Assessing Mission-critical Vehicular Safety Applications under Various Network Conditions

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Enabling communication among vehicles can facilitate the deployment of safety applications that can improve driving safety and reduce traffic-related fatalities. Assessing the reliability of these safety applications is essential to evaluating VANETs' contributions to improved safety and driving conditions. In this context, I maintain that reliability metrics that express the requirements of safety applications in terms of network performance are much more suitable than standalone network-level metrics, as the latter do not indicate whether the requirements of safety applications can be met. This work considers awareness as an intermediate layer between the application and the network layers, for identifying the different levels of reliability achievable by the different safety applications. Through a comprehensive simulation study, this work analyzes the level of awareness that networks can offer under various scenarios and a wide range of influencing parameters, including transmission power, message generation rate, vehicular density, message size, as well as radio propagation and fading effects. Insights are provided on how network performance metrics address application requirements and contribute to enhancing the reliability of safety applications. Finally, communication parameters necessary to offering high levels of reliability are determined for three representative safety-application requirements.

Acknowledgements

My thanks and praise go to Allah for giving me the ability and knowledge to accomplish this work.

I am grateful to my supervisor, Professor Otman Basir, who offered me the opportunity to be a graduate student at the University of Waterloo and gave me the guidance and inspiration to start this thesis.

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Dedication

To my parents, whom sacrificial care and support made it possible for me to reach this level of education.

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Chapter 1

Introduction

Vehicular safety has been an issue since the inception of automotive industry. Over the years, studies were conducted, technologies were introduced, and regulations were set aiming at minimizing the occurrence and consequences of vehicle accidents. Advances in wireless technologies and the automotive industry, along with the high demand for further improvements in driving safety, have led to the emergence of a novel class of wireless networks referred to as Vehicular Ad Hoc Networks (VANETs). Enabling communication among vehicles through VANETs can enable the deployment of safety applications that can improve driving safety and hence reduce traffic-related fatalities. VANETs' role in improving safety measures and driving conditions remains an open question. As a result, although many safety applications have been developed, none are standardized [45]. Many analytical and empirical studies have been proposed aiming at evaluating the efficiency of VANETs in terms of network performance as well as with respect to application-level performance metrics so as to evaluate the QoS of vehicular safety and non-safety applications. Particularly, reliability metrics must also be considered in evaluating the efficiency of vehicular safety applications.

This chapter discusses the motivation behind this research work and presents the scope of the work conducted by the author in assessing the reliability of safety applications under various network conditions. The chapter is concluded by a brief summary of the thesis organization.

1.1 Motivation

Improving the quality of transportation systems has motivated the launch of several research projects aimed at solving the challenges associated with safety as well as with traffic efficiency and so leading to better driving conditions in the future. Due to their high potential to meeting the requirements of future Intelligent Transportation systems (ITSs), VANETs are receiving considerable attention from many researchers, focused on resolving all the issues that prevent deployment of this technology.

Assessing the contribution of VANETs to improved safety and driving conditions remains a challenging task. Consequently, many of the safety applications that have been developed remain non-standardized [45]. Foremost, if fatalities still occur in operational conditions involving vehicular safety applications, then who is responsible?

Aiming at evaluating the efficiency of VANETs in enhancing safety conditions, a multitude of analytical and empirical studies have been conducted. Most of these studies evaluate the performance of VANETs in terms of network performance metrics. Even though network-level performance metrics are essential to understanding the behavior of VANETs, reliability metrics must also be considered in evaluating the efficiency of vehicular safety applications. In fact, performance requirements are typically expressed in terms of application-level metrics rather than network-level ones; however, the former directly relies on the latter. Based on this fact, an interrelationship between the layers can be established in a form that is influenced by network conditions and understood by the application layer. Using the definition of awareness as an intermediate step between application and network layers, the main motivation behind this thesis is to identify different levels of reliability that can be offered to safety applications, based on the level of awareness that networks can offer under various operational conditions, including transmission power, message generation rate, vehicular density, message size, as well as radio propagation and fading effects.

1.2 Scope of the Research

To determine different levels of reliability that can be offered to safety applications under various network conditions, the author has identified the following goals:

1. Demonstrate the relationship between awareness probability and PDR to establish an interrelationship between the network and application layers.

2. Analyze the impact of various network conditions on PDR using a comprehensive simulation study that involves different scenarios and some of the main influencing factors.

3. Investigate the impact of network performance on mutual awareness and consequently on safety applications' performance.

4. Provide insight on how network performance metrics address application requirements and enhance safety application reliability.

5. Conduct a study that examines the reliability of three representative safety-applications requirements to try to identify the communication parameters necessary for these applications to run efficiently.

1.3 Thesis Organization

This thesis is composed of five chapters: Chapter 1 is an introduction.

Chapter 2 briefly reviews the main topics relevant to this thesis, starting with an overview of Vehicular Ad Hoc Networks (VANETs) as a candidate solution for the issues of vehicular safety, then providing details on the challenges and the standards of VANETs, and finally, presenting details of other research projects that have contributed to the development of many safety applications. A summary of related work is presented at the end of Chapter 2.

Chapter 3 presents a methodology designed to assess the reliability of mission-critical safety applications using the level of awareness that networks can offer under various operational conditions. The first section of this chapter provides a description of the problem of safety assessment in VANETs that motivated the research conducted in this thesis, followed by some of the main concepts and definitions of the reliability metrics employed to assess the efficiency of safety applications. Then the methodology and steps needed to assess the reliability of safety applications using awareness metrics are described. The simulation framework and the different models used in simulating VANETs are presented last.

