, traffic efficiency, infotainment)[90], dissemination mechanism they use (flooding[57][33][45], relaying [27] [64] [104] and opportunistic forwarding [99] [33] [41]), architecture units involved (V2I/I2V, V2V and combination of both) [89], on network density(sparse, dense and normal)[89], on network models used (mobility in same direction, opposite direction or both directions)[103]. In this section, we focus on the frequently used dissemination methods which are classified according to the mechanism of dissemination they use.

[2] A Road-Side Unit (RSU) is a physical device located at fixed positions along roads and highways, or at dedicated locations such as gas station, parking places, and restaurants. It is used to extend connectivity of VANETs, run safety applications or provide internet to vehicles [3].

4.2.1 Flooding based

Flooding based dissemination is widely used technique in many applications as it has relatively less delay and simple approach[57][81]. In plain flooding nodes try to rebroadcast immediately any packet they receive for the first time. Plain flooding has a known and studied problem called broadcast storm [79]. There will be unnecessary retransmissions, extra overhead and high contention which leads to more collision. Many solutions are available in the literature such as heuristic based, geographically directed and neighbor coverage based. A common approaches of the heuristic methods are counter based, probability based and distance based. In the following paragraphs specific solutions presented in some papers are presented.

Counter based solution in [79] set a thresh hold on the maximum number of duplicate packets received by a node. If the same packet is received beyond the thresh hold it is immediately discarded. The decision to set the thresh hold can be based on simple random number or more sophisticated calculations which include cross layer information and coverage estimations. The same paper, [79], present a probabilistic solution for the broadcast storm problem. Up on receiving a packet for the first time, it is rebroadcast with a probability randomly selected from uniformly distributed sample between 1 and 0. Probability of 1 is equivalent to blindly flooding. In more precise performance requirments, the probability can be determined with some intelligent algorithms which depend on extra information such as signal to noise ratio. It is also possible to limit the storm problem by limiting number of hops a packet should traverse [33]. In [77] the authors designed hop limited flooding for specific application, AdTorent epidemic dissemination. Increasing hop limit lead to increase in reliability of the application, i.e. finding several sources to download. However, this effect will have increased flooding messages per query and consequently degrade network performance.

The most common approach in the literature to tackle the storm problem is the distance based back-off method, in which nodes has to back-off a time inversely proportional to their distance from the sender [89] [57] [33] [45] [33] [98] [24] [82]. In [33], Linda et al. used a simple time based suppression for broadcast storm. Their proposal focuses on hazard warning for group of vehicles in a specific zone. They use multi-hop forwarding strategy which depends on the distance of node from sender. The waiting time before a rebroadcast is inversely related to distance, such that nodes at the edge of the transmission range will have shortest wait time. This will reduce the redundant broadcast as other nodes which hear the broadcast will immediately drop it from their list before their timer is off.

Similarly Wisitpongphan et al. in [98] proposed three solutions that are probabilistic or time based broadcast suppression techniques namely: weighted p-persistent, slotted 1-persistent and slotted p-persistent. All these three protocols use their local information to find their forwarding probability.

1. In *weighted p-persistent*, node i receiving a packet from node j for the first time rebroadcasts it with the probability of p as shown in Figure 4.1 on the following page. Probability p depends on the distance between source and destination, i.e $p = \frac{D_{i,j}}{R}$ where $D_{i,j}$ is distance between nodes, and R is average transmission range of transmitter.

2. In *Slotted 1-persistent* nodes are grouped according to their distance from the source as shown in Figure 4.3 on the next page. Upon receiving a new packet from source node j, node i broadcasts with a probability of one in a times slot $T_{S_{ij}}$, where T_{Sij} is given by:

$$T_{S_{ij}} = S_{ij} \times \tau \tag{4.1}$$

In which τ is the estimated one hop delay including medium access delay and propagation delay, S_{ij} is assigned slot number given by:

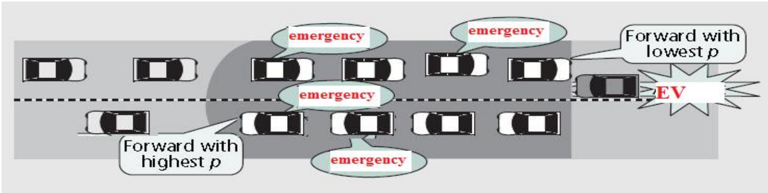

Figure 4.1: Weighted p persistent, an example [part of diagram taken from [98]]

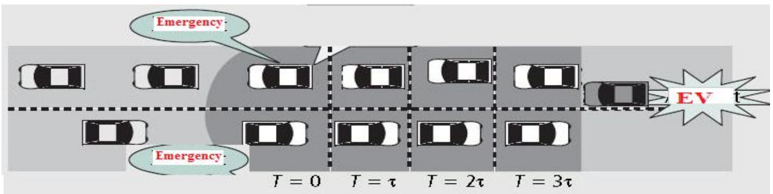

Figure 4.2: Slotted 1 persistent with 4 slots, an example [part of diagram taken from [98]]

$$S_{ij} = N_s \times \left[1 - \left(\frac{min(D_{ij}, R)}{R}\right)\right] \tag{4.2}$$

N_s is the number of slots which is determined by designer.

3. The *slotted p-persistent* mixes the techniques of the above two, broadcasts with a probability p in a time slot T_{Sij}.

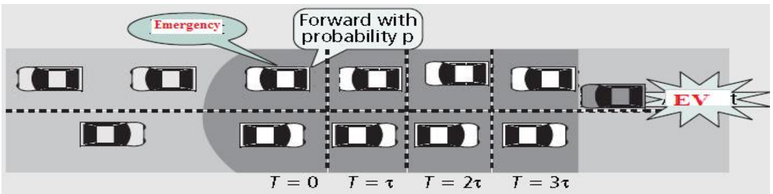

Figure 4.3: Slotted P persistent with 4 slots, an example [part of diagram taken from [98]]

Van Eenennaam in [93], identified a problem of synchronization between nodes in *Slotted 1-persistent*. This means, if there are more than one nodes in a time slot, all will draw their random MAC slot at the same time, which increases the collision probability. It is solved by introducing additional micro slot waiting time. This micro slot waiting time depends on the position of vehicles within one slot length(S). The physical length of one slot is given by:

$$S = \frac{transmissionrange(R)}{numberofslots(N_s)} \tag{4.3}$$

if the extra delay to break synchronization is denoted by T_{extra_delay}, then

$$T_{extra\_delay} = N_{ms} \times \left[1 - \frac{min((D_{ij} mod\ S),\ S)}{S}\right] \times DIFS \tag{4.4}$$

where, $DIFS$ is a MAC parameter, N_{ms} is number of micro slots with in one slot, which is given by:

$$N_{ms} = \frac{S}{averagevehiclelength} \tag{4.5}$$

where $mod(D_{ij}, S)$ gives the location of vehicle within a slot. The total time a vehicle has to wait will be:

$$T = T_{S_{ij}} + T_{extra\_delay} \tag{4.6}$$

$T_{S_{ij}}$ is defined as in equation 4.1 on page 26.

Authors in [75] defined three formal models for data dissemination. In their design the disseminated message contains information about itself and other vehicles it knows. To reduce the broadcast problems their model store data for some time and broadcast them as one packet in burst. Data aggregation is used to further use resources efficiently. They further modeled the dissemination relative to mobility direction as, the same direction, opposite direction and both directions. The results from their simulation shows opposite direction vehicles model is more efficient than using vehicles in both directions.

In [35], topology independent information dissemination algorithm is defined for spatio-temporal traffic information applications. The algorithm divides the target area in to grids and the resources are broadcast periodically. To reduce the broadcast storm problem use of grid based application level information evaluation and aggregation are used.i.e. information is collected and combined to create some hierarchy. Their simulation results also revealed that aggregated information broadcasting is efficient method, though it introduce delay on end to end communication.

A more general approach by Tonguz et al. in [89] considers all kinds of network conditions, sparse and dense. The DV-CAST protocol uses the neighborhood information and broadcast storm mitigation techniques given in [98] for efficient flooding usage. The connectivity information is obtained from hello messages and nodes make decision accordingly. In a well connected state, having one or more neighbors in forward direction, one of the slotted persistent algorithms is invoked. In case node is totally disconnected, it stores the broadcast until it delegates it to other vehicles or packet is expire.

All in all, flooding based dissemination mechanisms are easy to implement as they don't have serious cross check (destination address is broadcast mode) but result in extra overhead and energy and bandwidth waste. Usually they achieve high reachability or accuracy but the route they select is not necessarily the best or shortest. To have best optimized design combination of the broadcast mitigation techniques discussed above is used.

4.2.2 Relaying based

As seen in the above review, flooding based dissemination suffer from extra overhead and contention problems. One approach to avoid this is to select next hop for forwarding the data which is called relaying. In the uncertain vehicular network, this approach has two main challenges: 1) selection of next hop from neighbors, 2)Reliability of the selected node and the selection mechanism. This section presents the literature review of relaying based data dissemination protocols in VANETs.

In [64] a simple relaying method for urban data dissemination is proposed. The authors point out the line of sight and market penetration problems in city scenarios. The algorithm tackles broadcast storm and hidden terminal problems by dividing the transmission range in segments and put responsibility of forwarding to the furthest node in non-empty segment. The source obeys the the 802.11 CSMA/CA and broadcasts a request to broadcast, nodes in the segments respond with a clear to broadcast, but the time they wait to broadcast is inversely proportional to their distance from the source, hence the furthest non-empty segment will be first to respond with an ACK. After reception of an ACK the source sends data with a unique ID of the relaying node as such flooding is avoided. To overcome the line of sight difficulty in urban scenarios, repeaters are placed at road intersections and the over all effect is high success rate and efficient use of channel.

The paper in [104] also combat the data dissemination challenges mentioned in Section 4.2 on page 25 by mechanisms of data pouring and buffering. Nodes maintain neighbor list and chose furthest node as a relay. Data is poured periodically to the road and to avoid the broadcast problems buffering is done for some time and all are broadcast as a burst. The authors in their proposal included repeaters in intersections to combat network fragmentation.

In [27] an alarm dissemination protocol is designed to avoid pile-up of cars during unusual traffic conditions such as accidents or bad weather. The authors focus on the elimination of broadcast storm and overcome limitation of traditional routing protocols in VANETs. The algorithm restricts rebroadcast to relay nodes which are selected in a distributed fashion considering maximum reach of uncovered area. i.e furthest node. The distance between source and receiver is determined from information in the packet, which is source coordinates, and receivers location, intercepted from GPS device. The back-off mechanism they designed is inversely proportional to distance between source and receiver.

The reliability of forwarding relays can be ensured by introducing RTS/CTS method as in [64], in the cost of extra overhead to the network. However, if delay is tolerable RTS/CTS are small control packets and flooding with them is much better than flooding with data packets. In all, relay based protocols could be made more reliable in the cost of extra overhead and more delay.

4.2.3 Opportunistic forwarding

In section 4.2.2 on the preceding page nodes in the range were selected as a relay to forward data. In reality the next hop may not always be available within the transmission range of the sender, specially in sparse networks which is more probable to happen during early deployment of VANETs. This will lead to a phenomenon called fragmentation or network partition, i.e. there will be no end to end one hop connectivity. Opportunistic forwarding is one kind of dissemination mechanism aimed to combat this problem [70]. The main idea behind opportunistic forwarding protocols is to store the data until next hope is detected. This section discusses relevant opportunistic forwarding mechanisms as presented in the literature.

In [41], the authors address network discontinuity problem using opportunistic forwarding related to motion of vehicles. Vehicles carry data until they detect next hope in their way. The method doesn't mention how the carrier will detect availability of next hop and maximum time it has to hold the message. A possible solution could be exchange of hello messages at certain interval. The simulation results in a simplified highway scenario revealed that end to end delay decreases by using advantage of carry to next hop method.

The paper in [32] also focuses in tackling network fragmentation in VANETs due to low market penetration. The algorithm creates a neighbor list and restrict broadcasting only to vehicles in their list. This is maintained with the help of beacon messages. There is a tradeoff between neighbor list maintenance and message delay .i.e. frequent update of neighbor list introduce high contention, collision and hence high end to end delay.

Authors in [99] make analytical models for data dissemination in VANETs. The main focus was to design reliable protocols considering network partition and message propagation mode. They identified two modes of message propagation, forwarding process and catchup process. The forwarding process includes multi hop forwarding of data. In the catchup process, messages move with a vehicle until partition is over. The research also show the effect of traffic density, average and relative speed of vehicles, on information dissemination.

The approach in [56] use opportunistic forwarding in buy/sell query dissemination architecture named as FleaNet. Vehicles store the query they receive in their data base and when local match is obtained they use it. The broadcast query from buyer or seller has periodical broadcast fashion with opportunistic approach. There is no predetermined destination, broadcast is done under the assumption that some one interested may be around.

In all, the carry and rebroadcast method used in opportunistic forwarding mechanisms faces a difficulty to chose the right rebroadcast interval. Frequent rebroadcast will create extra over head and slow rate will result in network partition. Maintaining the neighbor list also creates more overhead and contention.

4.3 Routing in VANETs

Routing in wireless networks can generally be topology based or geographic (location/position) based [38]. Topology based protocols build a tree of the network based on identity of nodes. Geographic based protocols, on the other hand, use geographic location of nodes as a parameter one way or another. The traditional topology based MANET routing protocols are found to be not convenient for VANET applications [83]. Simulation results in [76] show poor route convergence and low throughput for reactive protocols such as AODV and DSR. Especially in [95], a practical test on AODV revealed its failure to maintain 3-way TCP handshake process. Similarly, proactive protocols such as DSDV introduce extra delay and bandwidth waste due to explicit route establishment phase [71]. Simulation results in [78] show even location based MANET protocols such as GPSR are inefficient when applied for VANETs. These researches suggest that Geo-routing is preferable to topology based routing for many VANET applications. The suitability of geo-routing for VANETs is based on several reasons such as:

- it improves over all performance of routing (assuming geographic proximity is equal to radio proximity, which actually is not always the case) [83]
- traditional addressing (MAC for IEEE 802 and IP for the internet protocol) are not practical for VANETs [58]
  - it may be difficult for a node to know other node's address (security and high mobility).
  - many of the VANET applications are in a group interest.
  - they need to maintain state information about topology, which doesn't scale in large networks.

Geo-routing as a class of routing protocols is very wide and has been on the research front line for decades. Geo-routing in wireless ad hoc networks can be Geo-unicast, Geo-multicast or Geo-broadcast. In Geo-unicast data is forwarded from source to a single destination node. In many location based geo-unicast protocols, the sender first send a probe messages to find destination. Once the destination reply with route reply messages indicating its location, then the data payload is send. Greedy forwarding algorithms are one kind of geo-unicast in which forwarding is done to achieve the best coverage. They are based on location information of source, current receiver and destination. The protocols aim to use the most close forwarding node to the destination, thats why they are named as greedy. An obvious problem is in case nodes have no forwarding neighbor. Solution is provided by void handling protocols such as GPSR, .i.e. they provide a backup algorithm in case there is no forwarding node within their range.

GPSR (Greedy Perimeter Stateless Routing) [59] tries to select closest node to the destination based on neighbor information. In case neighbor is not found it recovers using topology graph perimeter. To maintain the neighboring table nodes exchange beacons with each other. The location look up method used in GPSR may fail to accurately locate destination node if the destination show a significant move after its last topology update. In that case routing will happen in a place where destination node doesn't exist anymore. GPSR-MA(Enhanced GPSR Routing in Multi-Hop Vehicular Communications through Movement Awareness)[48] tries to solve this problem by extending the routing decision parameters to make position prediction. The simulation results indicate its suitability for unicast communication in highly mobile ad hoc networks such as VANETs. MORA, a Movement-Based Routing Algorithm for Vehicle Ad Hoc Networks[47], is another modification which adds direction of nodes to decide forwarding node. The metric used for forwarding decision is based on number of hops and a waiting function which depends on many factors including source-destination distance and node direction. A detailed description and comparison, based on method and time line, of unicast protocols for VANETs is presented in [28].

Geo-multicast is another kind of geo-routing in which multiple nodes are targeted as destination from a single source. Two basic solutions are: [38]

1. network-range flooding
2. unicast routing to each destination

Both the solutions are inefficient in terms of network resource usage. Position based multicast (PBM)[73] is multicast version of GPSR. It consists of greedy and perimeter multicast modes. The perimeter multicast forwarding is invoked when greedy multicast forwarding fails. The tree for multicast is built as the multicast packet propagates. One problem of PBM is its complex computation to select next hop node[38]. As the multicast packet has to include all the destination, it is also not scalable in large networks. The Scalable-PBM[91] was designed to improve the scalability. For this, it introduces hierarchical group management but it uses separate unicast routing for each destination which makes it inefficient. A detailed description of many geo-multicast protocols is presented in [38].

There is also a special kind of geo-muticast called Geocast. This kind of routing is used when destination nodes are identified by being in a specific geographic area. The specific area of interest is called geocast region or zone of relevance (ZoR). The ZoR relevance can also add special attributes in the routing such as direction of vehicles (the message may be important for vehicles in specific direction only), road ID, Vehicle type) [58]. Since BlueWave as an application involves group targets which potentially are identified with their geographic location, our discussion will focus more on it in the next subsections.

4.3.1 Geocasting

As mentioned in section 4.2 on page 25, VANET applications can be classified as safety related, traffic efficiency and, infotainment. Safety related applications require upper bound for delay and some sort of QoS to be differentiated form non-safety ones. In addition, safety related applications usually have group of vehicles as a target. For example, hazard warning is important to vehicles approaching the hazard area, accident notification is relevant to vehicles around the scene. This nature of the applications lead to the emerge of special kind of geo-multicast protocol called geocasting. The basic purpose of a geocasting protocol is to disseminate certain information to determined target area [74]. If the source is outside the target zone, there should be a mechanism to reach at least one node in the region, after which local distribution will be invoked. Several geocasting protocols has been designed focusing on different scenarios and applications. From application perspective, geocasting protocols can be classified into big categories as geocast for VANETs [61] [40] [24], geocast for MANETs [105] [53] and, geocast for general wireless ad hoc netwroks [80] [50][86]. In case the source is outside the geocast region or ZoR, it is also possible to categorize protocols according to the type of data dissemination they use to reach target zone. In [55] they classified them as data transmission oriented (flooding and its variants) and route based geocast protocols.

4.3.1.1 Data dissemination oriented geocast protocols

These protocols use flooding or flooding related methods to reach the target area called geocast region. The use of flooding leads to broadcast storm problems as discussed in Section 4.2.1 on page 26. The same is true for geocast protocols if not designed carefully.

The paper *Flooding based geocast protocols for mobile ad hoc networks* in [63] studied the impact of broadcast storm in geocasting and come up with three basic solutions: static forwarding zone, adaptive forwarding zone, and adaptive distance geocasting protocols. The authors defined a forwarding zone (FZ) as an area in which nodes inside forward packets towards the geocast region. In static forwarding zone the source defines a rectangular zone with one corner be its location and opposite corner be upper edge of geocast region. This method reduces the redundant broadcasts out side the FZ as such contributing to the mitigation of broadcast storm. Static forwarding zone are not flexible as nodes who hear the packet for the first time will always forward it no matter if the message has reached destination or is already a head on its way. Adaptive static zone tries to reduce the number of extra overhead by shrinking the FZ to the location of the current forwarder. This enables nodes behind the receiver but within the former FZ not to rebroadcast. The authors doesn't mention how to proceed with no next hop scenarios and what decision to take if a node receives the same packet from two neighbors one which includes it within the FZ and the other doesn't. To increase reliability a simple solution could be to consider the one which includes it within the forwarding zone. The third method, adaptive distance, uses relative distance to the sender for decision on broadcasting. If the packet is received from behind it definitely need a broadcast to nodes ahead, otherwise discard it. In the absence of next hop the algorithm invokes one hop flooding i.e. Even nodes from behind can forward. The paper doesn't mention how the absences of next hop is detected but one option is to sense the channel and if it doesn't overhear it implies there is no next hop. Two metrics used are overhead (extra packets broadcast) and reach-ability(how many of the intended nodes receive the message). Simulation results shows the existence of tradeoff between overhead and reach-ability. Forwarding based on FZ may not be always reliable as they could be empty FZ cases.

The method used in [86] uses voronoi diagrams to solve empty FZ problem. The voronoi region associated with node A consist of all the points in the plane which are closer to A than to any other node. Since the destination is an area, ZoR, rather than a single point, multiple destination possibilities exist. This leads to having several neighboring nodes belonging to the FZ. However, the voronoi algorithm by itself is extra computational overhead.

The method used in [68], GeoGRID, divides the region in to grids and forwarding is the responsibility of one node in each grid called gateway node. It is meant to reduce the overhead or redundancy of packets experienced in flooding based protocols. Selection of gateway gives priority to nodes near the center of the grid. Two version of the protocol are presented. First is the forward broadcast packet in which all gateways in each grid broadcast the message. The second method is ticket based forwarding in which only n+m gateways are allowed to broadcast out of m x n in total. Tickets are allocated by the source in evenly distributed manner. The main reason behind ticket based is the fact that gateway coverage can reach more than one hop and suppressing some gateways may reduce overhead.

4.3.1.2 Route based geocast protocols

This protocols accomplish packet delivery in two steps. First, anycast method is used to deliver the packet to any node in the geocast regions. Second, upon receiving the geocast packet selected node use localized flooding to distribute it to all reachable nodes. Such approach reduces the over head created by flooding based protocols to reach target area while keeping the accuracy at accepted level.

A similar approach to GeoGIRD is proposed in [105] by Zhou et al., combining anycast based routing with flooding. The proposed protocol utilizes the location information to route messages in grid-by-grid manner. The routing path of proposed protocol is the shortest route between hosts in grids. The grid structure is successfully used to eliminate redundant transmission of geocasting messages. The time complexity of route discovery and the routing overhead are also reduced comparing to flooding based.

GeoTORA [62] is a typical protocol in this category which uses anycast routing protocol called TORA (Tomprarly Ordered Routing Algortithm). TORA is a distributed routing protocol based on a link reversal algorithm. It attempts to provide multiple routes to a destination, establish routes quickly and minimize communication overhead. TORA uses the notion of heights to determine the direction of each link. Despite dynamic link failures, TORA attempts to maintain a destination-oriented directed acyclic graph such that each node can reach the destination. A source node essentially performs an anycast to any geocast group member (i.e, any node in the geocast region) via TORA. When a node in the geocast region receives the geocast packet, it floods the packet such that the flooding is limited to the geocast region.

MGRP(Mesh-based Geocast Routing Protocol)[31] is another route-based protocol. Unlike GeoTORA, this protocol establishes multiple paths via a mesh to send geocast packets. Mesh-based multicasting approach has been developed in order to avoid week performance with source tree-based and core-based multicasting protocols in ad hoc networks. A mesh is a subset of the network topology that provides multiple paths between multicast senders and receivers. In the creation of the mesh, the protocol floods JOINT-REQUEST packets to a forwarding zone until it reaches a node within the geocast region. The node in a geocast region unicasts a JOIN-TABLE packet back to the source following the reverse route taken by the JOIN-REQUEST packet. Once the first JOINTABLE packet is received by the source, data packets can be sent to the nodes in geocast regions.

In [36] an adaptive mesh environment for geocast is proposed. GAMER(Geocast Adaptive Mesh Environment for Routing) differs from MGPR in [36] it adapts network environment by changing size of forwarding zone with mobility of nodes which directly influences the density of mesh routes. As a result, when nodes are highly mobile, a dense mesh is created; when nodes are moving slowly,a sparse mesh is created. A source wishing to transmit packets to a geocast region will first flood JOIN-DEMAND packets in a forwarding zone. A JOIN-DEMAND packet is forwarded in the forwarding zone until it reaches a node in the geocast region. This node unicasts a JOIN-TABLE packet back to the source following the reverse route taken by the JOIN-DEMAND packet. When the source receives its first JOIN-TABLE packet, it can begin sending geocast packets via the mesh to the geocast region The CONE, CORRIDOR and FLOOD forwarding zones are the three candidates that a source node can choose in GAMER The authors of GAMER propose two versions of GAMER: passive GAMER and active GAMER. In passive GAMER, the JOIN-DEMAND packets are transmitted at a fixed frequency. In other words, a JOIN-DEMAND packet is sent at every JOIN-DEMAND packet interval regardless of whether a JOIN-TABLE packet is received. In Active GAMER, the JOIN-DEMAND packets are transmitted at the same fixed frequency and at a higher rate if a JOINTABLE packet is not returned within a given timeout period.

Authors in [39] designed a geocast protocol to make sure a guaranteed delivery of packets to geocast region. Adaptive Hand Shaking-based Geocast Protocol(AHBG) is based on hand shaking between neighbors to forwarding to forward data to destination destination. It has two modes of forwarding: table driven and hand-shaking based. In table driven mode, each nodes checks if it has information about the geocast region next hop when a packet is received. The next mode is Hand-shaking mode in which source node follow RTS/CTS/DATA/ACK procedure to forward information. The problem related to absence of next hop, dead zone, is also dealt in this paper. The algorithm returns back the data to previous sender if there is no next hop so that another route is selected. The main drawback of this method is its extreme delay specially in dead zone cases(no next hop).

4.3.1.3 VANET related geocast protocols

The above discussed geocasting protocols are general solutions for MANETs. VANETs have special behaviors which are not seen in the case of MANETs such as road constrained mobility and highly dynamic topology. This demands a different approach in geocasting techniques for vehicular networks. Many of the protocols are specific scenario and application related. As mentioned earlier it is difficult to obtain a universal geocasting solution in case of VANETs.

The authors in [32] proposed a role based geo-multicast protocol for sparsely connected highly mobile network. The protocol focus on a single scenario of road accident notification. The source vehicle announce the warning to vehicles approaching. The concept of ZoR is defined by maximum number of hops the message has to go across. If a certain maximum thresh hold is reached, the packet is ignored. The broadcasting scheme is used based on distance from sender. Vehicles undergo a back-off which is related inversely to their distance from source. The Authors further assumed a complete knowledge of neighbor list by nodes, which help them reduce the broadcast storm problem,i.e. Nodes only broadcast if there is at least one node in their transmission range. Two basic problems with this approach are: 1) the assumption of complete neighbor list will incur extra overload, which may be more bandwidth consuming than the alarm message it self; 2) The protocol is designed for sparse network density in which the broadcast storm problem is not exaggerated. In addition, the simulation results also reveal some breakdown in the protocol at 5% and 25% of the parameter ratio of equipped vehicles.

Abdelmalik et al. in [24] proposed an inter-vehicle geoacast aiming to solve the above mentioned problems in [32]. A similar scenario of accident notification as in [32] is considered. In contrast to the static geocast group (ZoR), vehicles define multicast group temporally by the location, speed and the driving direction of vehicles. The proposed solution,IVG, is completely independent of maintaining neighbor list. Hence, This reduces the background traffic caused by hello messages exchanged between vehicles and offers more bandwidth to the alarm message dissemination. To combat network fragmentation, IVG broadast message in periodic fashion. The broadcast rate depends on the speed of vehicle. Besides, the rebroadcast of Alarm message with in the geocast group is maintained according to distance based differ time. Vehicles further away from the source have short waiting time to rebroadcast, similar like in [32]. This decreases the broadcast storm problem.Another feature of IVG is that it also takes into account light-crowded networks. This is achieved by the rebroadcast of the alarm message by dynamic relays. These relays are self-designated with a completely distributed manner.

Joshi et al. in [57] designed a distributed geocast protocol to deliver a packet to a static geocast region or ZoR. The Authors defined zone of relevance(ZoR) in which vehicles receive the geocast message if they are inside. To enhance the reliability of packet delivery a forwarding zone (ZoF) is also defined as a geographic area in which nodes forward message if they are inside. The backoff mechanism used by vehicles is similar to the methods used above, distance based back-off. In addition, DRG uses periodic transmission of the geocast message to combat network fragmentation.

Authors in [61] designed a geocast protocol aimed for high QoS in data delivery. They called their protocol as RObust VEhicular Routing(ROVER). In ROVER control packets are forwarded to the ZoR and after creating the route data packets are unicasted. The source first flood ZRREQ(zone of relevance request) to all nodes in ZoR. Vehicles inside the ZoR which receive the probe messages replay with ZRREP(zone of relevance reply). Then data is routed through the trees created. The ZRREP messages has time limit to be valid to avois mis locating nodes as VANETs are dynamic. The good point of ROVER is it also has buffering potential late ZRREP messages. That means, the whole tree is formed in the process not proactively. Still, the delay on creating and individual route is very high and can only be applied for delay tolerant application.

A different horizon in [72] introduce time abiding geocast protocol. Message remains valid and avalialbe in the geocast region for certain time. The potential applications of such idea include virtual warning signals in VANETs. When a vehicle enters such an area, the virtual warning sign is displayed for the driver. Three approaches are presented to design the abiding geocast protocol. The first solution is use of server to store message and disseminate when vehicles are around. The second approach uses a selected node inside the geocast region to store the message and act like server. When selected node leaves the geocast region hand over is done to other nodes. The third option is based on neighborhood knowledge of nodes. Every node stores the geocast packages of its destination. If a new node arrives one of its neighbors send it the geocast packet.

4.4 Discussion

In this chapter we have seen one way of classifying the dissemination techniques in VANETs, based on their mechanism. The over all observation is that no single technique can stand as a generic solution. In fact many applications need combined effort of different techniques to over come the challenges of data dissemination in VANETs. A summarized comparison of dissemination mechanisms is given in Table 4.1 on the next page.

Mechanisms	Basic idea	methods	Advantages	Disadvantages
Flooding based	rebroadcast any new message received	counter based [79], distance based [98], geo-limited [42], time(hop) limited [33], neighbor list [89], data aggregation [75] [35]	Simple to implement, less delay	broadcast storm problem(on using plain flooding)
relay based	use selected node as rely only	distance based RTS/CTS [64], Data pouring and buffering [104]	reduced overhead	uncertain next hop selection, more delay
opportunistic forwarding	combat network fragmentation in case of no next hop	carry and forward [41], neighbor list (hello message) [32], catchup and forward [56]	increase the availability of next hop	difficult to set optimal broadcast interval

Table 4.1: Comparison of flooding based, relay based and opportunistic forwarding dissemination mechanisms

Chapter 5

Design of Geocasting Protocol for BlueWave

So far, we have discussed the requirements of BlueWave, the technologies and standards which support the application, and possible methods of information dissemination in vehicular networks. In this chapter, the combined knowledge from the last chapters is used to design a specific protocol for BlueWave application.

The first section will bring the argument of choosing geocasing for BlueWave in to discussion. Section 2 will focus on the actual design of the BlueWave protocol.

5.1 Why Geocasting for BlueWave?

In section 4.3 on page 30 we reasoned out why geo-routing is preferable for VANETs and we later described the variety of geo-routing protocols, specifically geo-unicast and geo-multicast. As indicated in the title of this thesis, geocasting is used for our BlueWave application. The reasons for using geocasting in this application can be summarized as:-

- For group communications, multicast is preferable to unicast as the number of packets routed by the source decreases. i.e. A multicast tree[1] from source to destinations is used instead of creating route to each destination.
- Many of the VANET applications don't need to know the identity of individual vehicle. This clearly reduces the packet overhead for routing. Our case BlueWave is one example, in which the warning message to get a clear road is valid to any vehicle which could potentially block the mobility of the emergency vehicle. Since location of a node decides whether it should receive a warning or not, geocasting is preferable.
- Clearly, in an ad hoc network each algorithm is expected to be distributed, i.e. nodes make decisions without full global knowledge. If they want to consider network information for their routing decision, they have to obtain the information first. The unicast and multicast protocols in [60][48][47] [91][73] all depend on prior knowledge of destination node which is done with beacon exchange. This will introduce extra delay to set up the route and consumes network resources. Hence, it is not efficient to base our protocol on a complete priori topology knowledge.
- Another argument is the size of the BlueWave packet in contrast to having global view. It is expected to be a small control packet, which means establishing a route to target nodes could be more bandwidth consuming than broadcasting the actual messages.

[1] multicast tree is an efficient path of data routing which creates copies only when the links to the multiple destinations split. http://en.wikipedia.org/wiki/Multicast

5.2 Design of the Geocasting protocol for BlueWave

In the above section, we reasoned out that geocasting is a better solution for BlueWave application. In this section the actual design of the BlueWave protocol is described on an abstract level. The fine details of the design will be presented in Sections 5.3 on the next page and 5.4 on page 46.

The ultimate goal of the protocol is to enable on time exchange of warning messages in a BlueWave process through a wireless medium. The design of such a protocol need to consider, mobility, scalability and fragmentation issues as described in Section 4.2 on page 25. In addition, the BlueWave requirements, as described in Section 2.2 on page 6, also need to be considered during design. Accordingly, the protocol should have the ability to differentiate target vehicles, limit the age warning messages, and deliver warning messages to targeted vehicles on time. Considering these requirements the general structure of designed geocasting protocol for BlueWave is given in the following paragraphs.

Top level Description of Designed BlueWave Protocol

The literature review in Section 4.3.1 on page 31 presented several geocasting solutions for MANETs and VANETs. It is good to recall that if the source is outside the ZoR (geocast region), some means is required to reach one or more members of destination group. Accordingly, geocast protocols are divided as *route based* and *data dissemination oriented*. In our BlueWave application the EV (source) is within the ZoR, as explained in Section 2.2 on page 6, which makes the need for creating a route to ZoR unnecessary.

The protocol runs on top of WAVE MAC and PHY layers and below the application layer as shown in Figures 5.1 and 5.2 on the next page. It has basic functionality, Basic BlueWave Protocol, which works in all vehicles and is described as follows:

When a vehicle receive a BlueWave message from the MAC layer the protocol extracts all relevant information (if any) and feeds to the application layer. From the application point of view this could be some warning at the driver's display board. The protocol then decides wether to rebroadcast the message or not.

The layered architecture in Figure 5.1 on the following page represent the basic functionality of the BlueWave protocol. The arrows indicate the communication direction. It can be seen that the basic protocol can receive and send data from and to the MAC, but can't receive data from application layer. This is because the application protocol in basic functionality has no control on BlueWave scenario, i.e. the protocol doesn't execute orders from upper layer. It only informs the driver.

It may happen that an EV in an *"Idle state"*[2] could receive a BlueWave message just like any other vehicle. In a different case, there could be a group of emergency vehicles moving towards the same target in which more than one warning sources will be available. These two cases require the EV to act like other vehicles. Therefore, the basic functionality of the BlueWave protocol applies to EV too.

In addition, The EV has extra role to generate BlueWave messages at certain rate when requested to start and cease on a request to stop. The extra functionality of the EV that is represented in Figure 5.2 on the next page is described as follows:

The request from application level depends on the construction of the actual system. For example,

[2]"idle state" in this thesis is defined as a state in which the host is not involved in any BlueWave activity.

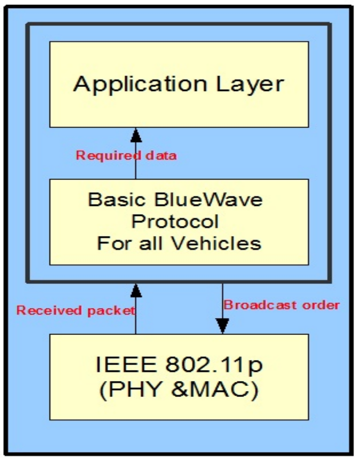

Figure 5.1: The layered structure of BlueWave basic functionality

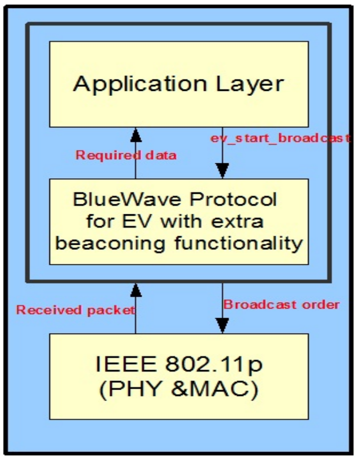

Figure 5.2: The layered structure of BlueWave protocol for the EV

it can be executed by pressing a button by the driver or triggered by some intelligent program which can detect the emergency situation. This message is sent to the protocol which actually creates the emergency message and send it to the MAC layer for broadcast. In similar way, a stop request will halt a BlueWave broadcasting cycle.

5.3 Basic BlueWave protocol

In the previous Section, we introduced the basic functionality of BlueWave protocol. The very general architecture of the protocol and connections between layers was described shortly. This section is dedicated to present the details of the Basic BlueWave protocol. As shown in in Figure 5.3 on the following page, the protocol has three states *"Idle state"*, in which host has no BlueWave activity; *"Message Processing state"*, which decides what to do with new received messages; and *"Data dissemination state"*, in which a rebroadcasting policy is applied according to the dissemination algorithm used. The occurrence of events such as *ev_New_packet_received, ev_relevant_to_host* leads to state change accompanied by necessary actions. The major actions are *Send to application, Order broadcast, Discard Message, and Generate event New packet received*; they are denoted by oval circles in Figure 5.3 on the next page. The general working principle of Basic BlueWave protocol from its state and action diagram can be explained as follows:

Initially vehicles are in an "Idle state" *by default, i.e. there is no BlueWave activity. If a new message is received from the MAC layer, then an event (ev_New_packet_received) is generated and vehicle go to state "Message Processing". If the "Message Processing state" results in to event of non-relevant message (*ev_not_relevant*), then the vehicle returns to "Idle state" after invoking the action "Discard Message" as shown in the left hand side of Figure 5.3 on the following page. Otherwise, two major events are checked in this state, one is to check if the message is useful to current host and the second is to check if the current host can be used only to forward the message. Both events, relevant to host and relevant to neighbors, changes vehicle state to "Data Dissemination state". However, the event relevant to host vehicle(*ev_relevant_to_host*) invokes an additional action which sends the data to application layer as shown at the righthand of Figure 5.3 on the next page. In the "Data Dissemination state" the message is prepared for rebroadcast according to the dissemination strategy used. A vehicle has two options to leave this state, either receive new message and go back to "Message Processing state" or execute rebroadcast order after a timer expire and go to "Idle state". A timer is set based on the*

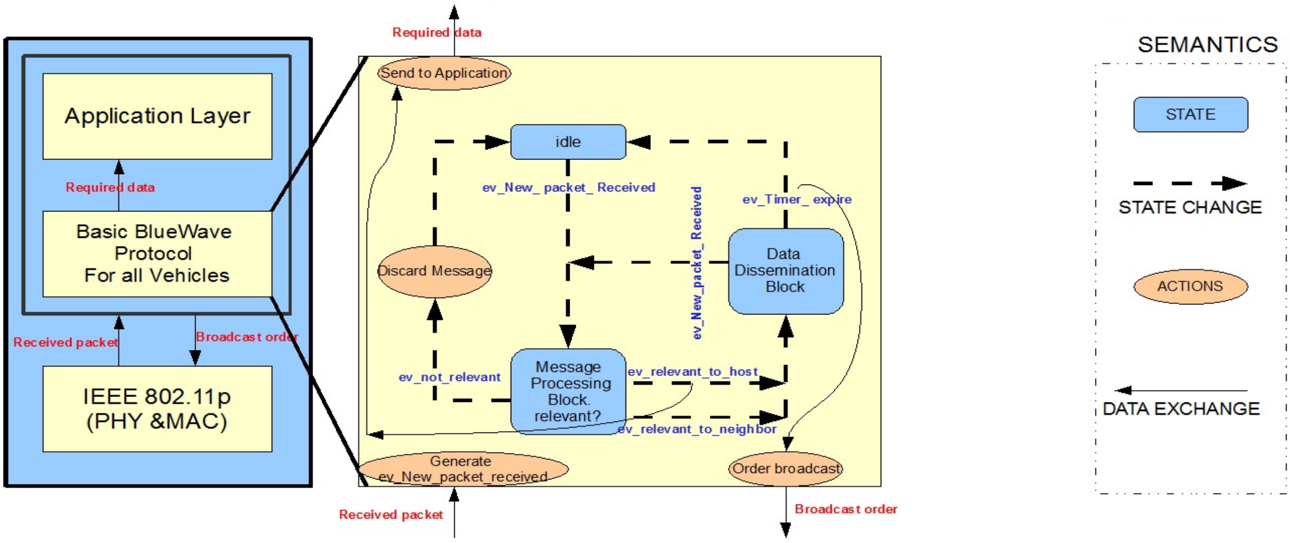

Figure 5.3: BlueWave protocol basic functionality, which works in all involved vehicles

dissemination algorithm which will be described in in Section 5.3.3 on page 44. For example, in plain flooding dissemination mechanism no timer will be set, which means nodes will immediately order the MAC to broadcast and go to "Idle state".

In the next subsections the detailed description of all the actions and states will be presented.

5.3.1 Message Processing

"Message Processing state" contains four functional blocks namely checking expire, checking duplicate, checking ZoR, and checking forwarding. Figure 5.4 shows the over all functional diagram of *"Processing Message state"*. Each block makes a decision of YES/No after checking the message against its algorithm. Upon receiving and processing a message, one of the following three events is likely to

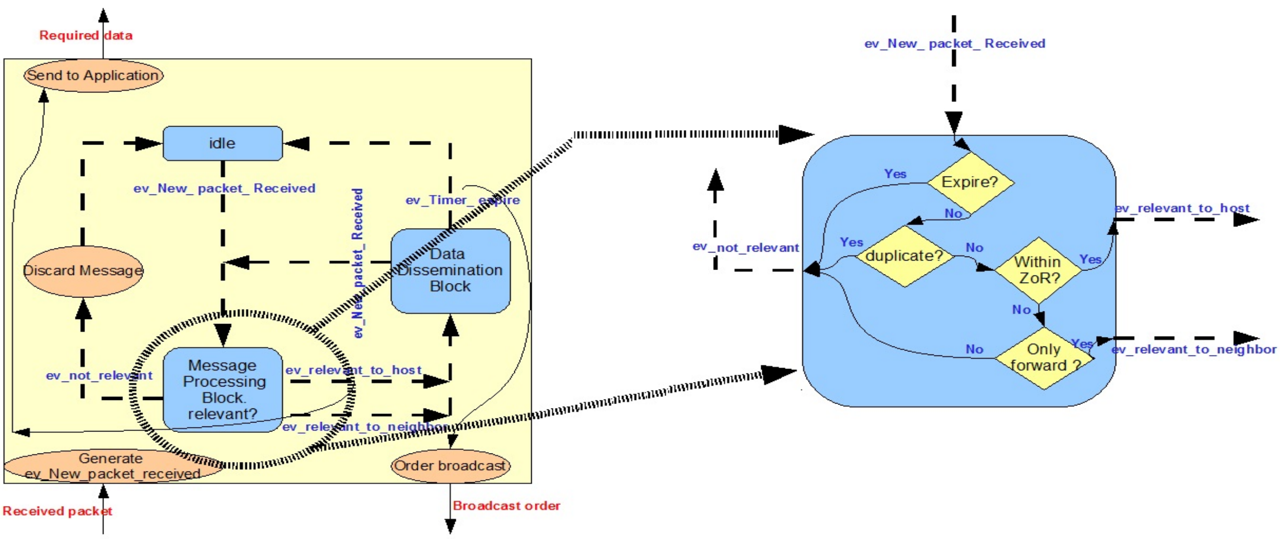

Figure 5.4: The detailed functional block diagram of message processing unit for Basic BlueWave Protocol

happen:

1. if a message is relevant to the host, then pass the message to the application layer, action *Send to application* which is indicated at the top left hand side of Figure 5.4 on the preceding page, and schedule a rebroadcast depending on the dissemination strategy used.

2. if a message is not useful to the current host but found to be important for neighbor vehicles[3], then schedule it for rebroadcast based on the dissemination strategy.

3. if a message is not useful to the current host and is not entitled for forwarding, then it will be discarded, action *Discard Message* as shown in the left hand side of Figure 5.4 on the previous page.

In the sequel, each functional block of the *"Processing Message state"* will be described.

5.3.1.1 Checking Message expire

The *"Message Processing state"* starts by checking the age of a message (time to live). The purpose of this function is to limit the validity of the message in time. This is one of the requirements of the BlueWave application as mentioned in Section 2.2.1 on page 6. In chapter 2, Section 2.2.4.3 on page 13, the time limit in which a packet is considered as valid in the BlueWave process is set as $Time\_to\_live = t_{overtake\_max}[worst\ case\ vehicle]$. If a message has already stayed for a time longer than $Time\_to\_live$, then the *"Message Processing state"* will halt its process and generate event *ev_not_relevant* as shown in Figure 5.4 on the preceding page.

5.3.1.2 Checking Duplicate Message

If a message is not expired, if it successfully passes the "Checking Message expire" function described above, then the host checks if it has received the same message or a more recently generated message than the received one. For such purposes each BlueWave message will have a unique sequence number which increments by one every time new message generated. Figure 5.5 on the next page represents the functional block of the duplicate checking algorithm. The operation of the function *"Checking Duplicate Message"* can be explained as follows:

*A receiver will register the sequence number of the last message it receives. If it receives completely new message, sequence number greater than last received, then it will exit the "Checking Duplicate Message" with answer No (which means received packet is not duplicate of previous ones). Otherwise, if the received message is a duplicate, it check if it is older than the one on schedule for rebroadcast (if any); this is shown in the second diamond of Figure 5.5 on the following page. If so, it discard the received message. In a different case, if the received message has the same sequence number with the one on schedule (if any), it discards both the one on schedule (if any) and received one. This is done because the protocol assumes other vehicles have already rebroadcasted the same message and there is no need to add extra. This process is shown in Figure 5.5 on the next page with the oval action for canceling scheduled message, followed by an arrow which lead to event of non-relevant message (*ev_not_relevant*), which further leads to action "Discarding Message" which is indicated in another Figure 5.3 on the preceding page.*

[3] The decision to forward a data to neighbors is significantly important when the forwarding zone (FZ) is larger than ZOR.

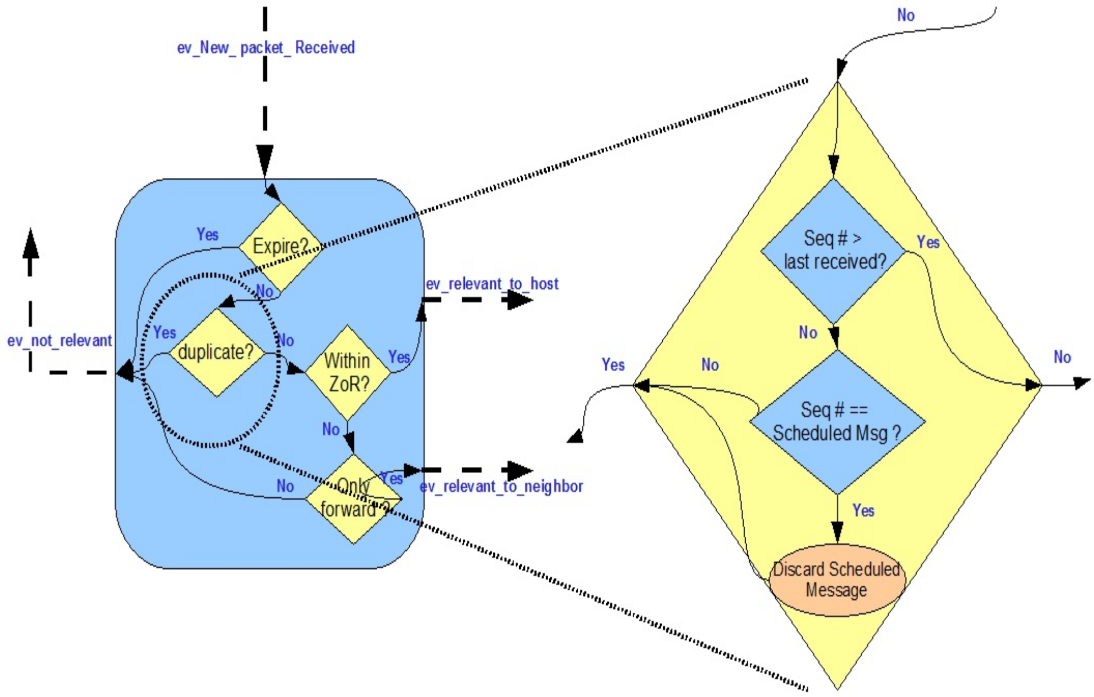

Figure 5.5: Duplicate message checking process

5.3.1.3 Checking the Zone of Relevance (ZoR)

The third part of the *"Message Processing state"* is checking if a receiver host is within the ZoR. The information about ZoR is carried with the BlueWave message. If a host vehicle receives non-expire and non-duplicate message within the ZoR, then the message is relevant to host vehicle. Consequently, an event relevant to host (ev_relevant_to_host) is generated as shown in Figure 5.4 on page 40. In this specific case the data is send to the application layer and state of the vehicle is changed from *"Message Processing sate"* to *"Data Dissemination state"*. On the other hand, if the host vehicle is not within the ZoR, the message is not relevant for host vehicle. Nevertheless, there is still a possibility to forward the data to other vehicles. Imagine a scenario in which the source vehicle (the EV in our case) targets an area which don't include its current location. In that case vehicles in between the EV and target area (ZoR) will receive the messages but have to forward it only. Therefore, an event of relevant message to neighbors (*ev_relevant_to_neighbors*) is generated as shown in Figure 5.4 on page 40. If the message is not relevant for host or its neighbors, then event message not relevant (*ev_not_relevant*) is generated, which leads to action *"Discard Message"*.