Chapter 4 describes the simulation experiments conducted to assess the reliability of safety applications under various network conditions and following the methodology described in Chapter 3.

Chapter 5 summarizes the research conducted for this thesis. A discussion on the work, along with conclusions and suggestions for future study are also provided.

Chapter 2

Background and Literature Review

2.1 Introduction

This chapter presents a brief background review on the main relative topics to this thesis starting with an overview of Vehicular Ad Hoc Networks (VANETs) as a candidate solution for the issues of vehicular safety, then providing details on the challenges and the standards of VANETs, and finally presenting some of the research projects that contributed to the development of many safety applications. A summary of related work is presented at the end.

2.2 Vehicular Safety and the Emergence of VANETs

Vehicular safety has been an issue since the early stages of the automotive industry. Over the years, studies were conducted, devices were developed, and regulations were set aiming at minimizing the occurrence and consequences of vehicle accidents. Improvements introduced to roadways and vehicle designs have significantly reduced injury and death rates. Nevertheless, collisions among moving vehicles dominate all causes of traffic injuries, fatalities, and property damage, with a total estimation of 1.2 million deaths in 2004, or 25% of the total cases [64]. According to data from the U.S. National Highway Transportation Safety Administration (NHTSA), in spite of the fact that approximately 5.3 million vehicle crashes in the US caused about 32000 casualties in 2011, these figures continue to drop with safety rules such those mandating safety belts and airbags. Fig. 2.1 demonstrates the improvement of driving condition safety over the years [61].

Aiming at introducing further improvements to driving safety and hence reducing traffic-related casualties, the United States Department of Transportation (USDOT) intends to push for regulations that mandate equipping vehicles with wireless technologies [62] so as to enable communication and cooperation among vehicles. Enabling such vehicle-to-vehicle (V2V) communication will pave the way for the deployment of safety applications that can significantly improve driving safety by preventing vehicle collisions. According to estimations by the USDOT, enabling communication between networks can address up to 82% of all crashes in the United States, potentially saving thousands of lives and billions

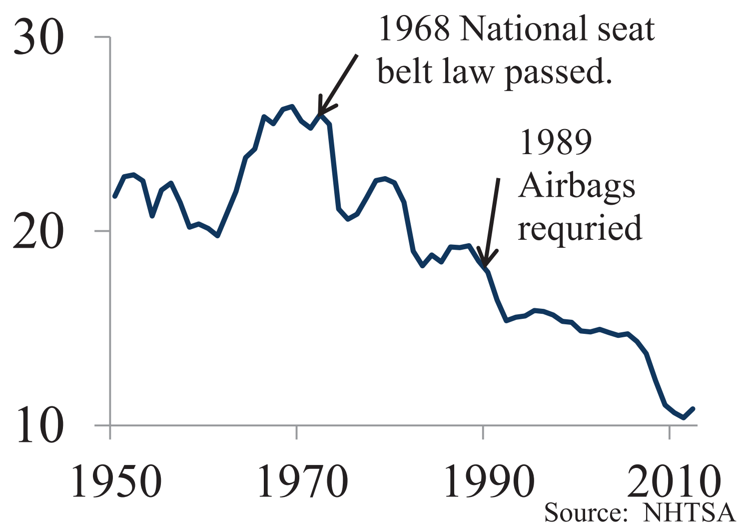

Figure 2.1: Total U.S. motor vehicle fatalities per 100,000 population, 1950-2012

of dollars [45].

2.3 Vehicular Ad Hoc Networks

The following subsections provide an overview of Vehicular Ad Hoc Networks (VANETs):

2.3.1 VANET Definition and Architecture

Advances in wireless technologies and the automotive industry along with the high demand for further improvements in driving safety have led to the emergence of a novel class of wireless networks referred to as Vehicular Ad Hoc Networks (VANETs). As their name implies, VANETs are formed between moving vehicles that are equipped with short-range wireless interfaces allowing for the exchange of data at high transfer rates and low data delivery latency. These networks provide the foundation of a wide range of communication services that can benefit drivers as well as passengers.

Motivated by their high potential, research on VANETs is receiving considerable attention from academia and industry, aiming at resolving all the issues that prevent the deployment of this technology in reality. To enable the communication between vehicles and their surroundings, two types of devices have been defined: the OnBoard Unit (OBU) and the RoadSide Unit (RSU). The former is embedded in vehicles in order to equip them with communication capabilities, whereas the latter provides fixed infrastructure that can support vehicles by connecting them to local and global services. Based on these two devices, three alternatives for VANET-deployment architectures have been proposed:

- Vehicle-to-Vehicle (V2V) architecture: This decentralized architecture allows the exchange of messages among vehicles in ad hoc manner, with no support from any sort of infrastructure. At this level, information is exchanged and decisions are made on a local basis (i.e., among a group of vehicles in proximity to one another).

- Vehicle-to-Infrastructure (V2I) architecture: In this communication mode, RSUs, which are deployed to cover wide areas, play a coordination role by providing suggestions or imposing certain driving behaviors on groups of vehicles according to information gathered about local and global traffic as well as about road conditions.

- Hybrid vehicle-to-road (V2R) architecture: In V2R, vehicles do not rely on fixed infrastructure in a constant manner; however, when such infrastructure is available they can exploit it to improve performance. In other words, the hybrid architecture combines the first two architectures, V2V and V2I, and hence it provides flexibility and robustness in the operation of VANETs.