5.3.2 ZoR for BlueWave

In the above section, we have mentioned the use of ZoR to check the relevance of a message to a host. Earlier in Chapter 2 we have seen the way the size of ZoR is determined from relative speed and over take time. Yet it is not clear how to represent the ZoR for different scenarios. This section introduces the way ZoR is represented in BlueWave protocol.

The ZoR is defined based on the requirements set in Section 2.2 on page 6 as the area between current location of the EV and ($d_{relative\_max}[worst\ case\ vehicle] + size\ of\ ZoR[worst\ case\ vehicle]$) forward. Since vehicles are expected to have GPS devices, the ZoR is represented with set of geographic coordinates. For straight road scenarios the ZoR can easily be a rectangular in shape marked by two coordinates at opposite corners. However, in reality all roads are not straight especially in urban scenarios where the EV trajectory could have several turns. Vehicles equipped with map navigation tools can still draw the curved ZoR with rectangular segments. Nevertheless, this will result in higher complexity in computation and increased size of the information. For example the two turn curved ZoR in Figure 5.6 needs at least four coordinates to represent it uniquely.

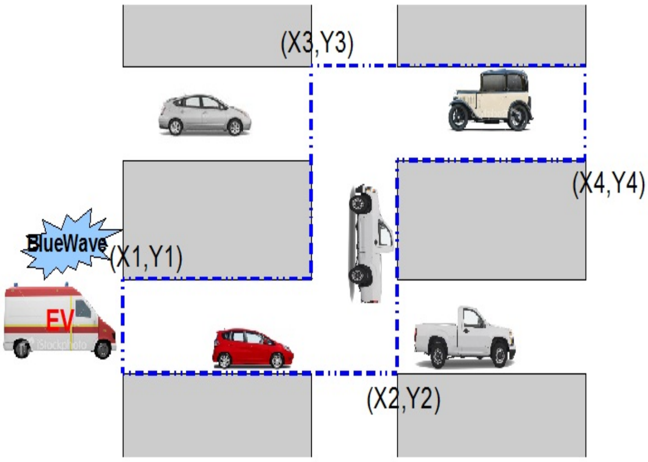

Figure 5.6: Representation of curved ZoR with segments of rectangles

A better approach to deal with curved ZoR is the use of elliptical coordinate system. The curved ZoR could be included within an ellipse as shown in Figure 5.7. In that case vehicles only need to now the two points (the Foci) and size of the major radius to identify a unique ellipse. The diagram in Figure 5.7 shows the use of ellipse in comparison to rectangular based trajectory for ZoR representation. The ellipse representation of ZoR also extends the warning to vehicles on the side streets which could possibly intersect the ZoR shortly.

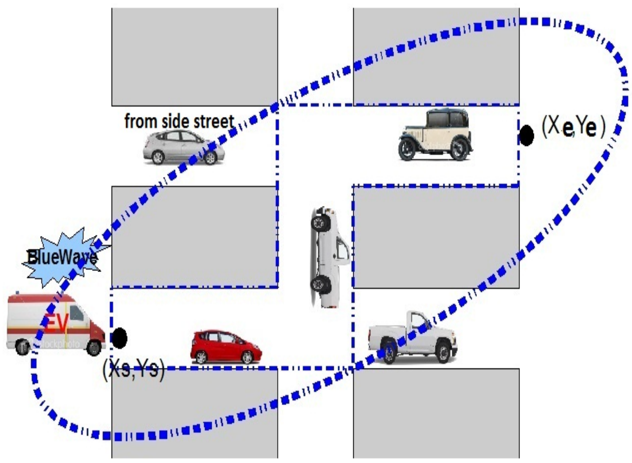

Figure 5.7: Elliptical ZoR for BlueWave protocol

To determine the exact locations of the ellipse the EV first determines its location. This is the first focus of the ellipse, represented as (Xs,Ys) in Figure 5.7. To set the second focus let us refer back to

Section 2.2.4.1 on page 10, in which the maximum size of ZoR is give as:

$$practical\ size\ of\ ZoR = d_{relative\_max} + size\ of\ ZoR[worst\ case\ vehicle]$$

where, $d_{relative\_max} = V_{relative\_max} \times t_{overtak\_max}$ and $size\ of\ ZoR[worst\ case\ vehicle] = \frac{N \times V_{relative\_max}}{B_{Rate}}$, in which B_{Rate} is the broadcast rate of the EV and N is the number of successive broadcasts by the EV in order the targeted vehicle to receive at least one warning message on time. The relationship between N and B_{Rate} is presented in detail in Section 5.4.1 on page 47.Since the EV is supposed to know its trajectory on beforehand, it can determine the geographic location at a distance "$practical\ size\ of\ ZoR$" from its location as shown in Figure 5.8. This point, (Xe,Ye), is the second focus of the ellipse. Once

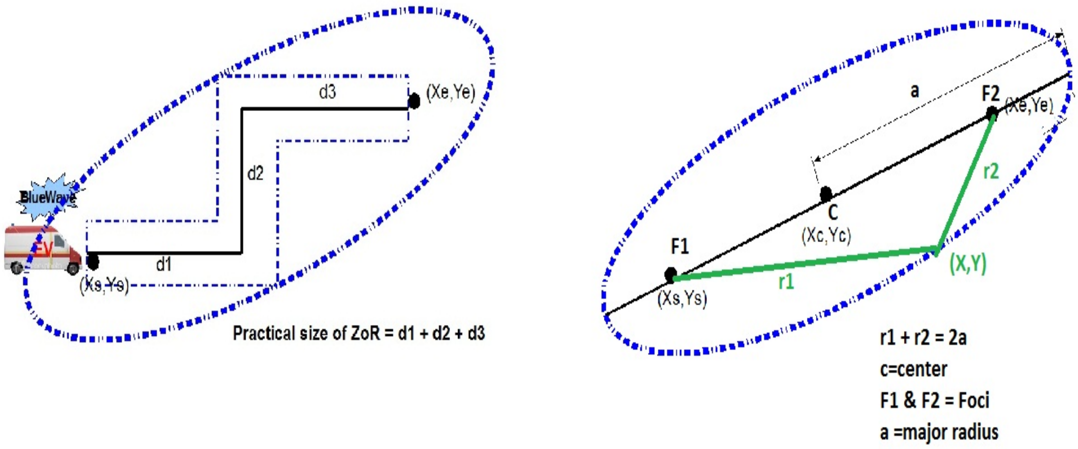

Figure 5.8: Determining the Foci of elliptical ZoR for BlueWave

the Foci are determined the center of the ellipse is simply the middle way of the straight line connecting them as shown in the right side of Figure 5.8. Finally, setting the length of the major radius, a, will complete the definition of a unique ellipse. For an arbitrary point (X, Y) an ellipse satisfies the following equation:

$$r_1 + r_2 = 2a \tag{5.1}$$

where r_1 *and* r_2 are the lengths of the arbitrary point from foci 1 *and* 2, a is the length of major radius.

In a BlueWave scenarios, the EV includes the foci $((Xs, Ys)\ and\ (Xe, Ye))$ and major radius (a) in the warning messages. Vehicles take their position as an arbitrary point, (X, Y), and compute $r1$ & $r2$, their distance from the foci, to check if $r_1 + r_2 < 2a$. If so, it means they are within the ellipse (ZoR). As discussed in [93], the GPS coordinates are normally expressed in degrees and minutes ($DDD.mm$) which uniquely identify the location from the earth surface, for example the GPS location of Senafe[4] is represented as $14\ 41'N,\ 39\ 24'E$. For higher accuracy a finer paramter of seconds is added and the GPS representaion look like $DDD.mm.ssss$. The above mentioned example will have a format of $14\ 41'\ 7"N,\ \ 39\ 24'\ 49"E$.

5.3.3 Data Dissemination

The third state of Basic BlueWave Protocol is *"Data Dissemination state"*. This state decides how long a message has to wait before it is sent to the MAC layer as a broadcast order. Any relevant

[4]A small town in Eritrea, which is place of origin of write of this thesis

message[5] will be prepared for a rebroadcast, but how to invoke the rebroadcasting order depends on the dissemination strategy used. In plain flooding dissemination mechanism for example, a rebroadcast is done immediately without any delay. A detailed description of dissemination strategies which are used for BlueWave is give in Section 5.5 on page 50. Figure 5.9 shows the block diagram of the actions and states of dissemination strategy for BlueWave. The action *"Set New Timer"* includes cancelation (reset) of current schedule (if any) and set new timers according to the dissemination strategy. The vehicle then enter the *"Waiting state"* until this timer expires. The expiration of the timer will lead to an immediate rebroadcast order of the MAC layer (action Order MAC rebroadcast in Figure 5.9) and shift of the vehicle to *"Idle state"*. In the mean time, if a new message is received it goes to *"Message Processing state"* leaving timers running. The main reason for not stopping the timers while going to *"Message Processing state"* is the fact that all received messages are not necessarily useful. If a relevant message is received, the *"Message Processing state"* has capability to cancel the scheduled timers and set new one.

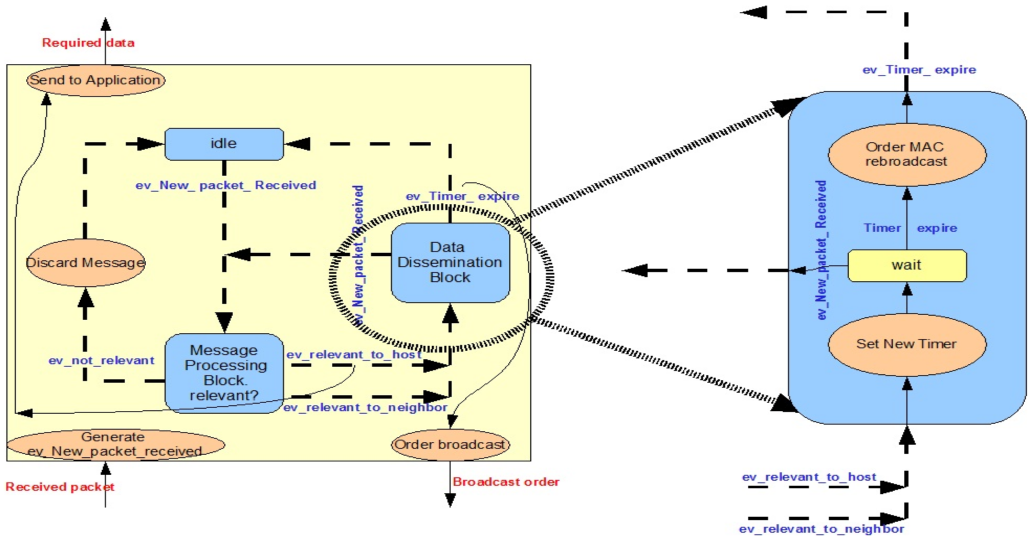

Figure 5.9: The block diagram of "Data Dissemination state"

If the dissemination strategy is plain flooding the waiting time is zero i.e action *"Set New Timer"* sets a waiting time of zero. In other words, after receiving a relevant message the host sends a rebroadcast order to the MAC layer immediately.

For dissemination mechanisms other than plain flooding, vehicles set a timer based on their dissemination strategy. In slotted 1-persistent for example, the waiting time is inversely proportional to the distance, D_{ij}, of the host vehicle (node j) from the sender (node i) given by:

$$T_{S_{ij}} = S_{ij} \times \tau \tag{5.2}$$

In which τ is the estimated one hop delay including medium access delay and propagation delay, and S_{ij} is assigned slot number which is determined by the following equation for a given number of slots N_s:

$$S_{ij} = N_s \times \left\lceil 1 - \left(\frac{min(D_{ij}, R)}{R} \right) \right\rceil \tag{5.3}$$

[5]relevant message is defined in Section 5.3.1 on page 40.

If the *"Data Dissemination state"* manage to rebroadcast a message, then it should change the last hop field to current location of rebroadcasting vehicle. The last hop field is part of BlueWave message which is described in Section 5.4.2 on page 49. As already mentioned in section 5.3.2 on page 42, the moving ZoR will mean that at time of rebroadcast there is a shift in ZoR from those coordinates defined in the original message. Nevertheless, the end to end communication delay of multihop communication of our type is in order of milliseconds [98]. it means the change in ZoR, which depends on movement of vehicles, is not considerable comparing to the size of ZoR. For example, if the communication delay is taken as $0.09s$, determined as worst delay of slotted 1-persistent in [98] in a highway of $10km$ long, the relative movement of ZoR will be:

$$reltaive\ movement\ of\ ZoR\ =\ 0.09s \times relative\ speed\ of\ the\ EV\ to\ target\ vehilce$$

assuming the worst case scenario of maximum speed [6] of the EV $37.7m/s$ and maximum speed of other vehicles $-36.1m/s\ in\ opposite\ direction\ to\ the\ EV$, the relative speed will be $73.8m/s$. Therefore,

$$relative\ movement\ of\ ZoR\ =\ 0.09s \times 73.8m/s\ =\ 6.642m$$

This value is small enough to be neglected during the rebroadcast, comparing with the size of ZoR which can be hundreds of meters.

5.3.4 Discard Message

The action *"Discard Message"* is one of the constituents of the Basic BlueWave protocol as shown in Figure 5.3 on page 40. After invoking this action, vehicles shift to *"Idle state"* .Three possible cases of discarding a message in the Basic BlueWave Protocol are:

1. If the same message is already received, then the received message will be discarded
2. If the received message is the same to the one on schedule, then both received and one on schedule will be discarded
3. If received message is older than last received message, then the received message is deleted.

5.4 BlueWave Protocol with extra functionality for EV

It is already mentioned in Section 5.2 on page 38 that the BlueWave protocol has basic functionality that is applicable for all involved vehicles and extra beaconing functionally for the EV. This section will present the design of the beaconing functionality of the BlueWave protocol for the EV.

The beaconing functionality is an additional protocol to the basic protocol described in Section 5.3 on page 39. The EV uses the beaconing protocol if it is in an emergency activity. Figure 5.10 on the following page shows the functional block diagram of the beaconing process only. In this diagram the Basic BlueWave protocol is not shown though it is part of the complete BlueWave protocol for the EV. The overall process of the beaconing functionality can be explained as follows:

Once the protocol gets the start order from the application layer, it set a broadcast rate and then start a cycle of broadcasting until stop request is received. The cycle includes the creation of new BlueWave message, setting a timer which is equal to $\frac{1}{broadcast\ rate}$*, and a "Waiting state" until the timer expires. The broadcasting is a simple forward of built BlueWave message to the MAC layer. In the MAC layer*

[6] These maximum values are set in Section 2.2 on page 6

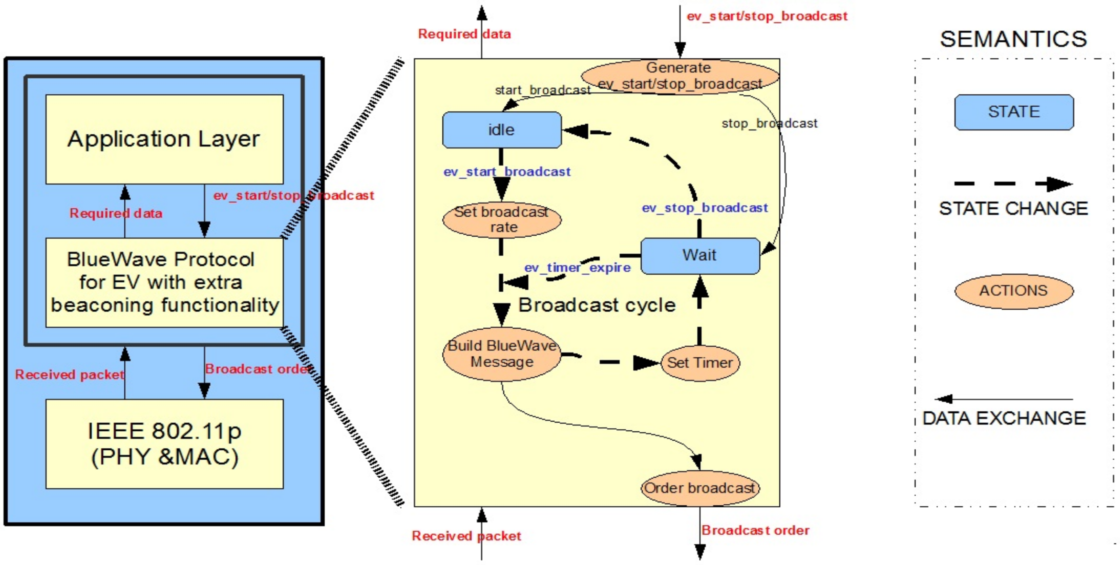

Figure 5.10: BlueWave beaconing protocol for the EV

the BlueWave protocol has no more control on packets and 802.11 medium access protocol governs them.

The logic to decide the broadcast rate and contents of the BlueWave message are described in the following subsections.

5.4.1 EV Broadcast Rate

As mentioned in the above introductory part, one of the main actions that happen during BlueWave process is the setting of a broadcast rate for the warning messages. Setting a broadcast rate needs a careful examination of its impact on the network. Frequent rates, say broadcast interval in order of milliseconds, may not be necessary as the network hardly show major topological change. For example, an EV moving at its maximum speed covers only $3.7m$ in $100ms$ or equivalently broadcast rate of 10 *messages per second*. On the other hand, having very low rates (long broadcast interval) is also not suitable as the network could potentially make change in topology. If we take broadcast rate of 1 *messages per* 5 *second* for example, the distance traveled in this time by the EV at it's maximum speed will be $188.5m$. This is a significant change in distance, the network topology and density of nodes can change within this distance especially in urban scenarios where roads are intersected at short distances. The selection of optimum broadcast rate may depend on many factors such as speed of the EV, density of the network and shape of the EVs trajectory. Therefore, setting a specific broadcast rate is not easy. A detailed study in the application layer of the BlueWave and traffic engineering of roads will be required to set optimum value of broadcast rate. However, the boundaries of the selection can be set based on standards. The IEEE 802.11p beaconing rate sets a maximum value of $10Hz$ [23]. This value can be used as the maximum broadcast, B_{Rate_max}, for the BlueWave process. To have a better understanding on the impact of selecting broadcast rate, the sensitivity of broadcast rate will be experimented in chapter 7. In the mean time we will continue to discuss the relationship of broadcast rate with other parameters of the BlueWave protocol.

The selection of a broadcast rate is related to the size of ZoR. In Section 2.2.4.1 on page 10 they are related as follows:

$$size\ of\ ZoR = \frac{N \times V_{relative}}{B_{Rate}} \tag{5.4}$$

where $V_{relative}$ is the relative speed of the EV to a targeted vehicle, B_{Rate} is the broadcast rate in *messages per second*, and N is the number of successive broadcasts by the EV so that the targeted vehicle receive at least one warning on time[7]. This implies that under a 100% reliable condition, the targeted vehicle will receive N warning messages on time. Hence, the size of ZoR is defined as the distance covered by the targeted vehicle in time interval of N successive broadcasts by the EV. The main challenge is in setting the proper value of N. Practically N depends on several factors such as channel condition (error probability), network topology (such as density, number of hops to go), available bandwidth (the effect of other applications). To have a feeling on the meaning of N let us investigate the situation with theoretical descriptions.

If the probability of successfully receiving a message by a targeted vehicle is ρ and we assume the events are independent[8], then the probability of getting at least one message successfully after N attempts is given by:

$$Probability_{atleat\ one\ success} = 1 - (1 - \rho)^N \tag{5.5}$$

The graph in Figure 5.11 gives the probability of getting at least one message for different values of N. Literally, the selection of N depends on the success rate we want to achieve and the probability of

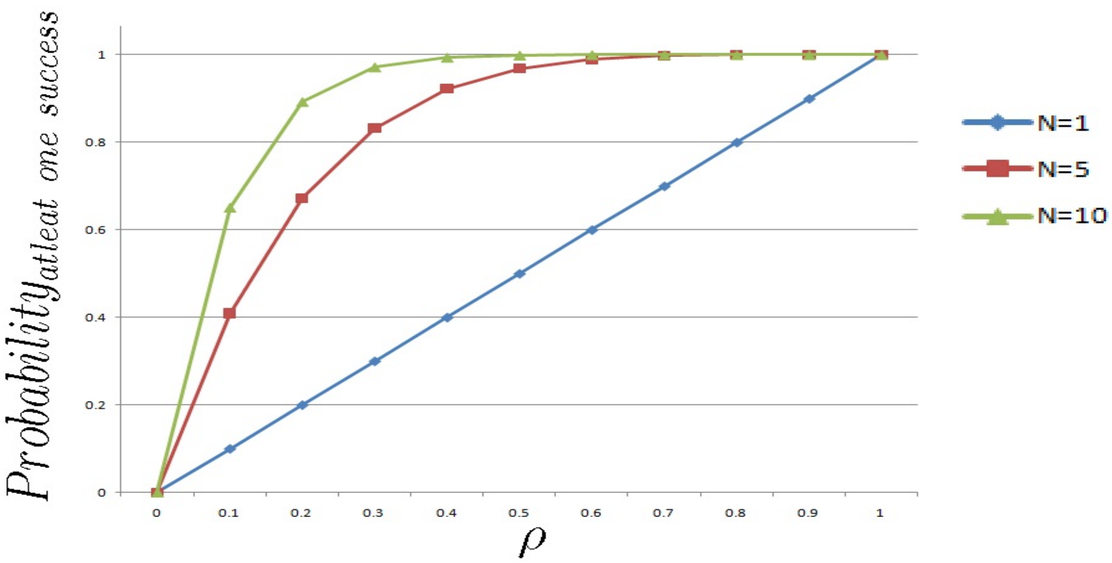

Figure 5.11: The probability of getting at least one message for different values of N

each attempt ρ. The most difficult part of this approach is determining ρ. It is different for different scenarios and network conditions. In addition, the events of success or fail are not totally independent, the network could have a correlation factor.Therefore, it needs a comprehensive research to settle in to a reasonable value for N. In this thesis due to time constraints a different way of sensing N is done with the help of simulations. We used the formula given by Equation 5.4 on the previous page for different values of N and measured the reachability[9] of the protocol. This preliminary experiments are run in a highway scenario which is selected for performance evaluation of the protocol in chapter 7. Figure 5.12 on the following page shows the impact of N for different broadcast rates in one of the experiments, car density of 60cars/km/lane, with 30 runs of each and 95% confidence interval. A complete analysis of

[7]The notion "on time" is defined in Section 2.2.4.2 on page 12

[8]Actually there could be a correlation between the events though difficult to determine. For example if one attempt fails due to network fragmentation, it is most likely that next attempts will also fail as the network will still have the fragmentation (especially at high broadcast rates).

[9]Reachability is defined as ratio of number of targeted vehicles which receive at least one message on time to total number vehicles targeted by the EV

these experiments is presented in Chapter 7. The important point to note is the reachability increases

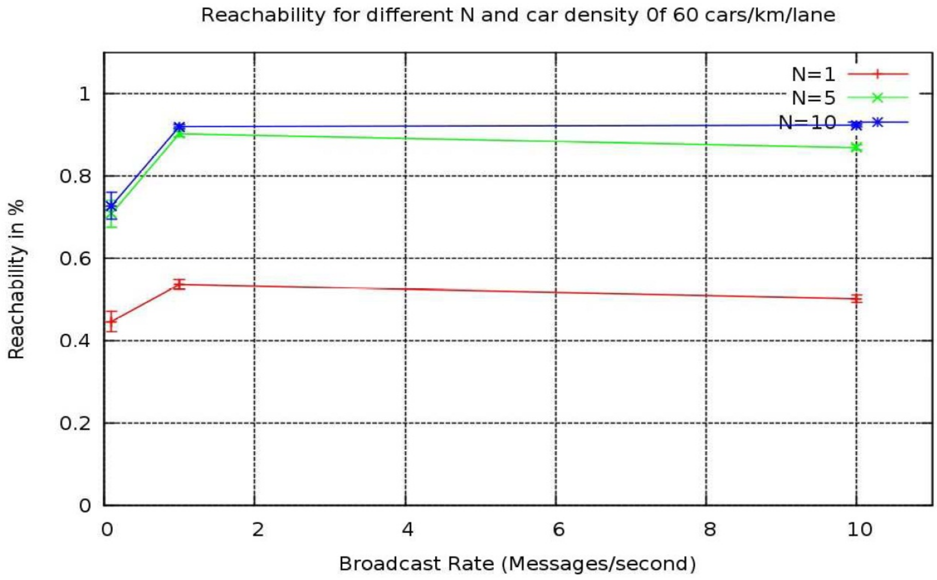

Figure 5.12: The reachability of the BlueWave protocol for different values of N

with N for any broadcast rate selected and at some point it get saturated and increasing N has no change. This is partially revealed in Figure 5.12 in which for $N = 5$ $andN = 10$ the reachability is almost the same. Based on this preliminary experiments we chose $N = 5$ for performance evaluation.