  The trends for VANETs architecture is heading towards the adoption of vehicle-to-everything communications, also known as, V2X. In this communication paradigm, vehicles can communicate directly with other vehicles, traffic lights, toll gates, and even pedestrians. Furthermore, vehicles can interact with infrastructures that can be dedicated RSUs, public or private hot spots (Wi-Fi hot spots), or even cellular radio networks (GSM, GPRS, UMTS, WiMAX, and 4G). The future architecture envisioned for VANETs is illustrated in Fig. 2.2.

2.3.2 Potential Applications and Services

VANETs comprise a promising technology that can enable a broad spectrum of applications and services which can benefit both drivers and passengers. Based on user-benefit perspective, the potential applications of VANETs can be divided into three categories [23]:

- Active Road Safety Applications:

  These applications are designed to minimize traffic accidents and their consequences

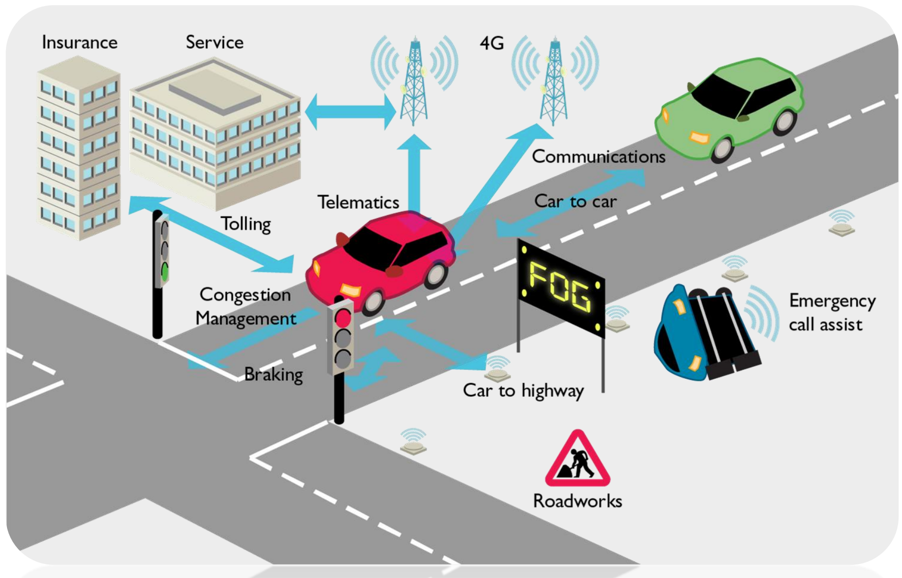

Figure 2.2: VANET architecture

and fatalities, thus improving driving safety. To deliver their services, active road safety applications exchange valuable information between vehicles in order to create awareness about various situations and threats on roadways. The prerequisite for building such applications is the connectivity among vehicles as well as between vehicles and infrastructure. By the exchange of important information, safety applications can deliver their services in the form of warnings and alerts to assist drivers in making better decisions or to trigger automatic reactions by vehicles themselves (e.g. automatic braking).

- Traffic Efficiency and Management Applications:

  One of the greatest services that VANETs can offer is the management of traffic flow and the efficient utilization of roadways. Through sharing real-time information about the status of road segments, these applications can coordinate the traffic and update electronic maps and navigation systems and hence reduce the time that drivers spend to reach their destinations. Speed management and co-operative navigation applications are two typical examples under this category of applications. Speed management applications aim at assisting drivers to manage their speed promoting a smooth driving experience with a minimum of unnecessary stops times. Speed limit notifications, and green light optimal speed advisories are two typical features. Co-operative navigation focus on connecting navigation systems with one another to cooperate in selecting optimal trip routes. This cooperation can enhance the utilization of roadways by avoiding the overloading of certain paths while other paths are under used. Co-operative adaptive cruise control and platooning are common examples.

- Infotainment Applications:

  Infotainment applications provide drivers with several ad-on services that can help them improve their productivity by granting them access to remote information. These applications can allow passengers and drivers to access luxury services such as Internet access from inside vehicles. Infotainment applications can be delivered locally or globally [23]. Co-operative Local applications offer entertainment through locally based services such as the broadcast of points of interests (e.g. hotels and restaurants nearby), local media downloading, and local commercial advertisements.

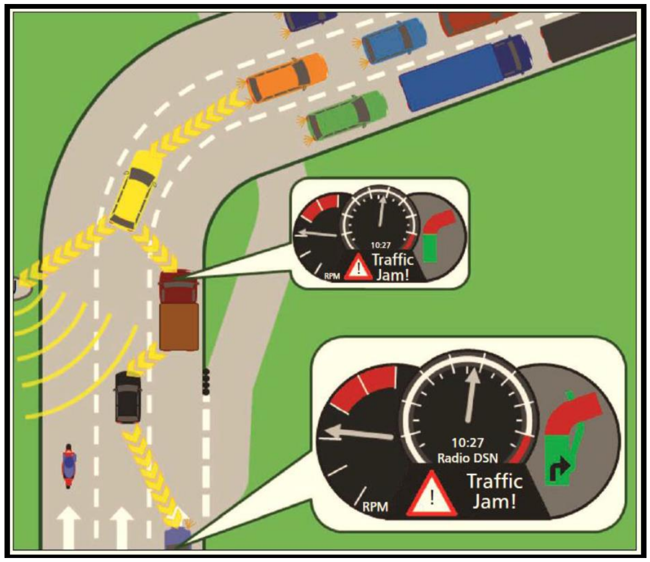

Figure 2.3: By vehicle-to-vehicle and vehicle-to-roadside communication, accidents can be avoided (e.g., by not colliding with a traffic jam) and traffic efficiency can be increased (e.g., by taking alternative routes) [41]

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Global Internet applications deliver services that rely on the connectivity to the global internet. As a matter of fact, connecting vehicles to the internet can enable enormous number of applications and services. Typical services include fleet and parking zone management, financial and insurance services, and vehicles life cycle management such as software updates and online service bookings.

Fig. 2.3 illustrates some benefits of VANETs applications.

2.3.3 Special Characteristics of Vehicular Networks

Vehicular Networks have unique features that distinguish them from other types of mobile networks. Some of these features are attractive as they alleviate the traditional design challenges of mobile networks. However, some other features introduce more challenges that need to be overcome to enable the deployment of VANETs. In the following, some of these features are discussed:

- **Unlimited Transmission Power:**

  Limited power supply of mobile terminals is a traditional problem that always existed and impacted the design of mobile networks. Due to the fact that mobile nodes in VANETs are vehicles, they can afford unlimited power supply during their operation time.

- **Higher Computational Capabilities:**

  Advancements in the development of embedded systems along with the ability of vehicles to provide continuous power supply can enable a great deal of features including sensing, computation, and communication capabilities.

- **Predictable mobility:**

  In contrast to classic mobile networks, where predicting the future positions of mobile nodes is difficult as they move randomly in all directions without any bounds . Mobile nodes in VANETs (i.e., vehicles) are restricted to move in roadways and in certain directions. Given this fact, the mobility of vehicles can be predicted and hence their location in the near future can be estimated upon the availability of information that describes road trajectories and vehicular movement patterns. While road trajectories can be obtained from digital maps and positioning systems, information that describe the movement of vehicles can be extracted from speed, direction, and acceleration. Possessing such knowledge about the mobility patterns of vehicles can be exploited to significantly improve the performance of vehicular networks.

- **Potentially Large Scale Networks:**

  Unlike classic wireless networks which have limited network size, VANETs can expand to span the entire road network. In such large networks, the number of participating nodes can be massive which makes the task of network management costly and complicated.

- **High Mobility:**

  Vehicles operate in highly dynamic environments that can expose them to extreme configurations. For instance, in non-busy scenarios, vehicles operating on highways can reach relative speeds of up to 300km/h [58] in a surrounding density of vehicles that can be as low as 1-2 vehicles per 1km. On the other hand, relative speeds in urban areas can reach up to 60km/h in a surrounding density of vehicles that can be very high, particularly in rush hours. To address such extreme configurations, efforts are needed to design networks that can maintain acceptable performance in all environments.

- **Connectivity and Network topology:**

  Because of the fact that vehicles are highly mobile nodes, their position change constantly leading to fragmentation in network connectivity. Such network partitioning might happen very often especially in sparsely populated scenarios of VANETs where large inter-vehicle gaps can lead to intermittent connectivity creating high dynamic network topologies. The degree to which the network is connected is highly dependent on the range of wireless communication as well as on the penetration rate. The latter is the percentage of vehicles that are equipped with communication capabilities.

2.3.4 General Requirements

According to specifications set by the European Telecommunications Standard Institute (ETSI) in [18], the general requirements to enable the deployment of VANETs can be classified as follows:

- **Strategic Requirements:**

  These requirements are related to setting the right plans of the deployment of VANETs. An example of these requirements is the minimum penetration rate needed to establish networks among vehicles. As a matter of fact, such requirements often need the involvement of high authorities like governments and standardization bodies to enforce policies and strategies so as to help increasing the penetration rate and meet the minimum connectivity requirements.

- **Economic Requirements:**

  These requirements are related to financial issues such as the estimation of the deployment cost and the revenue that will be generated if VANETs are successfully deployed. In addition, specific requirements need to be determined to ensure that services can be offered to users with reasonable prices so as to encourage the embrace of this technology.

- **System Capabilities Requirements:**

  To enable reliable services and applications over VANETs, several technical requirements need to be addressed. Some of these are presented in the following:

  1. Radio Communication Capabilities:

     Essentially, there is a demand for a standard that allocates dedicated frequency spectrum to be used by VANETs. Furthermore, such a standard, need to define different channels and dictate the way these channels can be utilized. Additionally, for vehicles to be capable of communicating with their surroundings, they must be equipped with smart terminals embedded with special antennas and transceivers.

  2. Network Communication Capabilities :

     To enable the sharing of information among vehicles, different data dissemination techniques need to be defined. Some of the proposed techniques include unicast, multicast, broadcast, and geocast. Furthermore, successful deployment of VANETs require advanced techniques for network management such as data aggregation, congestion control, prioritizing application messages and mobility management.

3. Vehicles Positioning Capabilities:

   In fact, accurate positioning systems are considered as one of the essential building blocks of VANETs. Obviously, Global Positioning System (GPS) is dominating as it is widely adopted in almost all VANETs architectures. In addition, other alternatives of positioning systems including the Global Navigation Satellite System (GNSS) can also be potential candidates.

4. Vehicle Communication Security Capabilities:

   Security and privacy are considered as the biggest challenge in VANETs due to the fact that vehicles are required constantly to participate in connecting other unknown nodes to route their traffic. Therefore, advanced security techniques are highly needed to address data integrity, confidentiality, authenticity of received data as well as the respect of privacy and anonymity.