5.4.2 The BlueWave Message

One part of the protocol job is to create a BlueWave message at certain rate. The contents of the message are based on general requirement of VANET messages and specific requirements of the BlueWave application. The COMeSafety has pointed out the common relevant information need to be exchanged through VANET[66] as follows:-

The common part the header should include:
Identity of the station: for reference purposes. This identity may be static for e.g. RSU, or dynamic pseudonyms for vehicles to protect privacy. In our case it will be the identity of the EV, which is the source of the information.
Time Stamp: which Identifies the message instant in which Position was measured in the transmitting station. It is a fundamental information for the Vehicle dynamics extrapolation.
Longitude: the estimated Longitude of the geometrical center of the station
Latitude: the estimated Latitude of the Geometrical center of the station
Elevation: the estimated Geographical altitude of the station
Speed: the estimated module of the speed of the station along the current direction. Clearly this data is set to zero for fixed stations.
Heading: the estimated value of the angle of the vehicle trajectory with respect to North. Speed and Heading together provide the speed vector, again set to zero for fixed stations
Dynamic data accuracy: a simple indicator of the Quality of the Positioning, Speed, Heading. Currently under discussion is the benefit if a covariance matrix of Position, speed, yaw-rate and acceleration of the vehicle is provided.

For cooperative awereness applications (such as BlueWave), the following data fileds are identified

as mandatory in a VANET message[66].
Vehicle Type: a parameter considering the type of vehicle (truck, bus, motorcycle)
Length: the length of the vehicle
Width: the width of the vehicle
Longitudinal Acceleration: the acceleration in the heading direction
YawRate: The vehicles yaw rate
Acceleration control: a Boolean status (onoff) of the commands which controls the acceleration of the vehicle: Brake Pedal, Throttle Pedal, Cruise Control, Adaptive Cruise Control, Limiter
ExteriorLights: the status of the exterior lights

In addition, some extra information required by the BlueWave protocol are needed. These includes:-
Expected lane:
in a multi-lane highway it is important to specify which lane the EV targeting and other vehicles make their decision accordingly. i.e. change lane or not
Zone of Relevance (ZoR):
This is a specific geographic area determined by the EV in which the warning is valid.
Location of Last hop:
This field is used to determine the distance between receiver and sender in one hop communication. This distance is important to calculate the slot time in the dissemination process.

5.5 Dissemination strategies for BlueWave

In Section 5.3 on page 39, we have seen that dissemination is main part of basic BlueWave protocol. So far we have not decided what kind of dissemination mechanisms are to be used for BlueWave protocol. This section discuses the dissemination strategies used for the BlueWave protocol.

5.5.1 Plain flooding

Plain flooding is described in Section 4.2.1 on page 26 as a simplest approach of data dissemination, in which nodes rebroadcast any message they receive for the first time. The maximum distance a packet could reach in a BlueWave process is approximately equal to a distance of $practical\ size\ of\ ZoR$[10] from current location of the EV. In its optimum operation at least $\frac{practical\ size\ of\ ZoR}{transmission\_range}$ hops are required from end to end. The end to end delay may not be significant comparing to the time required to overtake vehicles; it is estimated between $6.5s\ and\ 13.5s$ in Section 2.2.4 on page 8. Wisitpongphan et al. in [98] measured the delay incurred to be not more that $21ms$ in a $10km$ long 4 lane highway with 100 $cars/km/lane$. Therefore, the first design of dissemination strategy will be plain flooding.

5.5.2 Distance based optimization

In previous Section plain flooding is chosen as dissemination strategy based on the fact that the delay they have is not influential for BlueWave application and are simple to implement. Nevertheless, the most threatening part of plain flooding is their packet loss ratio in large multi hop networks. Wisitpongphan et al. measured a packet loss of 60% in the highway scenario mentioned in the above section. This value remains significant, 16% , in case of light traffic condition (10 $cars/km/lane$). Therefore, a logical option to look for optimization methods of the plain flooding. In our BlueWave dissemination optimization mechanism, a distance based algorithm proposed by Wisitpongphan et al. in [98] is used. The authors proposed three solutions that are probabilistic or time based broadcast suppression techniques

[10]practical size of ZoR is given in Section 2.2.4.1 on page 10

namely: weighted p-persistent, slotted 1-persistent and slotted p-persistent. A detailed description of these mechanisms is presented in Section 4.2.1 on page 26. Distance based back-off mechanism gives nodes a distributed waiting time in which far away nodes wait less time. This type of mechanism is widely used in VANET geocast protocols. One of the reasons for its wide usage is the use network layer information (distance) only. Besides, nodes make decision based on their local information only and is not complex as it doesn't include cross layer information exchange.

Out of the three dissemination mechanisms proposed in [98] *Slotted 1-persistent* is selected as basic means for broadcasting. It is chosen because it make sure there is a broadcast in each nonempty time slot, unlike the *weighted p-persistent* which introduces a probability p. Experiments in [98] also indicate that *Slotted 1-persistent* has better performance than the other two. Figure 5.13 illustrates the idea of slotted waiting time. The waiting time is give by

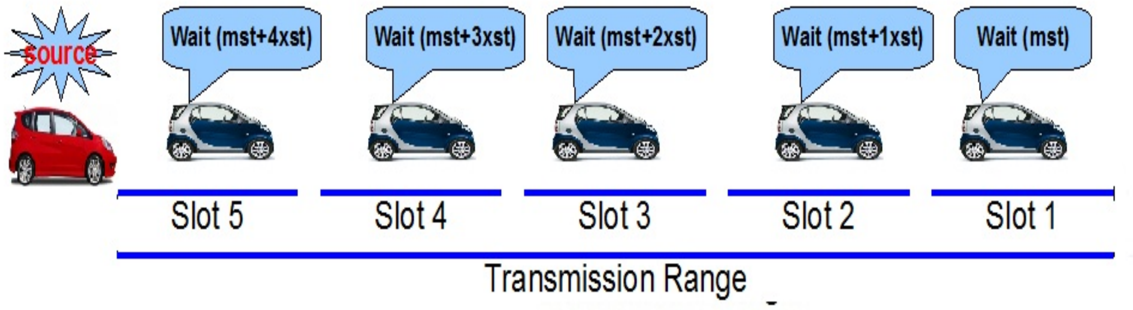

Figure 5.13: Slotted 1 persistent with 5 physical slots(st) and extra micro-slot(mst) for breaking synchronization

$$Time_{to\ slot} = S_{ij} \times st \tag{5.6}$$

In which st is one slot time derived from the estimated one hop delay including medium access delay and propagation delay, and S_{ij} is assigned slot number of destination node j, which is D_{ij} apart from source node i with transmission range of R. S_{ij} is determined by the following equation for a given number of slots N_s:

$$S_{ij} = N_s \times \left\lceil 1 - \left(\frac{min(D_{ij}, R)}{R} \right) \right\rceil \tag{5.7}$$

The slot synchronization problem as described in Section 4.2.1 on page 26 is solved according the micro-slot solution presented by Van Eenennaam in [93]. Therefore,

$$Time_{to\ microslot} = mst = N_{ms} \times \left\lceil 1 - \frac{min((D_{ij} mod\ Len_{Slot}),\ Len_{Slot})}{Len_{Slot}} \right\rceil \times DIFS \tag{5.8}$$

where, $DIFS$ is a MAC parameter, Len_{Slot} is physical length of one slot, N_{ms} is number of micro slots with in one slot, which is given by $N_{ms} = \frac{Len_{Slot}}{averagevehiclelength}$

5.5.3 Use of beacons for optimization

In reality the BlueWave will not be the only application to run in the network and the combined nature of many VANET applications require a beacon exchange anyway. Therefore, it is reasonable to assume that nodes will have partial view of the network. In that case, the dissemination strategy can be optimized by identifying the next hop from neighbor list and explicitly send a forwarding responsibility to it.

Chapter 6

Protocol Implementation & Defined Scenarios

In the last chapter, the BlueWave protocol was designed considering the application and communication requirements. Yet it is not known how this protocol will behave in real applications. One way of testing the performance of a protocol is by analyzing its metrics with the help of simulations or mathematical analysis or even practical experiments for specific scenarios. In cases such as BlueWave service, the total number of hosts can be extremely large and with non-deterministic distributions. Such networks has no proper mathematical model and making new is hard. This makes the concept of mathematical analysis for BlueWave off the choice. The other option, practical test, is not cost effective to be accomplished in small projects such as this masters thesis. The best choice to make such analysis is by the use of simulations. In other words, it is equivalent as to ask the computer machines to do the tedious mathematical calculations in short time.

This chapter present the choice of a suitable simulation platform, its configurations to run the designed protocol, and define relevant scenarios. The first section will include the implementation of the protocol on OMNeT++ simulator. Section 2 will describe the defined scenarios for performance analysis. Finally, Section 3 will give the configuration of the simulator to run the defined BlueWave scenarios.

6.1 Working with OMNeT++

OMNeT++ is a component-based, modular discrete event network simulator. It is used for network simulations of computer networks, though it is also used in IT systems and queueing networks or hardware architectures. It is an open source with component architecture for models. These components(modules) are programmed in C++, then assembled in to larger components and models using a high level language called NEtwork Description(NED).

OMNeT++ is chosen as a simulation platform in this thesis for its flexibility on modular programming and well organized documentation. A detailed description and comparison of OMNeT++ with other simulators such as ns-2, is given in [94]. OMNeT++ contains several frameworks, such as MIXIM, INET, MF, developed by different OMNeT++ community groups [1]. The mobility framework(MF) is developed by several people at the Telecommunication Networks Group at the Technical University of Berlin(TUBerlin), and is intended to support wireless and mobile simulations on top of OMNeT++. The core framework implements the support for node mobility, dynamic connection management and a wireless channel model. Additionally the core framework provides basic modules that can be derived in order to implement own modules. With this concept a programmer can easily develop own protocol

[1] http://omnetpp.org/

implementations for the Mobility Framework (MF) without having to deal with the necessary interface and interoperability stuff. The current version 4(also used in our experiments) of the MF is integrated to Eclipse IDE, which make it more easier to configure and test. An excellent description of OMNeT++ and mobility framework usage for vehicular networks is given in [93].

A network is a higher level module of the MF. As shown in Figure 6.1, a network contains a channelcontrol and host modules. The channel control is responsible for monitoring all the activities of hosts in the network. It decides which nodes should have a communication link. It uses free space propagation model which is too simplistic. In all, the channel control is the central data base for the activity of a network. A host on the other hand, contains all the OSI layers required for data communication. In addition, it contains mobility block, which governs the movement of a host and blackboard unit which is used for information exchange between different hosts.The components of host and their communication links is given in Figure 6.2 on the following page.

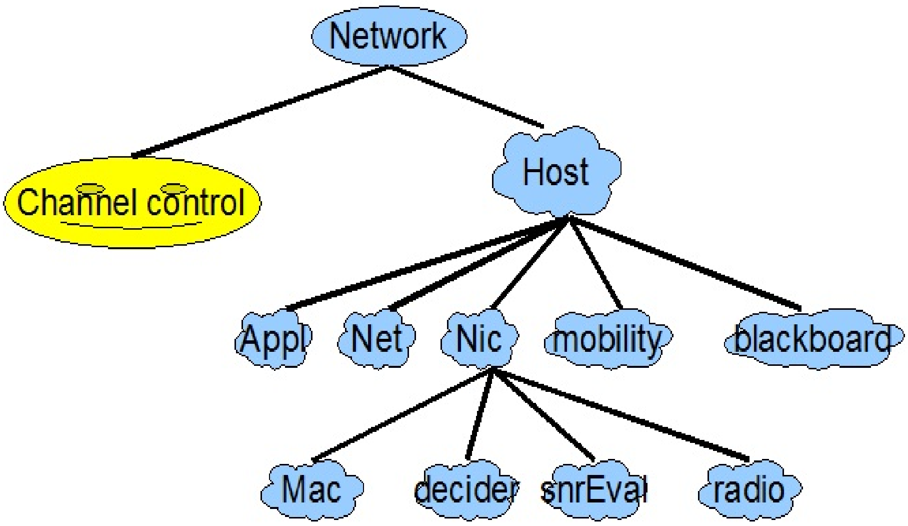

Figure 6.1: The network modular structure of OMNeT++ Mobility Framework

6.1.1 Implementing the BlueWave

In the above introductory part, we have seen the general framework of OMNeT++ and more specifically the constituents of the Mobility Framework network module. In this Subsection, the implementation of the BlueWave protocol in MF of the OMNeT++ is described.

The BlueWave contains two kind of hosts, the EVHost that generate original BlueWave messages at certain rate, and other vehicle's hosts which act as receiver and, if applicable, as forwarding node.

EVHost:
The EVHost adapts its basic architecture from the mobility framework host as represented in Figure 6.2 on the next page. No change is made to the Nic Module in case of BlueWave implementation. Application layer, Network layer, and mobility module are adapted to the needs of the The BlueWave protocol. Figure 6.3 on the following page shows the pseudo code for the main functions of the EV application and Netwlayer layers. The application layer generate a broadcast order at a rate of $\frac{1}{broadcastInterval}$ *Mesaages per second*. The network layer creates a new message every time it receive

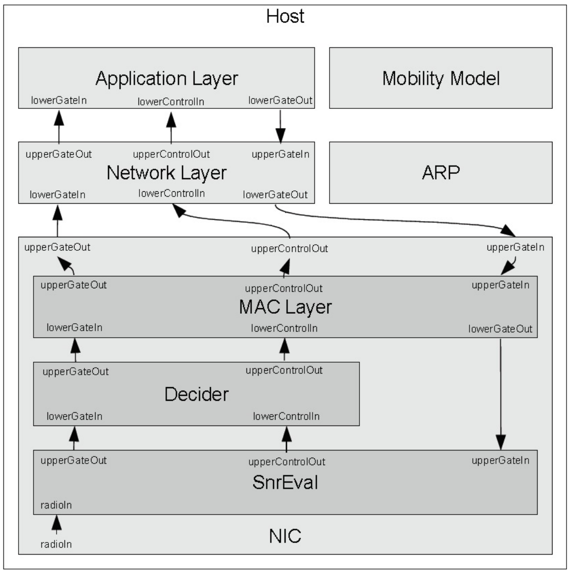

Figure 6.2: The components contained in Host of MF , picture taken from [93]

an order from the application layer.

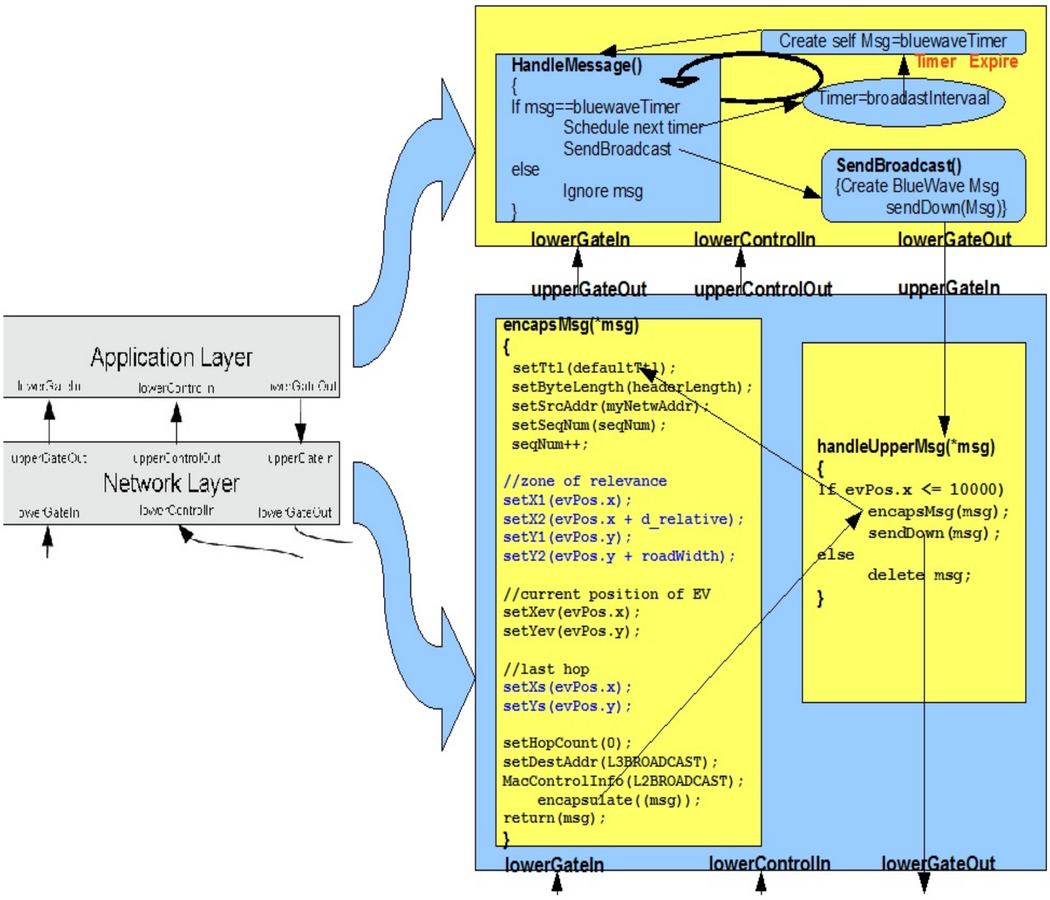

Figure 6.3: Main events and actions in the Application and Network layer of the EV Host

The EV extends the Network layer message of the mobility framework to contain additional parameters which are relevant to the BlueWave such as coordinates of ZoR. Figure 6.4 shows the inheritance and extended fields of network message for BlueWave application.

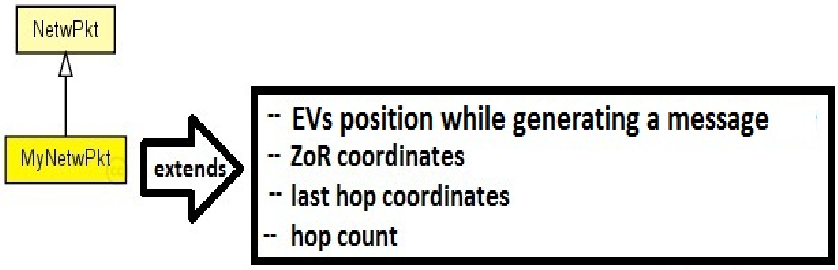

Figure 6.4: The extension of Network layer message of MF to support BlueWave protocol

Other Vehicles Host:
Incase of Other vehicles, the Application layer has no function at this level of the protocol implementation. We are interested on the Network layer activities and as such the possible application layer functionalities are not enabled. In the network layer, on the reception of new message from the MAC layer, it goes to the function which handles lower messages. The pseudo code for the main events and functions is shown in Figure 6.5 on the following page. The block function smartFlood in Figure 6.5 on the next page is applicable only incase of slotted 1-persistant dissemination algorithm. For flooding based algorithm no timers and distance based waiting is implemented. The function block handle lower message of Figure 6.5 on the following page will send msg to the mac(sendDown(msg)) instead of smartFlood(msg).

Mobility for the EV:
The EV adapts its mobility pattern from the BasicMobility module of the OMNeT++ mobility framework. It extends it such that the speed increases linearly with some acceleration rate, which is given as an input parameter, until it reaches its maximum speed.

IDMmob for other Vehicles:
The other vehicle's movement is governed according to IDM(intelligent Driver Model). Privouse implementation of the IDM for vehicular experiments was done in Martijn's thesis[93] by extending the channelcontrol and BasicMobility modules of the mobility framework. The same code and method of implementation is used in our case of IDM implementation. The detailed explanation of the IDM implementation is given in [93].

6.2 BlueWave Scenarios

In previous section we have seen the architecture of the MF in OMNeT++, which is the platform used to implement our BlueWave protocol. To configure the simulator and execute programs, we need to specify the scenarios to be experimented. This section is dedicated to define and describe the scenarios which later will be experimented in Chapter 7.

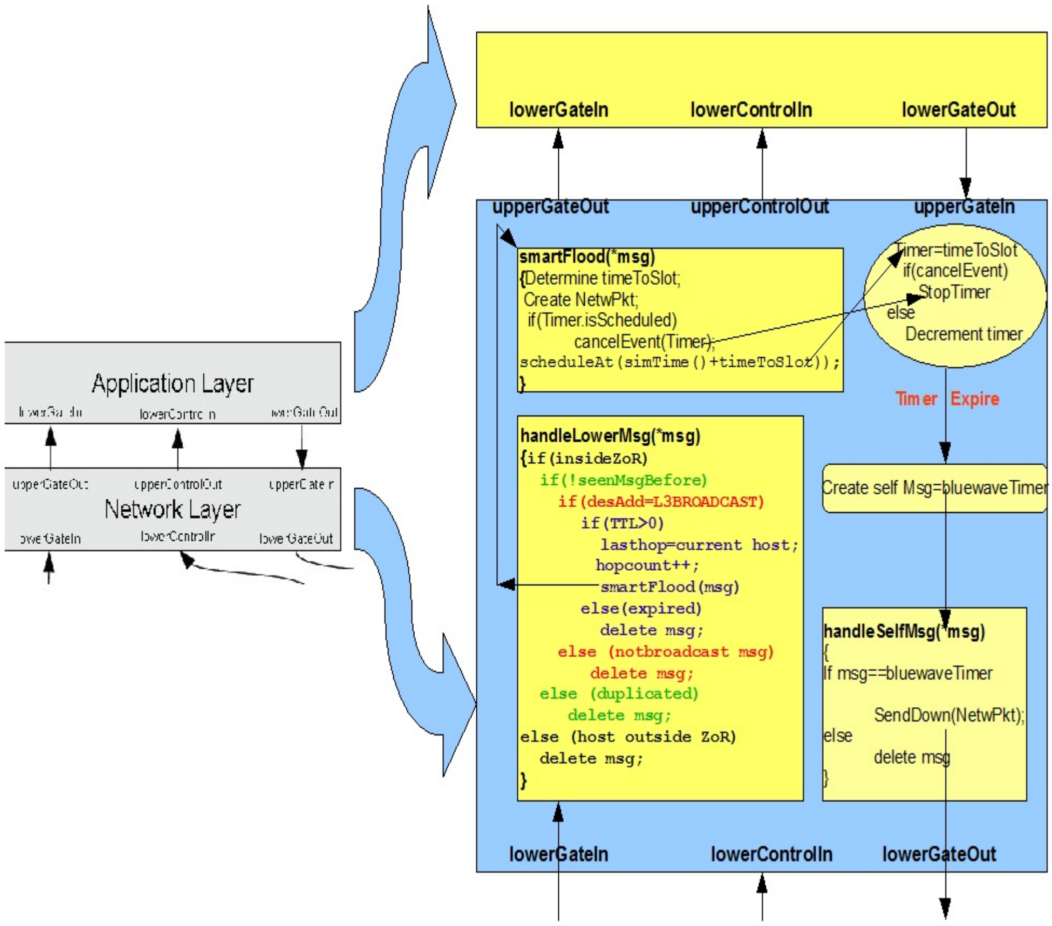

Figure 6.5: Main events and actions in the Network layer of the other vehicle's Host

The BlueWave as an application can happen on different road architectures and traffic density. In this thesis, we narrow the scenario in to straightway single lane of 10km long, i.e. the EV's target destination will be 10km away in straightway road as shown in Figure 6.6. This straightway will be used to test the BlueWave protocol for different traffic density and vehicle speed such as highway and urban speed limits.

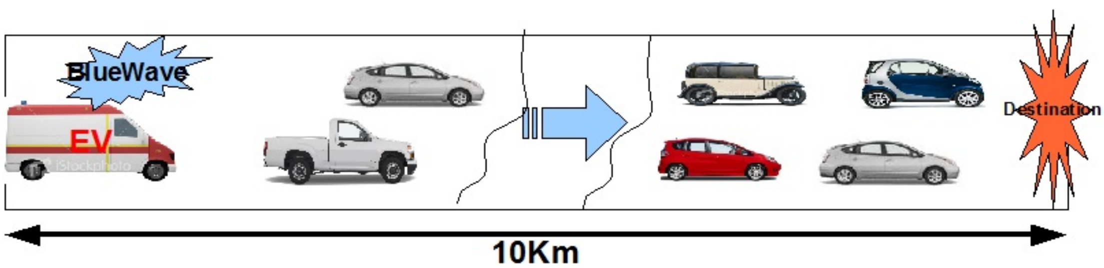

Figure 6.6: BlueWave scenario of 10km long straightway

The overall objectives of having these simulation scenarios can be summarized as follows:

- To investigate the impact of traffic density on performance of the protocol

- To investigate the impact of change in parameters of the protocol such as size of ZoR and EV broadcast rate.
- To investigate the impact of choosing dissemination algorithm(flooding and slotted 1-persistent)
- To investigate the impact of choosing scenarios on the performance of the protocol, such as highway, urban scenarios.