- **System Performance Requirements:**

  In order to allow for the evaluation of VANETs performance so as to further improve them, different metrics and measures need to be defined. Essential metrics include those which are needed to evaluate the performance of the connectivity in VANETs such as the maximum latency time and the rate at which information is updated. Another important metrics are those needed to measure the accuracy of positioning systems. Furthermore, additional metrics are required to assess the system reliability in terms of radio coverage, bit error rates, and the ability of the system to cope with security threats.

- **Standardization and Certification Requirements:**

  Standards and Common Policies are highly demanded as many industry players from different fields are involved in the development process of VANETs. Standardization activities are required in order to maximize compatibility, interoperability, safety, and the quality of designed solutions.

2.4 DSRC Standards and Operations

To meet the general requirements presented in the previous section and to allow for the deployment of VANETs, a great deal of research work has been conducted by various research groups and standardization bodies. These efforts resulted in the development of the Dedicated Short-Range Communication (DSRC) [45]. The word Dedicated in DSRC refers to the fact that the US Federal Communications Commission (FCC) has allocated 75MHz of licensed spectrum in the 5.9GHz band for short-range communications to support wireless communication within VANETs [31] [32]. The DSRC spectrum is divided into seven channels [45], among these channels one is defined as a Control Channel (CH) and is designated for safety applications, while the rest of the six channels are defined as Service Channels (SCH). For illustration, Fig. 2.4 presents the DSRC band plan channel designations.

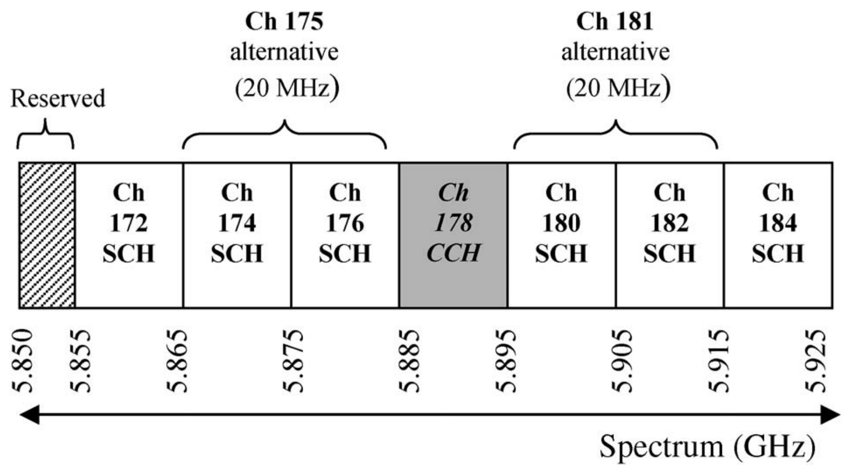

Figure 2.4: United States DSRC Band Plan channel designations. Reproduced from [45]

The DSRC protocol stack is depicted in Fig. 2.5 and illustrates the protocols and standards that will serve in each layer including: IEEE 802.11p [12], IEEE 1609/WAVE [15] [16][13][11][17], and SAE J2735 Message Set Dictionary [9].

At the bottom of the stack, in PHY and MAC layers, DSRC employs IEEE 802.11p which is a modified version of the well-known IEEE 802.11 (WiFi) standard. The modifications incorporated to the new standard reduce the overhead so that it can meet the stringent communication requirements over fast moving vehicles. Unlike IEEE 802.11 where every node need to be a member of a Basic Service Set (BSS) so it can communicate with others, the enhancements introduced to IEEE 802.11p allows nodes to operate out of the context of a BSS. Therefore, defining new techniques for establishing the connectivity

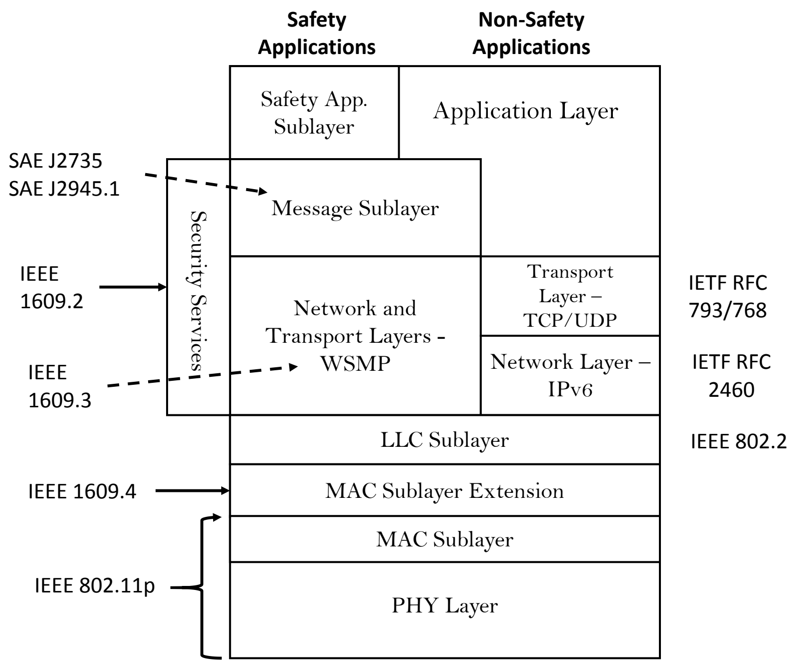

Figure 2.5: Layered architecture for DSRC communication in the US. Reproduced from [45]

among participating nodes [45].

At the physical layer, Orthogonal Frequency Division Multiplexing (OFDM) at 10MHz channel bandwidth is utilized to enable DSRC from reaching data rates between 3 to 127 Mbps [45]. The achievable data rates vary according to the modulation technique used on the subcarrier, as well as according to whether Forward Error Detection (FEC) coding is applied to the user bits which can reduce the effective user bit rate. Though this can improve the probability of successful decoding [45].

According to the specifications of IEEE 802.11, a number of combinations of modulation rate and FEC coding rate can be employed. However, most of the testing projects of DSRC in the US has employed the 6Mbps configuration (i.e., Quadratic PSK with rate 1/2 coding). This can be attributed to the fact that this option provides balance between the signal-to-noise requirements and the load of the channel [43]. According to [71], although IEEE 802.11 is suitable for broadcasting (i.e., beaconcasting) as it supports the transmission of safety beacons using Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA), this protocol can suffer from large delays when used for unicasting in VANETs. The reason behind this observation can be attributed to the fact that CSMA/CA sense the channel before transmitting to ensure that no collision will occur; however, it can not prevent all such collisions from occurring especially under the effect of hidden nodes [47]. This eventually leads to multiple retransmissions that are assigned with large back-off sending times.

On top of the IEEE 802.11 MAC and PHY layers, the middle layers of the DSRC stack utilize a collection of standards defined by the IEEE 1609/WAVE working group. The specified suite of standards include the IEEE 1609.3 which defines network-related services and components such as the WAVE Management Entity (WME) and the WAVE Short Message Protocol (WSMP) which is designed to be bandwidth-efficient so it can handle non-IP traffic, in particular the traffic generated by applications that are limited to single-hop communications and does not involve routing (e.g., safety applications). In parallel to the WSMP, DSRC also adopts well-known Internet protocols for the network and transport layers. Utilizing such protocols enables routing capabilities and hence supports applications that require multi-hop communications. To support coordination between channels in DSRC, the IEEE 1609 working group developed the IEEE 1609.4 standard which incorporates several enhancements into the IEEE 802.11p MAC layer, and interacts with the IEEE 802.11p LLC and PHY layers. Moreover, IEEE 1609.4 describes multi-channel operations and channel switching for efficient utilization of the radio spectrum dedicated for vehicular communications.

To meet the QoS requirements of mission-critical applications such as safety applications, DSRC addresses packet priority via assigning four different access categories (AC) per channel. According to these categories, messages that have the lowest priority can use AC0 while AC3 is assigned to messages that have the highest priority [45]. In the same fashion as in Wireless Local Area Networks (WLAN), MAC layer in DSRC stack utilizes the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) to maintain separate queues per each access category so as to manage the internal contention for the channel access [34]. In fact, employing the EDCA mechanism in DSRC allows for granting access categories to different channels based on the assignment of different settings of Arbitration Inter-Frame Spacing (AIFS) and Congestion Window (CW) time slots. Fig. 2.6 illustrates the mechanism of EDCA in DSRC standard.

Finally at the top of the DSRC stack, the SAE J2735 Message Set Dictionary standard specifies a set of message formats which support applications that are designed to deliver services over VANETs. Of this message set, the most important message that enables many safety applications is the Basic Safety Message (BSM). BSMs are used by vehicular safety applications to share critical information about the state of vehicles allowing the

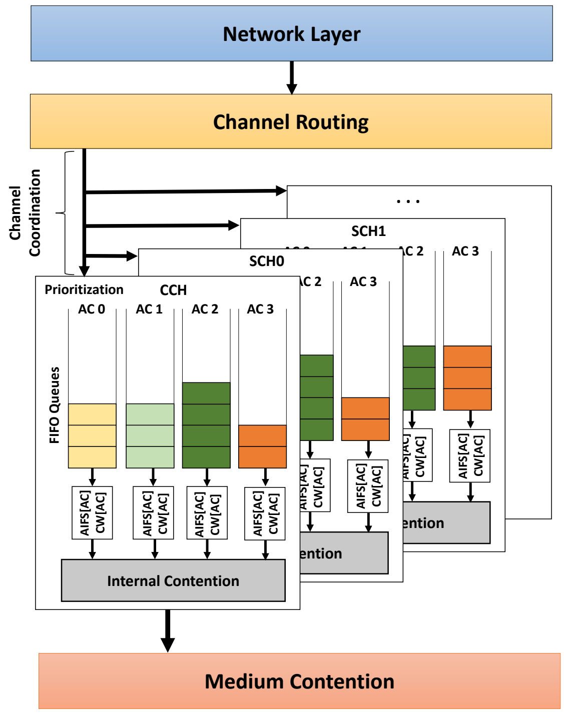

Figure 2.6: Channel prioritization. Reproduced from [28]

cooperation among them aiming at eliminating road accidents. The contents of a BSM can have two parts, the first contains mandatory data elements that provide information such as current position, braking status, motion, speed, and vehicle size. The second part of the BSM message contains optional data elements that provide information such as path history of the moving vehicle as well as path prediction.

2.5 Vehicular Safety Applications

Improving the quality of transportation systems has motivated the launch of several projects aiming at solving the challenges associated with safety as well as with traffic efficiency leading to better driving conditions in the future. Due to its high potential in meeting the requirements of the future Intelligent Transportation system (ITS), VANET has attracted the attention of the research community and is still an active area of research for more than a decade.