To achieve these objectives, the scenarios in our BlueWave analysis are organized as follows:-

1. **Scenarios to study the impact of protocol parameters:**
   The size of ZoR and EV's broadcast rate are the main parameters which will be studied. As mentioned in Sections 2.2.4.1 and 5.4.1 the size of ZoR and broadcast are inversely related. Hence, changing either of them will change the other one too.

2. **Scenarios to study the impact of traffic density:**
   The traffic density determines the number of vehicles and their distribution within the 10km experiment grid. To study the impact of network density, the protocol is tested for different car density from 20cars/km/lane to 100cars/km/lane.
3. **Scenarios to study the impact of dissemination strategy:**
   The performance of the protocol will be tested for flooding based and optimized (slotted 1-persistent) dissemination strategies.
4. **Scenarios to study the impact of speed limit changes:**
   The BlueWave protocol will also be tested for different speed limit scenarios, in this case an urban and highway speed limits.

6.3 Simulation Configuration

So far in this chapter, we have seen the implementation of our BlueWave protocol in MF of the OMNeT++ simulator and we limited our scope to a straightway scenarios. The implemented protocol has several parameters which are configured differently for different scenarios. This section is dedicated to describe the configuration details of the BlueWave protocol as implemented in OMNeT++. First the MAC and PHY layer parameters are specified. Next, the parameters of the BlueWave protocol will be specified as used for the simulations. Finally, the IDM mobility configuration will be discussed in detail.

6.3.1 MAC and PHY

The PHY and MAC layers are adopted from WAVE IEEE 802.11p. Even though the standard is not yet published, expected November 2010[11], the draft is used as a reference [23]. The working of the WAVE standard for vehicular scenarios is described in [54], which is also assumed as working principle of WAVE in BlueWave.

PHY layer

The PHY layer specifications of WAVE that will be used in our BlueWave are:

- 10MHz bandwidth channel
- carrier frequency of 5.88GHz (service channel one(SCH1) or channel 176 of DSRC). This band is reserved for safety and efficiency applications and is optimized for high throughput[4].

- transmission range of 250m. The 802.11p PHY supports transmission range up to 1km with 44dbm of isotropic power. However, in this research we use the shorter range of 250m to study worst case range.
- Transmit power level of 184mW is calculated from the configuration of OMNeT++ in similar manner as done in [93] for transmission rage of 250m. This is obtained from the assumption that the interference range in wireless ad hoc networks is estimated to be almost twice of transmission range [101].

MAC layer

The use of priority is adopted from IEEE 802.11e. The use of these priority in VANETs is described in [88] [96] [46] [29], and as such the highest priority level is used for BlueWave. According to the COMeSafety [4] the priority in a broadcast mode are applicable only to the first hop, i.e. it is only the EV will have highest priority.

- slot time 13us
- AIFSN of 2 for the EV(for Access category 4, the highest priority) and AIFSN of 9 for other vehicles(lowest priority)
- SIFS of 32us
- AIFS= AIFSN x Slot time + SIFS= 2 x 13 + 32 = 58us (for EV), and 9 x 13 + 32 = 149us for other vehicles
- CWmin= 3 ...for the highest priority $CWmin = (\frac{(aCWmin+1)}{4} - 1)$ for the EV, and CWmin =15 for other vehicles
- $Cwmax = (\frac{(aCWmin-1)}{2} - 1)$, but is not used as we have broadcast mode only (no retransmission).
- data rate of $3Mbps$. It is chosen as lower rates are more reliable. In addition, as reasoned out in [29], lower data rates are more reliable for broadcast mode as they have robust modulation technique and lowest coding rate.

6.3.2 BlueWave Protocol Parameters

The default values of the Bluewave parameters are configured as follows:-

- Size of ZoR and Broadcast rate: According to Equation 2.10 on page 12 the relationship between size of ZoR and broadcast rate depends on two values, the number of successive broadcasts by the EV (N) and relative speed ($V_{relaive}$). To include the worst case speed that may happen, $V_{relative}$ is taken as that of worst case vehicle defined in Section 2.2.4.1 on page 10, i.e $V_{relative} = 73.88m/s$. The value of $N = 5$ is determined to be suitable for these experiments from preliminary experiments presented in chapter 7.
- time to live (age of a packet): it is equal to $t_{ovetake\_max}$ which is also determined in Section 2.2 on page 6 as $13.5s$.
- slotted 1-persistent parameters:
  - Ns : The number of slots is division of the transmission rage in to Ns equal areas. The more dense network we have the higher number of slots we need for better performance .i.e. reduced waiting time as nodes have only to wait small amount and reduced collision probability as number of vehicles in each slot decreases. In our case a customary value of $Ns = 5$ is taken, which is adopted on similar researches [93] [98] [84].

– N_{ms}: The number of micro-slots is also defined in Section 4.2.1 on page 26 in Equation 4.5 on page 27. If the average vehicle length is taken as $5m$, and physical length of one slot will be:
$Len_{Slot} = \frac{R}{N_s} = \frac{250}{5} = 50m$, the formula taken from Equation 4.3 on page 27 in Section 4.2.1 on page 26 ,
then $N_{ms} = \frac{Len_{slot}}{vehiclelength} = \frac{50}{5} = 10.$

6.3.3 Mobility Configuration

The EV and other vehicles will have independent mobility pattern. The EV will move on its desired behavior, i.e. no blockage from other vehicles and move at maximum speed. Over vehicles will move according to the IDM(Intelligent Driver Model) as described in [92] [93]. The IDM describes the dynamics of the positions and velocities of each single vehicle. According to the IDM, vehicles avoid accidents by keeping minimum headway distance. For vehicle A, x_α denotes its position at time t, and V_α its velocity. Furthermore, L_α gives the length of the vehicle. To simplify notation, we define the net distance S_α:

$S_\alpha = X_{\alpha-1} - X_\alpha - L_{\alpha-1},$
where$(\alpha - 1)$ refers to the vehicle directly in front of vehicle α.

If the velocity difference, or approaching rate is $\Delta V_\alpha = V_\alpha - V_{\alpha-1}$, then the dynamics of vehicle α are described by the following two ordinary differential equations:

$$\dot{X}_\alpha = \frac{dX_\alpha}{dt} = V_\alpha \tag{6.1}$$

$$\dot{V}_\alpha = \frac{dV_\alpha}{dt} = a\left(1 - \left(\frac{V_\alpha}{V_0}\right)^\delta - \left[\frac{S^*(V_\alpha\ ,\ \Delta V_\alpha)}{S_\alpha}\right]^2\right) \tag{6.2}$$

$$S^*(V_\alpha\ ,\ \delta V_\alpha) = S_0 + V_\alpha T + \frac{V_\alpha \Delta V_\alpha}{2\sqrt{ab}} \tag{6.3}$$

$V_0,\ S_0,\ T,\ a,\ and\ b$ are model parameters which have the following meaning:
desired velocity V_0: the velocity the vehicle would drive at in free traffic
minimum spacing S_0: a minimum net distance that is kept even at a complete stand-still in a traffic jam
T is the desired time headway to the vehicle in front
acceleration a
comfortable braking deceleration b
The exponent δ is usually set to 4.

The default values of IDM in our simulations are adapted from similar researches in [92] [93] and requirements we set in Section 2.2 on page 6:-

- Desired velocity $V_0 = 130km/hr$ for a highway, as described in Section 2.2 on page 6. Similarly, for urban scenarios $V_0 = 60km/hr$
- Safe headway$T = 1.5s$ is in [92] [93].
- Max acceleration $a = 0.73m/s^2$
- Desired deceleration $b = 1.67m/s^2$

Chapter 7

Performance Evaluation

So far, we have discussed several aspects of the BlueWave protocol; from specifying its requirements up to implementation of the designed protocol in OMNeT++. Testing the performance of a protocol is a crucial part of developing a protocol. Hence, this chapter is dedicated to define the performance metrics used and discuss the results obtained from the evaluation experiments.

The first section defines the performance metrics used to evaluate the BlueWave protocol. Section 2 describes the specific BlueWave scenarios which are experimented for evaluation. The results obtained and their discussion are given in Section 3. Finally, the chapter will be closed with concluding remarks of the experiments and discussions.

7.1 Performance Metrics

In chapter 2, we have set some requirements of the BlueWave application in which the designed protocol is supposed to comply with. To evaluate the protocol against the requirements some relevant metrics are required. This section will specify the performance metrics used for the evaluation of the BlueWave protocol. We have three types of metrics defined in this section namely: reachability, system load, and spam created.

Before going in to the details of the performance metrics it is worth defining some of the terms used in the evaluation process.

1. **numberOfRelevantPackets:** These are total number of non-expired, non-duplicate BlueWave packets received by a vehicles which is within ZoR. Relevant packets are those which has a valid information[1].

2. **numberOfPacketsReceivedOnTime:** total number of relevant packets(as defined in item 2 above) received by a host vehicle on time [2].

3. **numberOfSpamPacketsInSideZoR:** all packets received inside ZoR with one or more of the following criteria:-

   - duplicated packet
   - time to live expired
   - all relevant packets received after the first relevant packet, i.e. all packets received if($numberOfRele$

[1]Valid information in BlueWave process is to know about the emergency situation and the EV

[2]The notion "on time" is defined in Section 2.2.4.2 on page 12.

4. **numberOfSpampacketsOutSideZoR:** total number of packets(no matter duplicated or expired) received outside the ZoR.

5. **numberOfPacketsGenerated:** The total number of packets generated by the EV though out the simulation.

6. **TotalActiveTime:** This is the total amount of simulation time in which a vehicle been active. i.e. the amount of time a vehicle stayed in the simulation grid.

7. **TotalActiveVehicles:** This is the total number of vehicles which has received or transmitted at least one message.

8. **TotanParticipatedVehicles:** This is the number of vehicles participated in the simulation no matter they were active or not.

9. **Total Tx time:** This is the total time a vehicle spend in transmitting packets during the whole simulation time. These transmitted packets are both successfully received by destination nodes and those lost some where in the channel.

10. **Total Rcv time:** This time is the total time a vehicle spends in receiving bits during the whole simulation process. These received bits includes any noise bits introduced by the channel. In short, as long as the physical layer is receiving any signal the medium is supposed to be busy.

7.1.1 Reachability

As mentioned in Chapter 2, one of the requirements of the BlueWave protocol is to announce targeted vehicles on time. To quantify the notion "on time" we defined a distance ($d_{relative}$) needed by a targeted vehicle to take action. At a distance less than $d_{relative}$ the targeted vehicle is supposed not to have enough time to clear a way. To make sure the targeted vehicle receive a message before it crosses the $d_{relative}$, an area up to $size\ of\ ZoR$ beyond is defined as on time region. The size of ZoR for each vehicle is given as:

$$size\ of\ ZoR = \frac{N \times V_{relative}}{B_{Rate}} \tag{7.1}$$

Where N is the number of successive broadcasts by the EV[3], $V_{relative}$ is the relative speed of the targeted vehicle to the EV and B_{Rate} is the EVs broadcast rate. Therefore, to quantify this requirement a performance metric called reachability is used. Reachability is the measure of the number of vehicles which have successfully received at least one BlueWave warning on time, i.e. receive at least one message when they are at a distance between $d_{relative}$ and $d_{relative} + size\ of\ ZoR$ from position of EV at time of broadcast.

$$\begin{aligned} Reachability &= \frac{Number\ of\ vehicles\ which\ receive\ at\ least\ one\ message\ on\ time}{total\ number\ of\ vehicles\ received\ at\ least\ one\ relevant\ message} \\ &= \frac{Number\ of\ vehicles\ with\ numberOfPacketsReceivedOnTime > 0}{Number\ of\ vehicles\ with\ numberOfRelevantPackets > 0} \end{aligned}$$

7.1.2 System load

A high level of reachability is desirable for BlueWave application. However, for any level of reachability we achieve it's respective impact on the other performance metrics is equally interesting to investigate. Therefore, system load is chosen as a complement metric to reachability to have a broad picture of the

[3] A detailed discussion of N is presented in Section 5.4.1 on page 47

performance of the protocol. One way of measuring load is by measuring the amount of time we occupy the channel (channel utilization).

Channel utilization is measured by taking the average time in which a vehicle is involved in either transmission or reception. The reception time includes that of erroneous packets and noise. The transmission time also includes both successfully transmitted and lost packets. In all, as long as a vehicle is not in an idle state it is assumed as using the channel.

$$Channel\ utilization\ [i] \ = \ \frac{Total\ Tx\ time\ [i] + \ Total\ Rcv\ time[i]}{TotalActiveTime[i]} \tag{7.2}$$

To have a complete picture, the average of all involved vehicles [4] will be taken as a final representation of channel utilization.

$$Average\ Channel\ utilization \ = \ \frac{\sum_{i=1}^{n}(Channel\ utilization[i])}{TotalActiveVehicles} \tag{7.3}$$

7.1.3 Spam created

The desired and most efficient behavior of the BlueWave system is when other vehicles receive only one warning message on time. However, vehicles may receive more than one BlueWave messages during the course of the simulation. A third performance metric is the measure of unnecessary packets created in the BlueWave process. There are two ways to measure the spam created:
1) Total Spam: which adds the over all spam created in the system.
2) PerPacketspam: which measures the spam created per each packet generated by the EV.

1. Total Spam:

   (a) Total Spam In Side ZoR: This the measure of unnecessary packets received while vehicles are within the ZoR

   $$\begin{aligned} TotalSpamInSideZoR[i] &= numberOfSpamPacketsInSideZoR[i] \\ TotalSpamInSideZoR &= \sum_{i=1}^{n}(TotalSpamInSideZoR[i]) \end{aligned}$$

   (b) TotalSpamOutSideZoR: This the measure of unnecessary packets received while vehicles are outside the ZoR

   $$\begin{aligned} TotalSpamOutSideZoR[i] &= numberOfSpamPacketsOutSideZoR[i] \\ TotalSpamOutSideZoR &= \sum_{i=1}^{n}(numberOfSpamPacketsOutSideZoR[i]) \end{aligned}$$

   where n is total number of vehicles involved in the simulation.

2. PerPacketspam: The total spam described above doesn't give a detailed information except the over all trend of the spam packets. In this section we define a metric which relates the total spam created to the network behavior in more detail. This is done by measuring the spam per each packet generated by the EV. In the BlueWave protocol the EV each generated packet defines a unique message which contains the up to dated coordinates of ZoR and other relevant information such as speed of the EV. Therefore, the number of packets generated also means the number of different ZoR defined by the EV through out the simulation. Besides, average spam created per each packet generated also implies average spam created in each defined ZoR. The same concept is applied to measure the spam created inside and outside of the ZoR.

[4] Involved vehicles are those which has at least used the channel for transmission or reception

(a) PerPacketspamInSideZoR: These are the average spam created within each defined ZoR (per each packet generated by the EV) throughout the simulation.

$$PerPacketspamInSideZoR = \frac{\sum_{i=1}^{n}(numberOfSpamPacketsInSideZoR[i])}{numberOfPacketsGenerated}$$

where n is total number of vehicles involved in the simulation.

(b) PerPacketspamOutSideZoR: These are average spam packets created outside the ZoR per each ZoR we defined (per each generated packet by the EV).

$$PerPacketspamOutSideZoR = \frac{\sum_{i=1}^{n}(numberOfSpamPacketsOutSideZoR[i])}{numberOfPacketsGenerated}$$

where n is total number of vehicles involved in the simulation.

7.2 Experimented Scenarios

1. Preliminary experiments (Tuning the parameter N):
As mentioned in chapter 5, the parameter N[5] is difficult to model mathematically. In order to have a feeling on its sensitivity the first set experiments are dedicated on investigating its impact on reachability. The simulator is configured as described in Section 6.3 on page 57 for $10km$ long single lane highway. The experiments are done for different combination of $N = [1,\ 5, and\ 10]$, broadcast rate $[0.1,\ 1, and\ 10] messages/second$, and car densities of $[20,\ 60\ and\ 100] cars/km/lane$. This gives a total of 27 different simulation runs of each is repeated 30 times to get some level of confidence interval, which make the total simulation runs to 810. Two dissemination algorithms, plain flooding and slotted 1-persistent , are experimented which doubles the total runs.

2. The main experiments:
The second set of experiments are done to study the impact of the BlueWave protocol parameters (Broadcast rate and size of ZoR), change in traffic density, change in speed limit (urban and highway comparison), and change in dissemination algorithm (plain flooding and slotted 1-persistent). The experiments are done in a 10km long single lane straightway with IDM as mobility for all vehicles except the EV. Based on results of the preliminary experiments, a value of $N = 5$ is taken for all the experiments. Besides, the car density is varied between the values $[20,\ 40,\ 60,\ 80,\ 100] cars/km/lane$, the broadcast interval ($\frac{1}{broadcast\ rate}$) varies between the values $[0.1,\ 0.4,\ 0.6,\ 0.8,\ 1.0] seconds$. These experiments gives 25 combination of different runs of each is repeated 50 times to give a total of 1250 simulation runs. These amount of run is done for both plain flooding and slotted 1-persistent algorithm, which doubles the total.

7.3 Results & Discussions

7.3.1 Tuning the parameter N

These preliminary experiments are set to understand the impact of parameter N on reachability. For a given broadcast rate the reachability that can be achieved by the protocol is measured for different N values. The same setup is repeated for different broadcast rates and different car densities. Figures 7.1, 7.2 on page 65 and 7.3 on page 65 give the reachability in % versus the broadcast rate for car densities of $[20, 60,\ and\ 100]\ cars/km/lane$. The experiments are done for different values of N

[5] which is the number of successive broadcasts by the EV so that a targeted vehicle receives at least one message on time

$(1, 5, 10)$ and for both dissemination algorithms (plain flooding and slotted 1-persistent) in a 10km long highway scenario. The obtained results have 95% confidence interval using the student's t-distribution with degree of freedom 30.

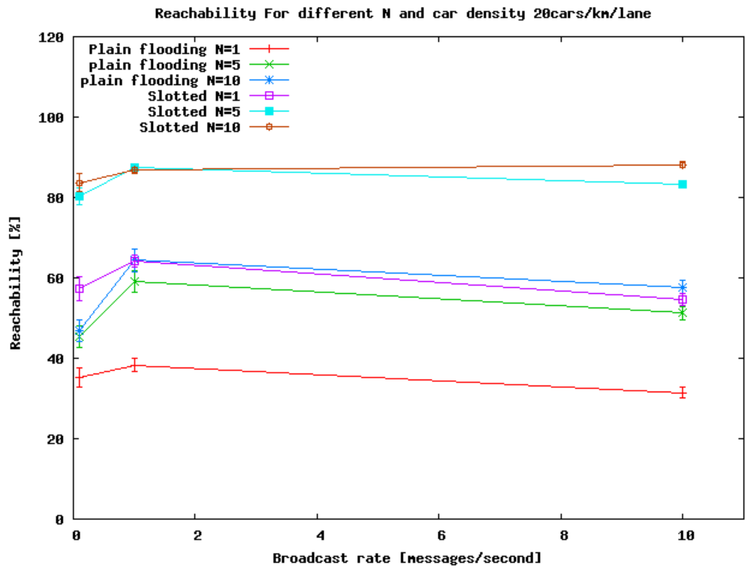

Figure 7.1: Reachability versus broadcast rate for car density of 20cars/km/lane N values of 1, 5 and 10

The overall behavior of reachability for different broadcast rates is similar in all of the 3 experimented car densities. For a given value of N the reachability increases with broadcast rate and after some point it falls back. Since the experiments are done for selected broadcast rates $(0.1, 1, 10Hz)$ it is not clear at what broadcast rate does it start to fall. However, the increase decrease trend is observed from points $0.1Hz$, $1Hz$, $10Hz$ as depicted in Figures 7.1, 7.2 and 7.3. In Figure 7.1 for example, for plain flooding and $N = 1$ reachability increases from 35% to 38% when the broadcast rate changes from $0.1Hz$ to $1Hz$ and then falls to less than 32% when the broadcast rate is $10Hz$. The general impression is that even if the graph between points $1Hz$, $10Hz$ changes, the change will be symmetric for all values of N. The changes in reachability for a given N are due to combined effect of change in broadcast rate and size of ZoR, which is inversely related to broadcast rate according to Equation 2.9 on page 11. At lower broadcast rates– higher broadcast intervals –there may be a major topology change in the network such that many nodes are overtaken without receiving a single message on time. At the same time lower broadcast rate also implies a wider ZoR which is expected to increase the reachability as more vehicles will have a chance to hear a valid warning within ZoR. At very low broadcast rates the effect of broadcast rate (low reachability in the graphs) is more significant than the effect of increase in size of ZoR (supposed to increase reachability). At very high broadcast rates the reachability decreases as seen the graphs, however, the reason now is due to the high decrease in size of ZoR obtained when increasing the broadcast rate.

In all, increasing N increases the reachability until a saturation point, at which a further increase in N has no more impact on reachability. In Figures 7.1, 7.2 and 7.3 this tendency of N is demonstrated for all densities though the reachability level is generally lower for plain flooding. It is due to the broadcast storm problem discussed in the literature part Section 4.2.1 on page 26. Increasing N means increasing the size of ZoR so that under ideal condition targeted vehicles receive N warning messages on time. In all obtained results $N = 1$ achieves low reachability as expected. Practically it is difficult to receive

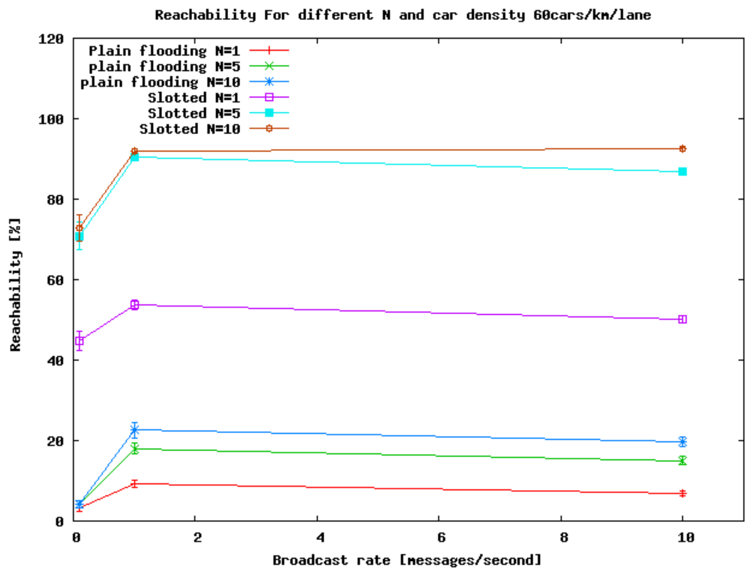

Figure 7.2: Reachability versus broadcast rate for car density of 60cars/km/lane N values of 1, 5 and 10

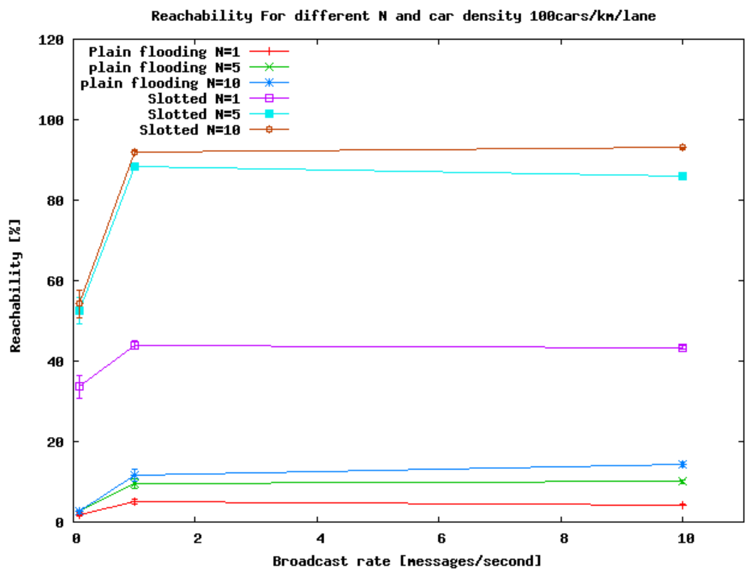

Figure 7.3: Reachability versus broadcast rate for car density of 100cars/km/lane N values of 1, 5 and 10

the warning on time on first attempt due to the uncertain wireless channel condition. Increasing N to a value of 5 dramatically increases the reachability level in all cases. The next experimented value of $N = 10$ shows a saturation at which the reachability changes a little from that of $N = 5$. Since we did not experiment the values of N between 5 *and* 10 (due to time constraint) it is difficult to conclude that $N = 10$ is a perfect saturation point. However, it is reasonable to set a value of $N = 5$ based on these experiments for it approaches the identified saturation point.