Supported by the United States Department of Transportation (USDOT), the Vehicle Safety Communication (VSC) is considered as one of the most important projects that contributed to the development of safety applications. This project which was executed during the period 2002-2004 provided valuable contribution to the standardization of traffic safety applications through a joint-effort by a consortium of seven car manufactures. As a result of this project, 34 safety-related applications and 11 non-safety related potential application scenarios are described with their specifications and requirements. In addition, VSC project addressed some of the communication requirements and offered an insight for the system design as well. The outcome of this project was the derivation of the communication requirements of eight representative safety applications. These applications are described in [70] and presented in the following:

- **Emergency Electronic Brake Lights (EEBL)**, defined as follows: The EEBL application enables a host vehicle (HV) to broadcast a self-generated emergency brake event to surrounding remote vehicle (RVs). Upon receiving such event information, the RV determines the relevance of the event and provides a warning to the driver. This application is particularly useful when the drivers line of sight is obstructed by other vehicles or bad weather conditions (e.g., fog, heavy rain).

- **Forward Collision Warning (FCW)**, defined as follows: The FCW application is intended to warn the driver of the HV in case of an impending rear-end collision with a RV ahead in traffic in the same lane and direction of travel. FCW is intended to help drivers in avoiding or mitigating rear-end vehicle collisions in the forward path of travel.

- **Blind Spot Warning+Lane Change Warning (BSW+LCW)**, defined as follows: The BSW+LCW application is intended to warn the driver of the HV during a lane change attempt if the blind-spot zone into which the HV intends to switch is, or will soon be, occupied by another vehicle traveling in the same direction. Moreover, the application provides advisory information that is intended to inform the driver of the HV that a vehicle in an adjacent lane is positioned in a blind-spot zone of the HV when a lane change is not being attempted.

- **Do Not Pass Warning (DNPW)**, defined as follows: The DNPW application is intended to warn the driver of the HV during a passing maneuver attempt when a slower moving vehicle, ahead and in the same lane, cannot be safely passed using a passing zone which is occupied by vehicles with the opposite direction of travel. In addition, the application provides advisory information that is intended to inform the driver of the HV that the passing zone is occupied when a vehicle is ahead and in the same lane and a passing maneuver is not being attempted.

- **Intersection Movement Assist (IMA)**, defined as follows: The IMA application is intended to warn the driver of a HV when it is not safe to enter an intersection due to high collision probability with other RVs. Initially, IMA is intended to help drivers avoid or mitigate vehicle collisions at stop-sign controlled and uncontrolled intersections.

- **Control Loss Warning (CLW)**, defined as follows: The CLW application enables a HV to broadcast a self-generated, control, loss event to surrounding RVs. Upon receiving such event information, the RV determines the relevance of the event and provides a warning to the driver.

Additionally, VSC project investigated the potential of different wireless communication technologies including cellular systems and Bluetooth with the main focus on DSRC as it is considered the most promising technology to enable vehicular communications. Building on the first project, the USDOT and the VSC2 consortium continued the research work in another project named Vehicle Safety Communications-Applications or VSC-A for short. The focus of this project was on proving that equipping vehicles with communication capabilities and positioning systems can significantly improve safety on roadways. Another major project was named Safety Pilot Project and was carried out in the period 2011-2013.

This project extended the evaluation work of four selected applications out of the six applications that was identified in the VSC-A project. The four applications investigated in this project are FCW, BSW+LCW, EEBL, and IMA. Safety Pilot Project involved different test cases that aimed at evaluating the benefits of the aforementioned safety applications and their impact on improving driving conditions in terms of safety. In Europe, the major research projects that addressed the V2X communications include the EU FP6 IP project SAFESPOT [14], and the Car-to-Car Communication Consortium (C2C-CC) which involved some of the leading European vehicle manufactures. The efforts of these projects have been included in the ETSI Basic Set of Applications document [18] which describes the use cases of the ETSI TC ITS applications. More than 50 use cases have been presented in this document that address the requirements of V2X communications with considerations for several application categories.

2.6 Related Work

Before presenting the progress of the research in evaluating the performance of VANETs, it is useful to first present some of the important evaluation metrics that are widely in use in literature:

Packet Delivery Ratio (PDR) as in [38] is the probability that all vehicles within the range of a transmitting vehicle, will successfully receive the transmitted packet. Formally, for a vehicle i, the PDR can be calculated as

$$PDR_i = \frac{PR_i}{PT_i}, \tag{2.1}$$

where PR_i is the number of packets sent by i that were successfully received by neighboring vehicles, and PT_i is the total number of packets sent by i.

Packet Reception Ratio (PRR) is defined as the percentage of nodes, out of the receiving nodes being investigated, that can receive packets successfully from the observed transmitting node [38].

Neighborhood Awareness Ratio (NAR), in [33], measures the proportion of vehicles within a time interval and in a certain range from which a message is received successfully. Formally, for vehicle i, range r and time interval t,

$$NAR_{i,r,t} = \frac{ND_{i,r,t}}{NT_{i,r,t}}, \tag{2.2}$$

where $ND_{i,r,t}$ is the number of vehicles within r around i from which i receive a message in t, while $NT_{i,r,t}$ is the total number of vehicles within r around i in t.

Application-level Delay (TD) is defined in [23] as the time duration from the moment at which a packet is generated at the application layer of a transmitting vehicle to the moment at which the first successful packet is received by the application layer of the receiving node.

T-Window Reliability according to [23], is the probability of successfully receiving at least one packet out of multiple packets at distance d from a broadcasting vehicle during a tolerance time window T. Formally,

$$P_{app}(x,T) = 1 - (1 - P_s(d))^{\frac{T}{\tau}}, \tag{2.3}$$

where, τ is the beacon generation interval and $P_s(d)$ is the node reception probability.