7.3.1.1 Concluding remarks on setting N

From these preliminary experiments we have a good feeling about the parameter N, but not precise and perfect. The achieved level of reachability are not close to 100% (100% is desired requirement of the BlueWave application). These experiments lack extended test of the the parameters broadcast rate and N so that a better reachability could be obtained. Getting the right combination of broadcast rate and N needs a further extensive research. Since the over all designed BlueWave protocol by itself has several idealistic assumptions it is difficult to consider the accuracy of single values on the results. Nevertheless, the most important aspect to note is the changes in performance with changes in the value of the parameters. Hence, a value of $N = 5$ is considered as a suitable value to execute the rest of the experiments.

7.3.2 Impact of Broadcast rate (size of ZoR)

All the experiments are obtained with confidence interval of 95% using student's t-distribution for degree of freedom 50. In the all the experiments the broadcast rate is varied between the values $[1, 1.25, 1.66, 2.5,\ and\ 10]messages/second$. The equivalent length of practical size of ZoR according to Equation 2.9 on page 11 and $N = 5$ will be $[1366.78, 1292.9, 1219.91, 1145.14,\ and\ 1034.32]meters$ respectively.

7.3.2.1 Reachability

The impact of change in broadcast rate and size of ZoR on reachability are plotted in Figures 7.4 and 7.5 respectively. The vertical axes represent the level of reachability achieved in % and the horizontal axes give the broadcast rate in messages/secnod of the EV (Figure 7.4) and practical size of the ZoR in meters (Figure 7.5). Since the broadcast rate and practical size of ZoR are inversely related the graphs in Figures 7.4 and 7.5 have opposite trends of reachability.

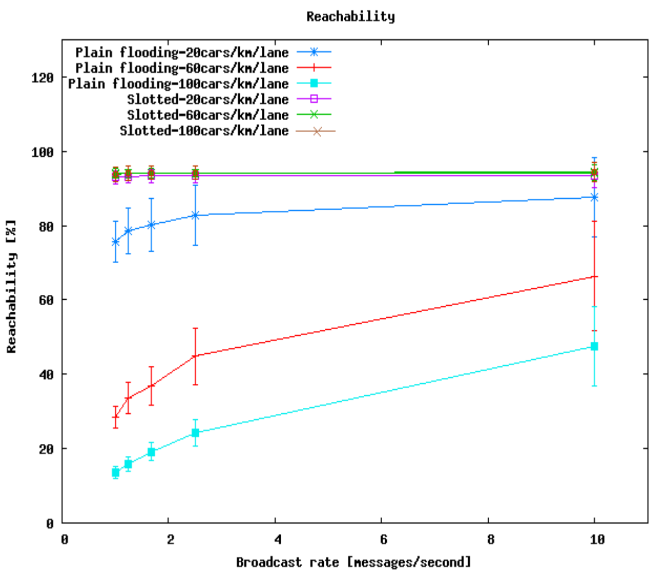

Figure 7.4: Reachability versus broadcast rate for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

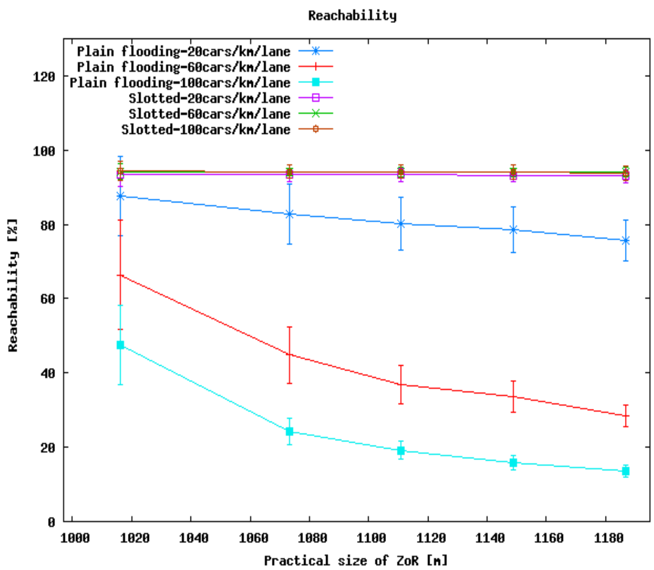

Figure 7.5: Reachability versus size of ZoR for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

Plain flooding in general achieves a low level of reachability, for example for at car density of 60cars/km/lane it has reachability of $approximately\ from$ 30% to 60% while changing the broadcastrate from $1Hz\ to\ 10Hz$, comparing to slotted 1-persistent $(93\% - 94\%)$. This is because all vehicles try to rebroadcast immediately after receiving a packet for the first time and that leads to high possibility of collision in the MAC layer. Hence, the packets usually die at first hop. Our preliminary experiments also show that the maximum hop traversed in plain flooding do not exceed 2 for majority of generated packets. However, at low densities they achieve better reachability due to less number of nodes are to contend for rebroadcast. Figure 7.4 on the preceding page shows an increase in reachability for plain flooding with increase in broadcast rate. Increase in broadcast rate increases the chance of rebroadcast attempt at first hop, which depends on the probability of winning the MAC contention. On the other hand, increase in broadcast rate causes decrease in the size of ZoR which literally implies presence of less number of vehicles each time the ZoR is defined. With respect to this, the decrease in size of ZoR should decrease the chance of having more nodes receiving the warning on time. However,in plain flooding, increasing or decreasing the size of ZoR beyond two hops[6] has no effect on reachability as the packets die at first or second hop due to collisions. It is important to note that the change in practical size of ZoR due to change in broadcast rate occurs beyond $d_{relative\_max}$. Besides, the relative distance ($d_{relaitve\_max}$) given by Equation 2.2.4.1 on page 11 is greater than 2×250. Thats why the impact of change in size of ZoR is overridden by the impact of change in broadcast rate in plain flooding. The graph of plain flooding in Figure 7.5 on the preceding page reveals this fact, a decrease level of reachability with an increase in size of ZoR. The confidence interval of plain flooding increases with broadcast rate as shown by the error bars in Figures 7.4 and 7.5. This is due to the uncertainty of the MAC layer contention, more contentions (due to increased broadcast rate) create a wide range of values beyond the mean.

An important characterstics of reachability in plain flooding is the rate of change with broadcast rate is different for different car densities. If we observe Figure 7.4 on the previous page, the rate of increase in reachability with broadcast rate at car density of 20cars/km/lane is smaller than that of car density 100cars/km/lane (the line of the later is more steeper). In other words, the impact of increasing in broadcast rate is more significant in dense networks. As the number of nodes that share the medium increases the chance of success for an independent transmission will drop exponentially. Lets call this $P_{s,n}$ (chance of success for a certain number of contenders n). Let k be the number of times you attempt such a transmission. Reachability is now defined as the probability that at least one of those k attempts is successful. For small n this will already be quite high, and repeating the transmission attempt will therefore not gain you that much. For large n, which is obtained with increase car density, however the chance of success of a single transmission is quite small, so here it would make perfect sense to try it again and again and again, in the hope that in the end at least one transmission went right. So for large n there is much more to gain than for small n.

In case of slotted-1 persistent a high level of reachability is obtained as shown in Figures 7.4 and 7.5. The slotted 1-persistent uses a smart way of flooding which helps messages reach to the far end of the ZoR. The reachability remains almost constant for changing broadcast rate. This is due to the dynamic relationship between parameters N, size of ZoR, and B_{Rate} as related by Equation 7.1 on page 61. When the broadcast rate is low the size of ZoR is wide enough so that the EV makes N slow attempts for at least one message to reach targeted vehicles. In an opposite case, high broadcast rate, the size of ZoR shrinks so that the EV makes N fast attempts for at least one message reach targeted vehicles. From the results obtained keeping the reachability stable for any broadcast rate is achieved in slotted 1-persisten. A reachability close to 100% is not met as seen in Figures 7.4 and 7.5. A possible reason is the limitation of parameter N on scenarios which may have fragmentation. Since the N attempts by the EV are highly correlated to each other by the topology of the network [7] it is difficult to overcome

[6] at its maximum possibility is twice of the transmission range–in our case will be 2×250

[7] Their correlation is explained by the fact that if the first packet lost due to topology of the network, then the next attempts are more probable to fail as topology of the network hardly changes in the time interval of N successive attempts.

network fragmentation.

7.3.2.2 Channel utilization

Figures 7.6 and 7.7 give the characteristics of channel utilization while changing the broadcast rate between the values $[1, 1.25, 1.66, 2.5\ and\ 10]Hz$ or equivalently changing the size of ZoR as related to broadcast rate by Equation 2.2.4.1 on page 11. The x-axes represent the fraction of time each node on average uses the channel. The y-axes are broadcast rate in messages/second and practical size of ZoR in meters.

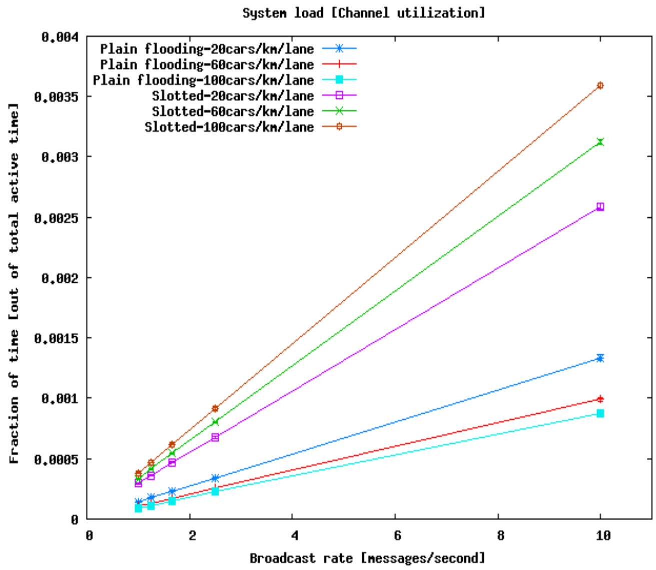

Figure 7.6: Channel utilization versus broadcast rate for densities of 20,60,&100/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

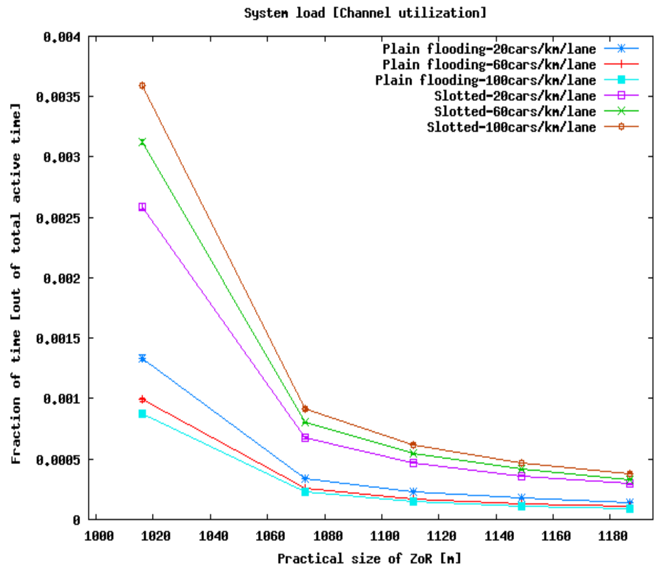

Figure 7.7: Channel utilization versus practical size of ZoR for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

The channel utilization linearly increases with increase in broadcast rate. This is due to the fact that for a given network increasing the broadcast rate of the EV will increase the over all activity in the network as well. i.e. activities like rebroadcast attempt and receiving packet. When the change in broadcast rate is translated in to size of ZoR, the change in channel utilization is no more linear due to the non linear relationship of broadcast rate and size of ZoR. This fact is revealed in Figure 7.7 in which the channel utilization decreases exponentially with increase in size of ZoR.

If we see at the impact of dissemination strategy, the slotted 1-persistent dissemination algorithm uses the channel more than plain flooding. The main reason is the ability of slotted 1-persistent to forward packets to remote destinations in multihop fashion. This increases the number of nodes receiving and transmitting in the medium. In case of plain flooding all the nodes try to use the channel at the same time for short time, which usually ends in collisions. These collisions also reduce the number of nodes involved in transmitting or receiving beyond 2/3 hops from the source.

The channel utilization as defined in this chapter gives the fraction of time a vehicle is busy out of its total active time. Based on the results obtained, the channel utilization is extremely small, the maximum value is the one for slotted 1-persistent at car density of 100cars/km/lane and is less than 0.37% at broadcast rate of $10Hz$. The small size of BlueWave packets contributes to this effect. In addition, the model we design is experimented without interference from other applications which reduces vehicles receiving time and possible collisions. This means a vehicle has an ample time to process other applications apart from the BlueWave application. The challenge in concept of channel utilization is the definition of the channel by it self. Which channel is busy for such fraction of time? Since the vehicles are scattered it is difficult to trace the whole simulation grid and know where and when it is been busy (at least from the current framework of OMNeT++ simulator). Therefore, the channel in our case is the interference range of a vehicle. For example, 0.37% channel utilization is equivalent as to say there was no BlueWave activity by the vehicle on its interference range for more than 99.63% of its active time. Again the channel utilization do not necessarily happen at one location and this further complicates its meaning. In all, the channel utilization gives an estimation on availability of a vehicle for other applications to run during the whole simulation process.

7.3.2.3 Spam created

Figures 7.8, 7.9, 7.10, and 7.11 on the next page represent the total spam packets created in the system during the whole simulation time. In all cases the number of spam packets crated change linearly with increase in broadcast rate and exponentially change with size of ZoR.

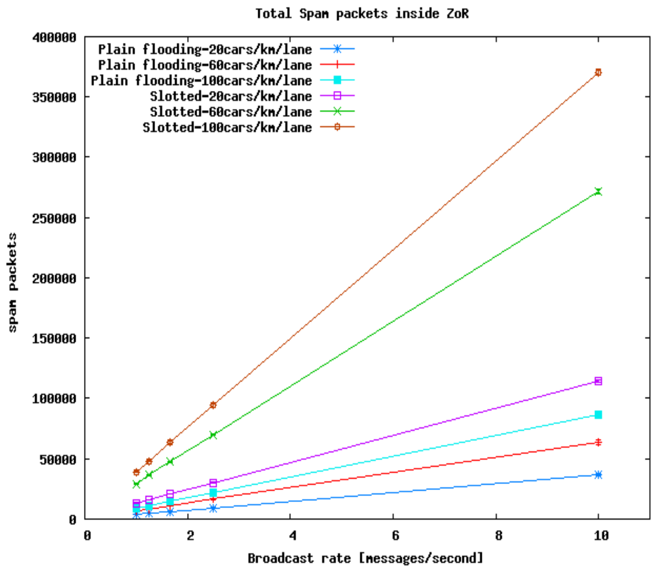

Figure 7.8: Total spam packets inside ZoR versus broadcast rate for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

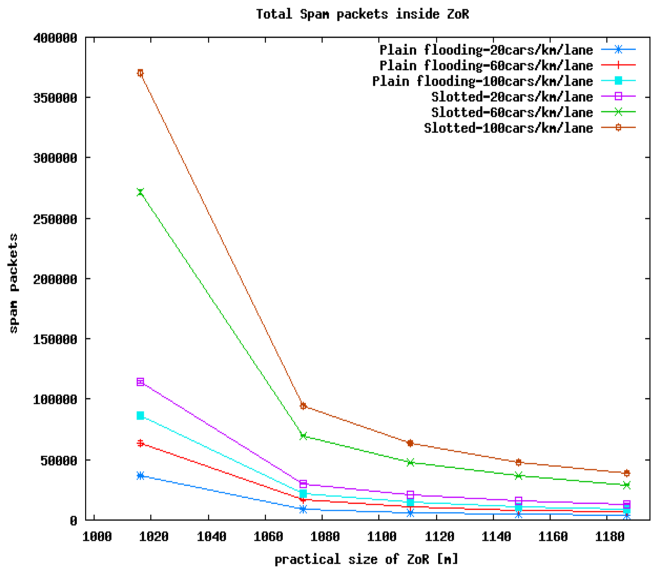

Figure 7.9: Total spam packets inside ZoR versus size of ZoR for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

In general, the number of spam packets created inside and outside ZoR increases with increase in broadcast rate. This due to the increase in activity[8] with broadcast rate. These facts are shown in Figures 7.8 and 7.10 for both plain flooding and slotted 1-persistent. If we compare the two dissem-

[8]probably the same activities are repeated by the factor of increase in broadcast rate, because the topology hardly changes with in the order of broadcast interval.

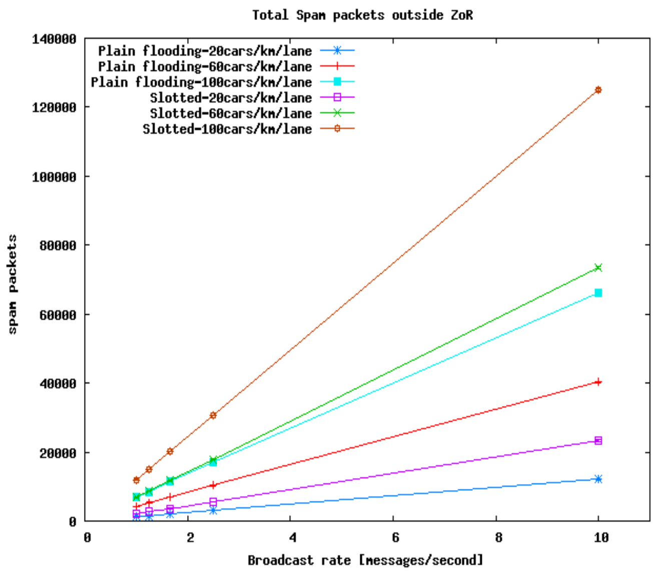

Figure 7.10: Total spam packets outside ZoR versus broadcast rate for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

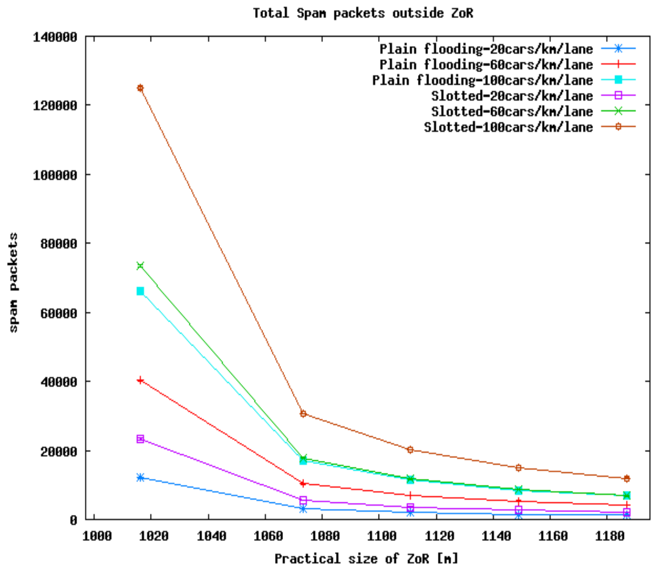

Figure 7.11: Total spam packets outside ZoR versus size of ZoR for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

ination strategies, the plain flooding dissemination mechanism creates lower number of spam packets than the slotted 1 persistent. The main reason is the inability of the plain flooding mechanism to traverse packets more than 1/2 hops. This limits the number of nodes that participate in the BlueWave activity and as such the total spam decreases. The slotted 1-persistent on the other hand manages to rebroadcast packets to further nodes which increases the number of spam packets of received by vehicles.

Figures 7.12, 7.13, 7.14, and 7.15 on the following page give the spam packets created both inside and outside the ZoR per each packet generated by the EV [perPacketSpamInside/OutSideZoR]. Since each generated packet defines a unique ZoR, these spam packets also means an averag spam packets created per each defined ZoR.

Similar to the total spam packets created, the perPacketSpamInside/OutSideZoR is lower in plain flooding than in slotted 1-persistent. It is already mentioned in the above paragraphs that the main reason is the failure of plain flooding to participate nodes which are beyond first/second hop from source due to collisions. In slotted 1-persistent, on the other hand, the main reason for its high perPacketSpamInside/OutSideZoR is the high level forwarding capability which in turn participates many nodes in reception and transmission. As shown in Figure 7.12, the number of perPacketSpamInSideZoR decreases with increase in broadcast rate in slotted 1-persistent. This is due to the decrease of size of ZoR with increase in broadcast rate, which reduces the number of nodes within ZoR and that in turn reduces the spam created. This idea is illustrated in Figure 7.13 in which perPacketSpamInSideZoR increases with increase in size of ZoR. On the other hand, Figure 7.14 shows an increase in perPacketSpamOutSideZoR with increase in broadcast rate. The spam outside the ZoR is limited by the transmission range of vehicles and increase in broadcast rate increases the chances of receiving spam while out side ZoR. Figure 7.15 magnifies this idea by showing a decrease in perPacketSpamOutSideZoR.

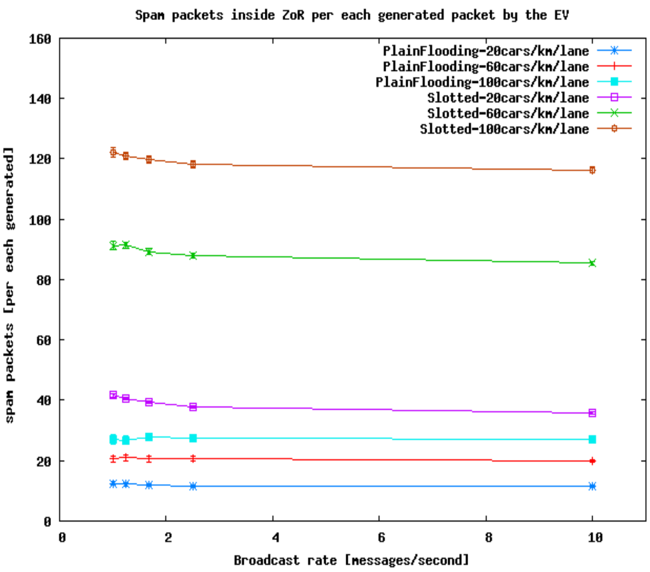

Figure 7.12: Spam packets inside ZoR per each generated by the EV (per each defined ZoR) versus broadcast rate for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

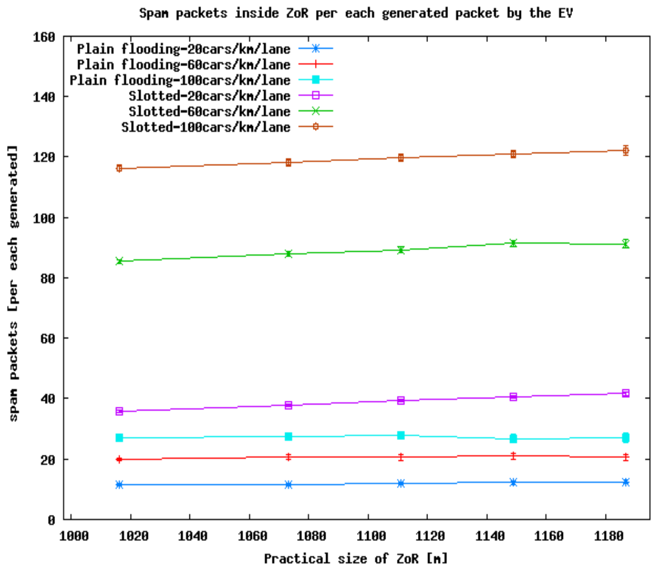

Figure 7.13: Spam packets inside ZoR per each generated by the EV (per each defined ZoR) versus size of ZoR for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

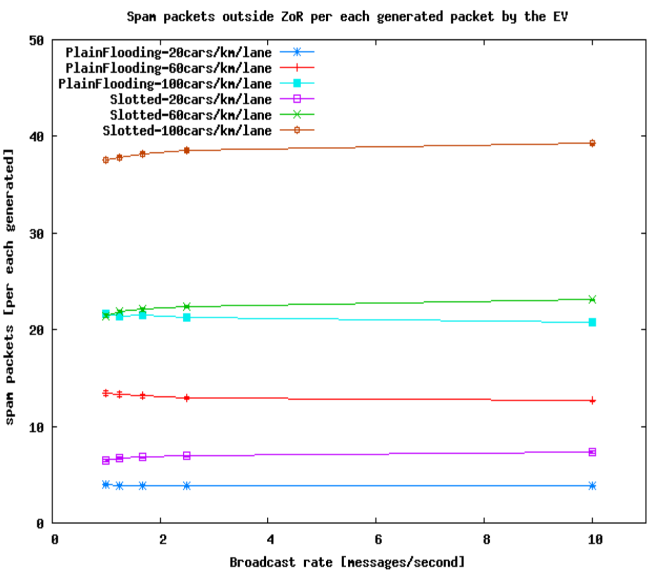

Figure 7.14: Spam packets outside ZoR per each generated by the EV (per each defined ZoR) versus broadcast rate for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

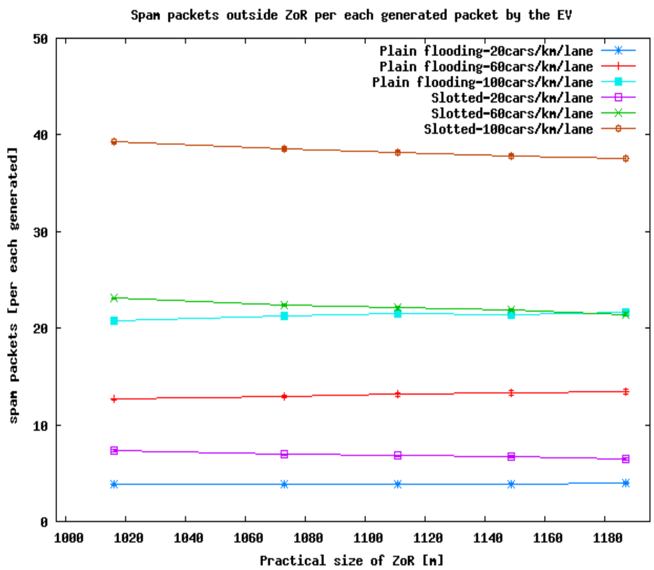

Figure 7.15: Spam packets outside ZoR per each generated by the EV (per each defined ZoR) versus size of ZoR for densities of 20,60,&100cars/km/lane in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

7.3.2.4 concluding remarks on impact of broadcast rate (size of ZoR)

The reachability level is maintained constant while changing the broadcast rate though not 100%. However, the channel utilization and spam created greatly decreases with broadcast rate. Considering reachability as a main objective of the protocol, lower rates seem to be more advantageous from these experiments.

7.3.3 Impact of car density

In this section the results of the experiments done to investigate the impact of traffic density are presented. Car density between the values of $[20, 40, 60, 80, 100] cars/km/lane$ are used each experiment. The results obtained have 95% confidence interval using student's t-distribution with degree of freedom of 50.

7.3.3.1 Reachability

Figure 7.16 gives the reachability in % against change in car density in a $10km$ long highway scenario. The graphs are for both plain flooding and slotted 1-persistent at broadcast rates of $2.5Hz$ and $10Hz$.

In slotted 1-persistent the impact of car density on reachability is not significant as seen in Figure 7.16. For all experimented car densities and broadcast rates the reachability stays at high level, above 93%. This due to the ability of slotted 1-persistent to avoid high rate of collision using its distance based waiting algorithm. With increase in density the possibility of collision within a slot increases, but we have used a microslotted additional waiting method, as described in [93], to avoid such slot synchronization[9]. In addition, the selection of value of $N > 1$ helps in maintaining high level of reachability.

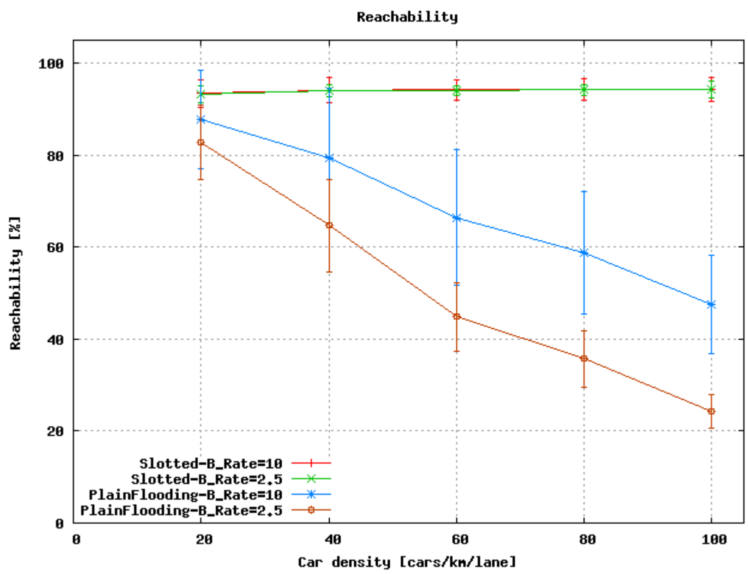

Figure 7.16: Reachability for different car density in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

In plain flooding, the impact of car density is clearly seen in Figure 7.16, where increase in car density decreases the reachability. The increase in car density creates more contention in the MAC layer, which

[9] Slot synchronization happens when two or more nodes within the same slot draws the same waiting time from the MAC

increases the collision probability and as such decreases the number nodes that may receive the warning on time. As already discussed in Section 7.3.2.1 on page 66, the impact of broadcast rate in plain flooding is visible in Figure 7.16 too. The reachability increases with increase in broadcast rate. Again as mentioned in Section 7.3.2.1 on page 66, the impact of broadcast rate is more significant at higher densities. It is worth to note that at low car density such as $20 cars/km/lane$ the plain flooding achieves a reasonability high reachability level, around 87%, for broadcast rate of $10Hz$ as shown in Figure 7.16. This happens because we have a sparse network that allows many nodes to win the rebroadcast contest with out a collision.

7.3.3.2 Channel utilization

The results of system load, expressed in terms of channel utilization, for different car densities are given in Figure 7.17. The channel utilization is put in the y-axis and is expressed by fraction of time in which a vehicle is active either transmitting or receiving out of the total active time[10]. This value is averaged per each active vehicle[11] involved in the simulation.

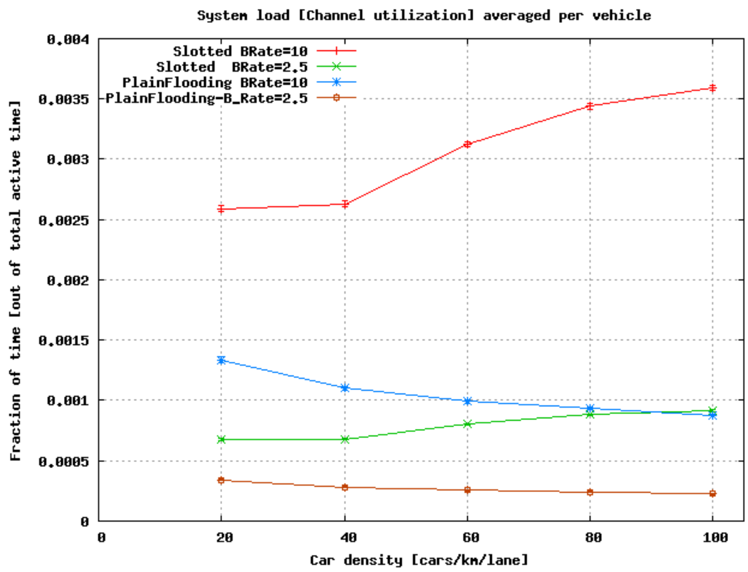

Figure 7.17: Channel utilization for different car density in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

The channel utilization increases with increase car density for slotted 1-persistent as shown in Figure 7.17. Slotted 1-persistent participates many vehicles that are several hops away from the source. This multihop communication demands involvement of many vehicles (which increases the channel utilization as it is averaged to number of vehicles using the channel) and for long time (as there is a hop delay though not studied in our case). Figure 7.17 also shows an increase in channel utilization with increase in broadcast rate from $2.5Hz\ to\ 10Hz$. The same reason as in Section 7.3.2.2 on page 68, increase in network activities, hold true for this case too. The rate of increase in channel utilization while increasing broadcast rate is higher at higher densities. This is depicted in Figure 7.17 in which the increase in channel utilization in slotted 1-persistent for broadcast rate of $10Hz$ is more steeper than that of $2.5Hz$.

For plain flooding, the channel utilization decreases with increase in car density as shown in Figure

[10] total active time is the total time a vehicle spent in the simulation grid

[11] Active vehicles are those which has participated in either reception or transmission during the simulation

7.17. This is mainly due to the increase in collision probability with increased vehicular density. Therefore, more packets will die in first or second hop which limits the use of channel to vehicles in that area. In other words, all nodes try to access the channel at the same time and after a more probable collision occurrence they remain silent until another packet is received.

7.3.3.3 Spam created

Figures 7.18, 7.19, 7.20, and 7.21 on the next page represent the spam packets created by the system both inside and outside of ZoR, for both plain flooding and slotted 1-persistent algorithms while changing the density of cars in the network. As a general trend in all the cases, an increase in car density increases the amount of spam created in the system.

Total spam created is a simple addition of spam packets recorded by each involved vehcile in the simulation. As shown in Figures 7.18 and 7.19 it increases with increase in car density. In both cases, inside and out side ZoR, the spam created by slotted 1-persistent is much higher than that of plain flooding as it involves many vehicles and several rebroadcast opportunity of packets (some of them are spam). In fact more interesting to see is the number of spam created outside ZoR are much lower

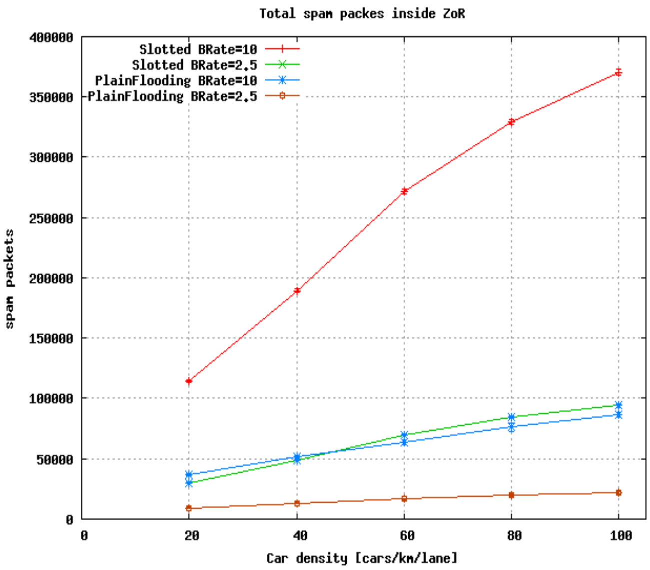

Figure 7.18: Total spam crated inside ZoR for different car density in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

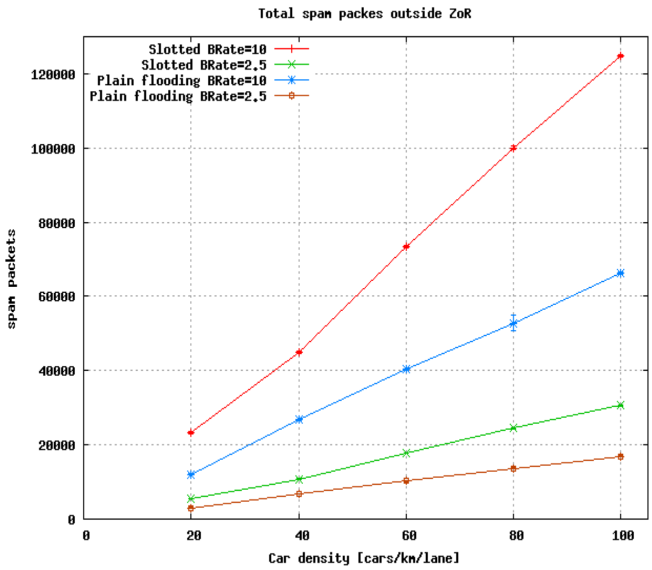

Figure 7.19: Total spam crated outside ZoR for different car density in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

than the spam created inside ZoR. This is because the vehicles we can reach outside ZoR is limited by the transmission range of vehicles. On the other hand, vehicles inside ZoR can forward packet beyond their transmission range in multihop communciation, which makes the spam much higher than that of outside ZoR.

Figures 7.20 and 7.21 on the following page try to translate the total spam created in to per each generated packet by the EV [perPacketSpamInside/OutSideZoR] or per each defined ZoR throughout the simulation. The over all behavior is the same to that of total spam which is described in the above paragraph. Nevertheless, the values represented by the figures gives more sense now than representing them as a total number. For example, in Figure 7.20 on the next page the slotted 1-persisten creates

60 perPacketSpamInSideZoR at car density of 40cars/km/lane and for the same car density it creates 14 perPacketSpamOutSideZoR as shown in Figure 7.21. This literally means every time the EV tries to reach its targeted vehicles within the ZoR it also creates 60 unnecessary packets inside ZoR and 14 packets reach at vehicles that are outside ZoR. These values still have limitations on specifying what they mean for individual driver. However, from system design perspective they could give us a guide on how the system performs. Ideally no spam is desired inside or outside the ZoR, i.e. all packets need to be purposeful.

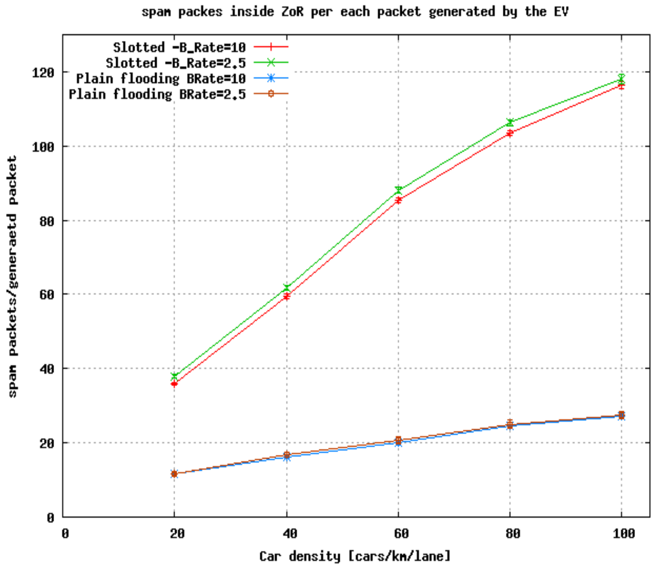

Figure 7.20: Spam crated per each packet generated by the EV (per each defined ZoR) inside ZoR for different car density in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

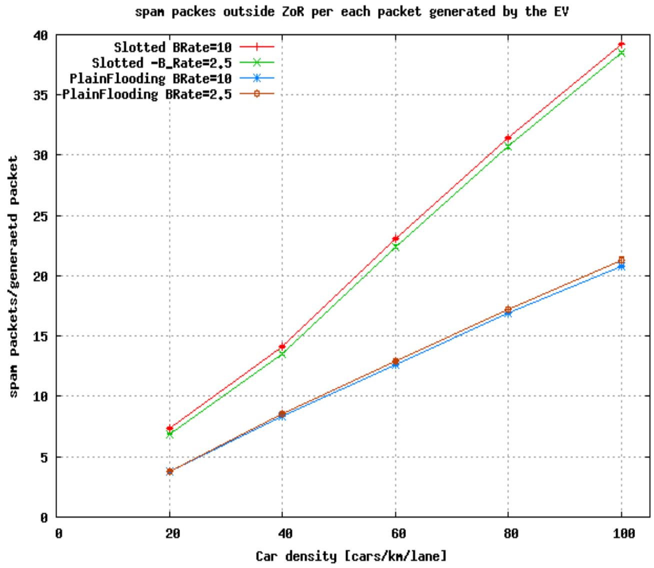

Figure 7.21: Spam crated per each packet generated by the EV (per each defined ZoR) outside ZoR for different car density in a highway scenario, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

Another interesting observation from Figures 7.20 and 7.21 is the impact of broadcast rate on perPacketSpamInSide/OutSideZoR. Higher broadcast rate, $10Hz$ in our case, experience less perPacketSpamInSideZoR than low broadcast rate ($2.5Hz\ in\ Figures$ 7.20 *and* 7.21). This phenomena is reversed in case of perPacketSpamOutSideZoR, i.e. higher broadcast rate has higher spam level. The main reason for such behavior is the decrease in size of ZoR with increase in broadcast rate. That means a decease in size of ZoR decreases the number of vehicles within the ZoR which further decreases the perPacketSpamInSideZoR. In the case of outside ZoR, the number of vehicles that could be reach is limited by transmission range of vehicles and increase in broadcast rate increases the possibility of many vehicles to get spam packets.

7.3.3.4 concluding remarks on impact of density

High density means many vehicles in the network which increases the consumption of resources and spam packets created. The plain flooding usually have lower channel utilization and spam rate than slotted 1-persistent. The disadvantage of plain flooding is its low reachability level. At density of 20cars/km/lane in Figure 7.16 on page 72 the plain flooding achieves high level of reachability. At the same point of car density of 20cars/km/lane in Figure 7.17 on page 73 the channel utilization decreases by almost 50% when using plain flooding instead of slotted 1-persistent. Therefore, at sparse networks the use of dissemination mechanism can be comprised. Nevertheless, it depends on the reachability level requirement of the application. The most desirable value of reachability is 100% as set in chapter 2. It is worth to note that with the current evacuation method our protocol has failed to delivers 100% reachability level.

7.3.4 Impact of speed limit

In the following subsections the results of testing the Bluewave protocol on urban speed limit ($50km/hr$) are presented. The experiments are done for broadcast rates of $[1, 1.25, 1.66, 2.5, \textit{ and } 10] messages/second$. The equivalent length of practical size of ZoR according to Equation 2.9 on page 11 and $N = 5$ is $[1366.78, 1292.9, 1219.91, 1145.14, \textit{ and } 1034.32] meters$. Furthermore, the results obtained have 95% confidence interval using student's t-distribution with degree of freedom of 50.

7.3.4.1 Reachability

Figures 7.22 and 7.23 give graphs of reachability level achieved by both slotted 1-persistent and plain flooding algorithms in urban and highway scenarios.

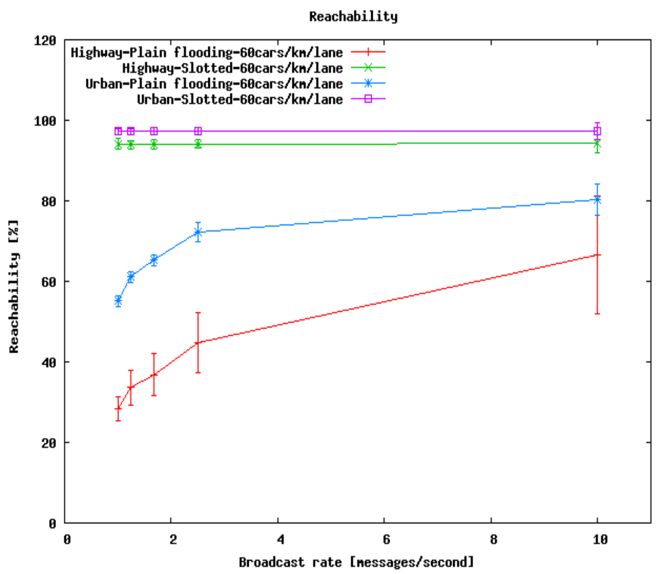

Figure 7.22: Reachability level in % for different values of broadcast rate in both highway and urban scenarios, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

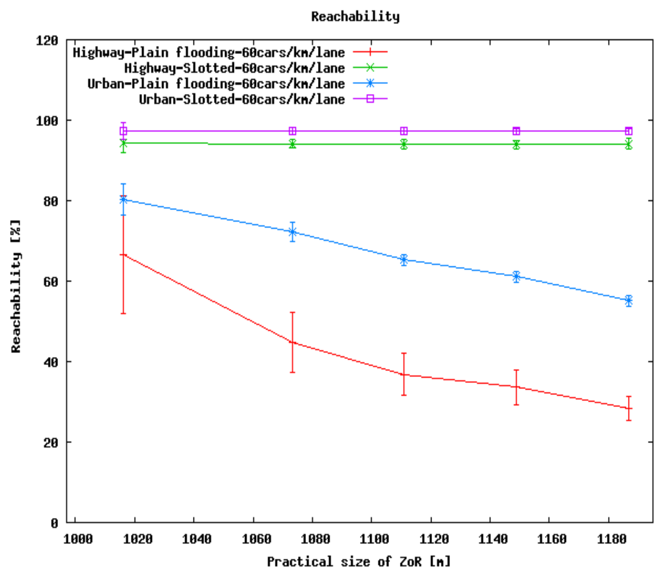

Figure 7.23: Reachability level in % for different values of size of ZoR in both highway and urban scenarios, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

In both plain flooding and slotted 1-persistent the urban case outperforms the highway scenario. The main reason that could suit this phenomena is the decrease in speed of both EV and other vehicles in urban scenarios. A lower speed results in a lower relative speed of vehicles with respect to the EV, which in turn decreases the length of the on time benchmark , $d_{relative}$, that is given by Equation 2.6 on page 10. This means vehicles normally needs less distance of separation from the EV to complete their action on time. Hence, the reachability level in Figures 7.22 and 7.23 remains higher for urban scenario.

7.3.4.2 Channel utilization

The comparison of channel utilization in urban and highway scenarios are presented in Figures 7.24 and 7.25. The over all feeling we have from these results is that increase in broadcast rate (or decrease in size of ZoR) increases the channel utilization in both highway and urban scenarios. However, the channel is used more in urban scenario. A direct reason for more channel utilization in urban scenarios is the slow motion of vehicles elongates the Bluewave process which demands higher channel resources.

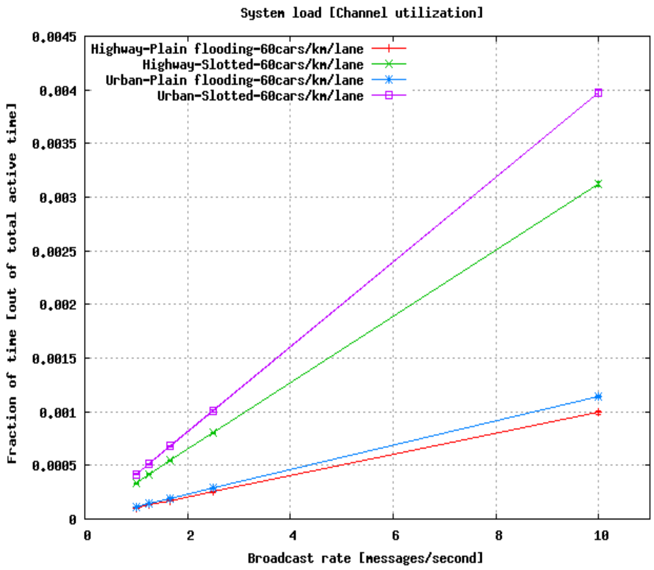

Figure 7.24: Channel utilization in fraction of time [out of total active time] and averages per each active vehicle for different values of broadcast rate in both highway and urban scenarios, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

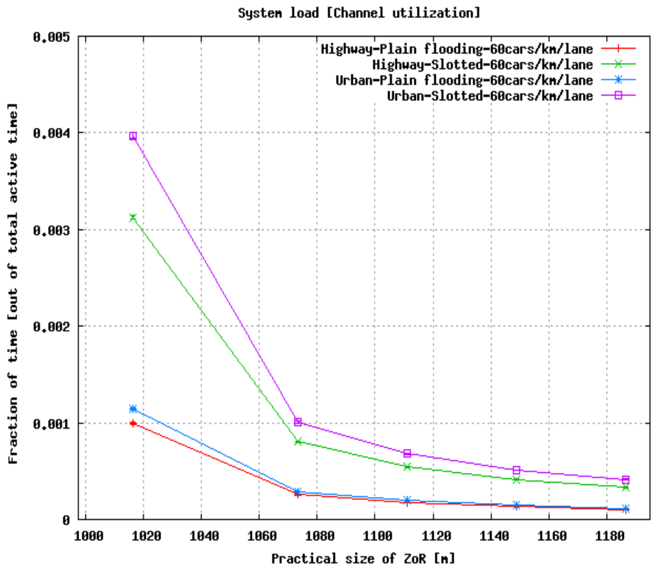

Figure 7.25: Channel utilization in fraction of time [out of total active time] and averages per each active vehicle for different values of size of ZoR in both highway and urban scenarios, results obtained with 95% confidence interval using the student's t-distribution with 50 degree of freedom

7.4 Concluding remarks of the overall experiments

In this chapter, the evaluation of the BlueWave protocol is done with the help of simulations. A wide range of experiments were done first to determine the proper usage of parameter N and then to evaluate the performance of the protocol. The preliminary experiments for tuning N resulted a value of 5 to be used the rest of the experiments. It is worth to note that the determination of parameter N requires an extensive research. The tried values of N and broadcast rate are too few to conclude what the best N is. Practically N depends on the network situation and channel condition, which are not deterministic on beforehand. It means N is not supposed to be static for all kinds of network density and broadcast rate.

The second part of the experiments are meant to evaluate the protocol if it meets the requirements set in chapter 2. The performance metric reachability is directly related to the requirement of the BlueWave application to receive warning messages on time. Clearly, our results do not achieves 100% reachability for the experimented range of parameters. One possible reason is due to the fact that closeby vehicles at time the EV starts to broadcast are already too late to take action. Another reason could be the selection of the parameter N. It is supposed to make sure targeted vehicles receive at least one warning on time. Theoretically if N is infinite the reachability should at least be close to 100%. However, a reachability level up to 94% is achieved in most cases for the slotted-1 persistent algorithm independent of network density and broadcast rate. This is an important characteristics of the protocol as we don't actually know where it is going to be applied (dense or sparse networks). Therefore, the on time requirement is partially full filled with good level of scalability (As seen in Figure 7.16 on page 72 we obtained almost same high level of reachability for car densities 20 to 100cars/km/lane). From the experiments done it is difficult to asses what the impact of reachability less than 100% is on the over all BlueWave process. The model doesn't include the impact of reaction of drivers on the network performance. It rather handles mobility and protocol as independent entities. One can imagine in practical cases it could lead to delays and blockages of the EV if some of the vehicles do not receive the warning on time.

The second performance metric measured in the process is channel utilization, which shows a direct increase with network density and broadcast rate. The way our channel utilization defined (fraction of time) is difficult to relate to the requirement of set in chapter 2 in terms of bandwidth usage. One obvious problem is the nodes are scattered and there is not fixed channel that can be monitored how it is used. Nodes rather consider all the medium around their interference range as their channel. Therefore, the evaluation is individual vehicle basis not the whole network as a single channel. Nevertheless, we can get the idea how much out of its total active a vehicle on average uses the channel. That is actually what we measured as channel utilization in our experiments. The over all observation of channel utilization is that the protocol uses very small resource compared to their total active time. Figure 7.17 on page 73 shows a maximum channel utilization at car density of 100cars/km/lane and broadcast rate of $10Hz$ is not more than 0.37%. Which means for more than 99% of its active time a vehicle can run other applications. This result is convincing as the packets are delimited by ZoR and vehicles are supposed to participate in the BlueWave process only inside the ZoR.

The third metric used to evaluate the BlueWave protocol is the level of spam created inside and outside of the ZoR. The number of spam packets created increases with density and broadcast rate for both slotted 1-persistent and plain flooding algorithms. The values we measured only give the over all characteristics of system. It could be more interesting if those measurements are translated to the impact on individual vehicles. Another way of looking the spam is per each packet generated by the EV, which literally means per each defined ZoR in the simulation. Still such approach lacks to reveal the impact of spams towards individual vehicles. This is because we do not know (from the current implementation of the protocol) which vehicle, where, and when it has been targeted by the EV. We only record all scalar values at the end of the simulation.

There are many remarks to be made on the results obtained. One of the factors that may influence the results is the propagation model. We take a very simplistic free space propagation model which do not include the effects of fading and other factors that may happen. Another point to note is the availability of other applications. In practice it is highly possible that other applications will share the medium. This can affect the results obtained as there will be more contention to access the channel and more interference from other applications. Furthermore, the mobility model and communication protocol are modeled as independent parts of the system. In practice the information within the Blue-Wave packets could determine the behavior of drivers.

Another limitation is the transmission range considered in this research (a static range of 250m is taken). According to IEEE 802.11p the transmission range could be as long as 1km for vehicular networks with power radiation limit of 40dBm. Changing the transmission range could possibly change the values obtained. It is important to note that increasing transmission range also means increasing the interference range of vehicle which may have negative impact on the performance of the network, not studied in this research though. In addition, the parameter $d_{relative\_max}$ as defined by Equation 2.6 on page 10 depends on $t_{overtake\_max}$, which is not deterministic. Changing $d_{relative\_max}$ implies changing the practical size of ZoR which may change the obtained results.

In all, the values could greatly deviate in practice and on different scenarios. Nevertheless, the changes observed are expected to remain as a characteristics of the protocol. A good example for this argument is the results of the experiments done on Section 7.3.4 on page 76 for speed limit of urban scenario. The values obtained are changed as seen in Figures 7.24 on page 77 and 7.25 on page 77, but the over characteristics of the graphs remains unchanged comparing to the highway results.

Chapter 8

General Conclusions

So far, we presented the work done in this thesis from defining the problem up to evaluating the proposed solution with the help of simulations. This chapter is dedicated to complete the thesis by concluding the over all work.

The first section recaps the general over view of the work completed and draws a concluding remarks. Section 2 will specifically try to answer the research questions launched at the beginning of the work. Finally, Section 3 points out the possible extensions of this thesis work.

8.1 Conclusions

In this thesis, we identified the signaling limitations of BlueWave application. The light signals are greatly dependent on the availability line of sight, and the siren sound depends on situation of the driver such as loud music, better insulated doors and windows. In addition, the system do not differentiate its target and fails to assist drivers on how to react to the emergency situation even if it does. Many of the solutions available extends the light and siren signaling using radio signals from EV directly to target vehicles. A common limitations of such technologies are their failure to support multihop communication and the fact not based on well established standards such as the IEEE 802.11. Hence, we proposed to design a system which is cooperative (vehicles share information), support multihop communication, and based on WAVE (WiFi version for vehicular networks).

Before jumping to design of the protocol, the requirements of the BlueWave system were set from application and communication perspectives. The main requirements of the application are: 1) The warning has to reach target vehicles on time such that they get enough time to take proper action; 2) Limit the warning only to selected vehicles which are within the ZoR ; 3) Limit the age of the warning. From the communication angle, the requirements set are: 1) The protocol need to define specific geographic are in which nodes inside are only entitled to use messages; 2) Define the time to live of the messages; 3) Make sure the application bandwidth usage is as low as possible; 4) Make sure the system is scalable and immune to fragmentation. These values were quantified for the ease of the evaluation process and we derived the size of ZoR in Chapter 2 of this thesis accordingly.

After extensive literature review on data dissemination techniques and routing mechanism related to VANETs, we designed the BlueWave protocol. The protocol has two parts, the first is a basic BlueWave protocol which is valid for all vehicles. The second part is an additional functionality implemented in the EV only. In this extra functionality, the EV generates the BlueWave messages at some broadcast rate. Based on the requirements of the BlueWave system, the protocol checks time expire, relevance of message to nodes based on ZoR information.

Next, the performance of the BlueWave protocol was tested in a highway scenario of 10km long using OMNeT++ simulator, a discrete event simulator. The main objective of the protocol is to warn vehicles on time. Hence, the most important metric is reachability. In almost all of our results a high level of reachability is achieved (from 90%–94%). An intersecting behavior of the protocol is that it maintains its high level of reachability in all experimented network densities, from 20–100cars/km/lane, and broadcast rates, from 1 Hz to 10Hz. However, the absolute requirement of the application is to have 100% reachability. In that respect, the protocol designed could not attain 100% reachability, which can be considered as a remark for feature work. In general the channel utilization and the number of spam packets created increase with car density and broadcast rate. Since we achieve high level of reachability independent of broadcast rates, choosing lower broadcast rates seem a better approach.

In all, our protocol achieves high level of reachability and offers a flexibility on scalability and choosing broadcast rate. It may happen that the values obtained may fluctuate in different scenarios, perhaps practical applications. But the overall changing characteristics of the protocol is expected to remain the same as we obtained in this research. The results of urban speed sceanrio in Section 7.3.4 on page 76 reveals this argument.

8.2 Answers to research questions

Q1. **What are the requirements of BlueWave services from communication and application point of view?**
The requirements of the BlueWave protocol are set in Sections 2.2.1 on page 6 and 2.2.2 on page 7. The requirements can be summarized as:

1. Messages need to reach target vehicles on time
2. Messages should have limited age
3. Messages should be valid only inside ZoR (define specific ZoR)
4. The Protocol should use as minimum as possible bandwidth
5. The protocol should be scalable, and immune to fragmentation

Q2. **How to disseminate BlueWave messages in vehicular networks?**
By means of literature review, we have identified several methods of information dissemination for VANETs, which are presented in Chapter 4, Section 4.2 on page 25 of this thesis. Based on the dissemination mechanism they use, we identified three strategies from the literature review:

1. Flooding based dissemination techniques, discussed in detail in Section 4.2.1 on page 26
2. Relaying based dissemination techniques, discussed in Section 4.2.2 on page 28
3. Opportunistic forwarding based dissemination techniques, discussed in Section 4.2.3 on page 29

For our Bluewave protocol a distance based dissemination protocol (the slotted 1-persistent) is chosen as the main dissemination mechanism as described in Section 5.5 on page 50.

Q3. **How to measure the performance of the designed method?**
In relation to the requirements set in Chapter 2, we defined performance metrics in order to evaluate the designed system. Chapter 7, Section 7.1 on page 60 fully presents the definition of the following three performance metrics:

1. Reachability: Used to measure how many of the targeted vehicles receive a BlueWave warning message on time. Fully defined in Section 7.1.1 on page 61.
2. System load: Defined in terms of channel utilization which is fraction of time on average a vehicle is busy. Described in detail in Section 7.1.2 on page 61.
3. Spam created: It measures the amount of unnecessary packets created by the system inside and outside of the ZoR. A complete description is given in Section 7.1.3 on page 62.

Q4. **Does the dissemination method fulfill the requirements of the BlueWave services?** Based on the experiments run and results presented in Chapter 7 of this thesis, it can be concluded that the protocol designed do not fulfill all the requirements. The requirement of telling target vehicles on time for example is never 100% in all the results obtained.

The requirement to limit the age of the packet was met by quantifying the maximum time a packet should be valid in Section 2.2.4.3 on page 13 and by checking time expire in the BlueWave protocol as described in Section 5.3.1.1 on page 41. There is no any report of the protocol violating this requirement from our results.

The third requirement is to validate messages within the ZoR only. This requirements is also met by first defining the coordinates of the ZoR (as described in Section 5.3.2 on page 42), then putting these values in every Bluewave message (see Section 5.4.2 on page 49) and finally make every vehicle check the coordinates according to the implemented algorithm (as described in Section 5.3.1.3 on page 42).

The fourth requirement is about using minimum bandwidth. The requirement by it self is not clear enough to have quantitative value. However, from our simulation results in Chapter 7, it can be concluded that every node on average used the channel for very small fraction of time (a maximum value of less than 0.32% of their active time as depicted in Figure 7.17 on page 73). Though it is difficult to understand what this value mean in terms of bandwidth usage, but it is clear the protocol is using small part of the resource. Hence, it can be counted as fulfilled.

The last requirement of the protocol is related to robustness against fragmentation and scalability issues. Based on our simulation results the protocol shows good scalability by maintaining the reachability level at constantly high value (around 94% in Figure 7.17 on page 73) for car densities of 20 to 100cars/km/lane. Regarding fragmentation no clear assessment has been done in this research.

8.3 Future work

The research on BlueWave started with limited scope and objectives. With more investigations a lot of research options crossed our mind. Some of the ideas are simple enough to be carried in this research but left due to time constraints. Others need more time and resources that could make them independent research projects. In the sequel the possible extensions of this master's thesis research are listed:

1. Use of beaconing to optimize the dissemination process:
   It is already mentioned in Section 5.5.3 on page 51 that vehicular networks somehow are expected to have beacon exchange. The IEEE 802.11p has specification for this beacon frames and their broadcast rate (not more than 10Hz). It means vehicles (including the EV in our case) will have a partial view of the network from these beacon exchanges. The EV can estimate the density

of network and accordingly adjust its broadcast rate. Another point is to explicitly identify the forwarding node (similar to the mechanism described in Section 4.2.2 on page 28. This idea is not tested in our experiments due to time constraint. Since these beacons have to run parallel to the BlueWave application, their impact on performance of the network could be an interesting issue to investigate.

2. Sensitivity of waiting and clearing time:
   In Section 2.2.4 on page 8 the waiting and clearing times, $t_{wait} + t_{clear}$, are estimated to be in the range of 5 to 12s. later in Section 2.2.4.1 on page 10 the worst case (maximum of 12s) is used to determined the overtake time ($t_{overtake\_max}$). This value determines the length of practical size of ZoR as given by Equation 2.11 on page 12. Experimenting the sensitivity of these values could be an interesting feature work. Because changing the waiting and clearing time changes the size of he practical size of ZoR which may have an impact on the performance of the protocol.

3. Proper design of Propagation model:
   The propagation model used in this experiments is free space model which considers only the propagation loss. In practice so many factors such as buildings, ground reflections affect the characteristics of the channel. Therefore, one way of extending the research could be modeling a proper propagation model which represents the real world scenarios.

4. Additional performance metrics:
   The performance metrics used in our research gives the behavior of the network from system perspective such as total spam, spam per defined ZoR, and reachability out of total active vehicles. What is missing from our metrics is the impact of protocol performance on individual vehicles. A better instrumentation of the simulator may be a good idea to monitor the impact of the each packet generated and shift the analysis from general over views to per vehicle basis.

5. Better experimentation of the parameter N:
   The parameter N as defined in Section 5.4.1 on page 47 is a complicated parameter. To have a better feeling and understanding on N a further study could be on making N dynamic depending on the network density and other channel characteristics. Assuming the EV will anyways have a partial view of the network (from above described beacon exchange), it could be possible to estimate the channel condition and network density.

6. Impact of Message contents on Mobility:
   In our research we modeled the mobility and protocol independent. In fact from the nature of the BlueWave application the information contained in the message affects the mobility (though not deterministic). A big research as an extension of our work could be to study the impact of information content (such as turn right if translate to application language) on the performance of the protocol. It is worth to note that designing the human behavior under such situations could never give us the exact model. However, it may help to study how the protocol performs on specific occasions. In fact the mobility model used (IDM) as descried in [93] is not calibrated to the real behavior of drivers and hence seek further research.

Appendix A

Appendix

A.1 History of WAVE

After the united states congress mandated creation of ITS program at the beginning of 1990's, the US Department Of Transport (DOT) in collaboration with Intelligent Transportation Society of America(ITSA) and other parties had developed a new framework. They called this frame work as National Intelligent Transport Systems Architecture (NITSA). Its main objective was to plan, develop, and integrate different ITS services[87]. For several applications of the NITS such as electronic toll collection, wireless technology become the core component. However, these services were using very narrow bands which are prone to interference. This limitation forced ITSA to request a new licensed 75MHz bandwidth channel at around 5.9GHz. The request was accepted by Federal Communications Commission (FCC) and the spectrum between 5.85 and 5.925GHz was allocated for ITS based radio services. Though late, The EU(European Union) Commission also decided to have a single radio frequency band for vehicle communication systems across Europe (5.9 GHz) [1]. In the mean time, the ITSA proposed a single standard for PHY and MAC layers which later was developed by ASTM(American Society of Testing and Materials) i.e. ASTM's E2213-02[2]. This standard was adopted by FCC in 2004. At the same time the IEEE 802.11 work group determined the importance of having vehicular version of WiFi and amended 802.11p on the bases of ASTM's E2213-02. In order to have a complete vehicular frame, a separate IEEE work group drafted the 1609.x series. This additional draft deal with security, multichannel usage, resource management and network services. The combined use of IEEE802.11p and IEEE1609.x give a complete protocol stack for vehicular communication known as WAVE(Wireless Access for Vehicular Environment)stack [87] [30].

A.2 IEEE 1609.series

Multichannel Operation–IEEE 1609.4

The WAVE system in general is expected to support architectures with multi channel operations. The IEEE 1609.4 standard presents the services for channel coordination, enhancement of IEEE 802.11 MAC, and MAC Service Data Unit (MDSU) delivery. Four services are described in the standard: (1) Channel routing is a service used to identify IP and non-IP (WSMP) data transfer from LLC to MAC layer. WSMP header contains the channel, power level, and data rate associated with the data packet as specified in IEEE 1609.3. The MAC puts to corresponding buffer (queue) if the WSMP has a valid channel number otherwise it is discarded. Similarly in IP routing, the MAC puts packets to data buffer if the transmitter profile is registered at MAC sub-Layer Management Entity (MLME), otherwise it is discarded; (2) User Priority service is introduced to differentiate between differen classes of application as in IEEE 802.11e. WSMP data uses control priority of EDCH function in the CCH and IP data use service priority version of EDCH function in SCHs; (3) Channel coordination service is enhancement of 802.11 MAC and interacts with the LLC and IEEE P802.11p PHY; (4) MSDU data transfer service includes three services namely, control channel data transfer service, source channel data transfer service and data transfer services. The over all aim of these MSDU services is to give high priority to WSMP data frames.

Information exchange in WAVE can be of two types: management frames and data frames. In IEEE 1609.4 management frames exchange are defined as WAVE announcement frames and use only the CCH. Data frames can be WSMP which ar allowed to use both CCH and SCHs or IP data which are restricted to less prioritized SCHs usage. All WAVE devices use a predetermined set of EDCH parameters when accessing the CCH. On the other hand, EDCH parameters are announced with WAVE announcement frame from provider and are used by receivers for service channel priority.

Network Services–IEEE 1609.3

The IEEE 1609.3 represents three layers of OSI model, LLC, Network layer, transport layer, collectively known as WAVE network services. The network services an be functionally divided in to data plane, dedicated to carry data traffic, and control (management) plane services, responsible for system maintenance and configurations.

The data plane protocol stack of WAVE network services contains LLC layer which works according to IEEE 802.2, Sub-Network Access Protocol (SNAP) as specified in IEEE 802 and IP transmission as specified in IETF RFC 793. The upper layers include IPv6 as specified in RFC 2460, UDP of RFC 768 and TCP as defined in RFC 793. The architecture supports traditional IPv6 data which are less prioritized and WSMP frames which has higher priority. The WSMP implementation includes message forwarding with two primitives. When WSM request is received, the WSMP checks the length if it is valid it passes to to LLC. On the other hand, when WSM received message is received, WSMP passes it to destination application.

The management plane of WAVE network services collectively called WSME(WAVE Short Message Entity) contains several services and functions. (1) Application registration: Every WAVE device willing to use network services has to register in WME. The applications are also registered with unique provider service identifier (PSID). Three tables are used to register required information namely: provider service information table, user service provider table table and application status table (may include port and IP numbers of applications). (2) WBSS Management: This is responsible for the initiation of WBSS on the behalf of any application. The operation includes link establishment, manipulating applications in WBSS, termination of WBSS and application status maintenance. (3) Channel usage monitoring: The monitoring of the channels enables service data to chose the least congested SCH. The standard IEEE 1609.3 actually doesn't tell how to do this operation. (4) IPv6 Configuration: IPv6 configurations includes managing local, global links and multicasting. (5)RCPI Configuration: Received Channel Power Indicator (RCPI) is a query sent by WME on behalf of application to know the status of received signal. (6) MIB maintenance: Maintenance Information Base(MIB) includes system-related infirmations (such as network infirmations, address information, registration port, forwarding port, WSM maximum size) and application related information including provider service information, user service information, application status and channel information.

Security Services–IEEE 1609.2

The WAVE application has wide range of operations which makes security provision too difficult. The car 2 car network can have large size as long as the raod extends and to even primary security features such a authentication to big number of users doesn't scale. In addition, the applications are delay sensitive and current PKI(Public Key Infrastructure) based security functionalities are in doubt. The security as a whole remains as a generic problem, still the IEEE 1609.3 defines basic security infrastructures for WAVE devices. The document describes the use of symmetric algorithms, asymmetric algorithms, hash functions and provision of anonymity.

Resource Management–IEEE 1609.1
Resource Management(RM) of WAVE defines the nature and behavior of WAVE applications. Its main purpose is to give applications access to system resources and can be located in either RSU or OBU. The RM accepts requests from RMAs(RM applications)to access some services receive the response of service providers. The commands needed for the operation by RM are executed by as software in OBU called RCP(Resource Command Processor). The RMA controlled resources can be memory write/read, user interface as part of ONBU, special interface to the OBU, optional vehicular security devices connected to OBU and so on.

A.3 VANET's Research Overview

The overall research on vehicular networking can be seen in four big blocks:-

1. MAC and PHY layers related
2. Data dissemination in VANETs
3. Mobility & Simulation packages
4. Security & privacy issues

The MAC and PHY related issues are deeply studied as they are derived from the already accepted and stable WiFi protocols. However, there are still many open issues such as medium access mechanism, which currently is contention based. Therefore, it doesn't guarantee delay bound for critical applications. Security and privacy are important factors in any communication network. After all, users need some protection from external attackers or privacy right violations. Otherwise, the acceptance of the technology in the public will die and may hinder its further development. The use of traditional authentication methods based on PKI(Public Key Infrastructure) introduce extra delay which may not be tolerable in safety applications. In addition, broadcast nature of applications seeks anonymity protection, which complicates the security provision [65] [87].

Simulation and mobility model is another challenging aspect of VANTEs. Mobility or traffic flow models in general are classified in three categories [85] [51]: *Macroscopic, Meso-scopic, and Microscopic. Macroscopic* models consider over all system level flow behaviors similar to fluid dynamics. METACOR, Gas Kinetic and Fluid dynamics models are some of the examples in this part. *Meso-scopic* models such as CONTRAM consider movement of groups of vehicles such as platoon average acceleration or speed. The *Microscopic* is most important for detailed analysis as it involves the behavior of each and every vehicle and related communication parameters. Commonly used *Microscopic* models are cellular automat (CA), IDM/MOBIL, SK model and optimal velocity. Network simulations are widely available as open source such as OMNeT++ and NS-2 or commercial version such as OPNET. They are built based on complete protocol stacks to enable wireless communication between vehicles.

The integration of network and mobility simulators is an important aspect. Bad integration may result in erroneous and unrealistic results. The choice of right mobility model on the other hand, has a great effect on performance of network. Models can be good for specific application or scenario and selecting simplest model is recommended. Complex mobility models may not produce best results [85]. Depending on the way mobility and network models are integrated, VANET simulation packages can be divided in to *open loop* and *closed loop types*. *Closed loop* simulations have predetermined traffic pattern and it will no change throughout the simulation no matter how the communication part behaves [69]. This model is more appropriate for non-safety application such as advertisements. However, if the received message has capability of changing the behavior of vehicle driver, then a *closed loop* type is recommended. In a closed loop the communication network may causes change in mobility pattern, and this changes the topology of the network which in turn changes the communication behavior of the network [69].

A.4 Wireless Broadband Technologies

Wireless Broad band networks are metropolitan area networks supposed to cover the "last mile" of communication systems. The "last mile" is a term used to represent the distribution of networks to end users. The coverage of Wireless broadband networks could reach as wide as big cities connecting different LANs. They are capable of of handling different services such as video, data and voice at high data rates. Their network distribution is cellular in nature in which the base station controls medium access. Some wireless broadband networks are supposed to support highly mobile communications by using seamless handovers. This moving nodes can be vehicles as well, which entitles them to be candidates for vehicular communications. WiMax, IEEE802.16, IEEE802.20 and WiBro are some of the many wireless broadband standsrds/technologies mostly seen in the market.

IEEE802.16 is a metropolitan local areas standard in the range of 10 to 66GHz frequency [30] [citeieee802.16]. Different version have been released for different purposes since its initial launch in 2001. The IEEE802.16e is one version for mobile users and supports both handover and roaming at vehicular speed up to 120Km/hr [30]. On the other hand, WiMax(World-wide inter-operability for Microwave Access) is a forum intended to make IEEE802.16 products inter-operable with eachother [21].

WiBro (Wireless Broadband) is a South Korean broadband standard developed from IEEE802.16e. It uses a dedicated 100MHz bandwidth channel at 2.3GHz targeting data rate as high as 50Mbps at speed of 120Km.h [30]. It uses OFDM with 10MHz wide narrow bands and covers up to 1km radius. The IEEE802.20 on the other hand is another Mobile Broadband Wireless Access (MBWA) standard which is not yet approved [citeieee802.20]. Its mission is to specify an inter-operable physical and MAC layer on the licensed bands of 3.5GHz or less, with optimized IP based transport. It also supports media independent handovers on IEEE 802 family networks and cellular 3G, 2G. Different categories of vehicles up to 250 Km/hr will be supported in metropolitan area networks with better data rates than the existing systems [22].

Wireless Broadband technologies have a deterministic access scheme,i.e. the medium access is controlled by central station and who to access the medium is deterministic. This introduces an extra end to end delay as nodes can't communicate directly, and make it challenging to be applied for time critical vehicular applications. It also requires nodes to be within the coverage of base station, which is not always possible in vehicular environment. For example, an emergency message from non covered area need hop by hop transmission using vehicles around it. Therefore, wireless broadband technologies have a big challenges ahead to support vehicular networks and create ubiquitous communication, safe and robust networks. However, in the C2CCC architecture, wireless broadband technologies have a role on infrastructure to vehicle part of the communication [18].

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