Using the aforementioned metrics and others, in-depth studies have been conducted aiming at assessing the performance of the DSRC stack at different layers. In [34][26][48], researchers investigated the performance of the physical layer using common metrics such as throughput and end-to-end delay in order to quantify the quality of service. Vlavianos et al. [73] executed a measurement-based study to evaluate the link quality in IEEE 802.11 networks. In their study, four primary metrics for capturing the quality of a wireless link were used. These metrics are the Received Signal Strength Indicator (RSSI), Signal-to-Interference-plus-Noise-Ratio (SINR), Packet Delivery Ratio (PDR), and Bit-Error Rate (BER). After completing their experiments, they observed that each metric has its own advantages but also has one or more limitations. In [27], Boban et al. simulated application-level performance by analyzing the impact of accurate channel model selection on throughput, PDR, and latency. For the purpose of evaluating the behavior of beacon message transmission in the MAC layer, analytic models have been proposed in [50][72][25]. For instance, in [50], Ma, using a Poisson arrivals, approximated the periodic generation of beacon messages. However, all of these models suffer from inaccuracies. Instead of analytical models, discrete event simulations have also been conducted in [35][75][69], for the sake of assessing the performance of beacon-message dissemination in the DSRC system. In one study, Noori et al., in [63], utilized simulation models to study the probability of beacon delivery in urban scenarios with different road types. In their study, the authors demonstrated the impact of increasing vehicle density on the successful delivery of beacon messages. Furthermore, Mittag et al., in [57], also relied on simulation studies to compare the broadcasting performance of single hop communication mode versus that of multi-hop. The study showed a comparable performance between the two modes, as concluded that only limited benefits can be achieved by using the multi-hop instead of the simple single hop mode. In another research, the impact of controllable parameters such as modulation schemes and transmission power on the performance of IEEE 802.11p radios is studied by Bai et al. in [24]. They also studied the impact of uncontrollable factors such as distance, environment, and velocity of communicating vehicles. In the research work conducted in [52], Martelli et al. studied the Packet Inter-reception Time (PIT) and analyzed its correlation with PDR and other environment parameters through an extensive measurement campaign based on IEEE 802.11p technology. Their study shows, first, that PIR and PDR are loosely correlated, and second, that PIR does not depend on the speed of vehicles nor on the distance between them. Moreover, Martelli et al. demonstrate that PIR follows a power-law distribution that results in the occurrence of periodic durations with long-lasting outages, a situation that can severely degrade awareness among vehicles.

Even though MAC and network-level performance metrics play an imperative role in clarifying the behavior of VANETs, it is also essential to consider application-level performance metrics so as to evaluate the QoS of vehicular safety and non-safety applications. In [23][21][49], studies have been conducted to specify the requirements of application performance by characterizing application metrics. Bai et al., in [22], analyzed the link-level behavior of V2V communication under the impact of different traffic environments. Based on realistic experimental data, they could characterize application-level reliability of the DSRC for vehicle safety communication. Furthermore, Bai et al., in [23], defined the Region of Interest (RoI) of VANET applications in terms of three qualitative categories: long, medium and short. In addition, the authors presented the application-level latency and the T-window Reliability (TWR), as two application-level metrics that can be used to evaluate the performance of VANETs. Focusing on congestion-control policies, Sepulcre et al., in [68], employed the application reliability metric of [22] along with application requirements (necessary warning distance) calculated based on vehicles kinematics, to address the communication trade-off between meeting application requirements and preventing channel congestion.

To conclude this chapter, a multitude of analytical and empirical studies were proposed to evaluate the efficiency of VANETs. In fact, performance requirements are typically expressed in terms of application-level metrics rather than network-level metrics; however, the former directly relies on the latter. According to this dependency, this work attempt to use reliability metrics that provide a link between the requirements of application layer and the performance of the network layer. Such metrics are presented in the next chapter in a form that is influenced by network conditions and that can be understood by application layer.

Chapter 3

Assessing the Effectiveness of Mission-critical VANET Safety Applications under Various Network Conditions

3.1 Introduction

This chapter presents a methodology that was designed to assess the reliability of mission-critical safety applications using the level of awareness that networks can offer under various operational conditions. The rest of this chapter is organized as follows: The first section provides a description of the problem of safety assessment in VANETs which motivated the research conducted in this thesis, followed by the presentation of some of the main concepts and the definitions of the reliability metrics that are employed in this work to assess the efficiency of safety applications. Then a description of the methodology and the steps needed to assess the reliability of safety applications using awareness metrics are provided. The simulation framework and the different models used in simulating VANETs are presented last.

3.2 Assessing the Reliability of Safety Applications

VANETs' role in improving safety measures and driving conditions remains difficult to assess. As a result, although many safety applications have been developed, none are standardized [45]. Foremost, if fatalities still occur in operational conditions involving vehicular safety applications, then who is responsible?

To evaluate VANETs' contribution to improved safety and driving conditions, researchers must be able to assess the reliability and efficiency of vehicular safety applications. Chapter 2 presented a multitude of analytical and empirical studies that aimed at evaluating the efficiency of VANETs in terms of network performance. Even though network-level performance metrics are essential to understanding the behavior of VANETs, reliability metrics must also be considered in evaluating the efficiency of vehicular safety applications. In fact, performance requirements are typically expressed in terms of application-level metrics rather than network-level metrics; however, the former directly relies on the latter. This thesis research has been designed to assess the reliability of mission-critical safety applications using the level of awareness that networks can offer under various operational conditions.

For the purpose of this research, awareness is presented as an intermediate step between application and network layers that can facilitate performance evaluation of applications. In this direction, the relationship between awareness probability and PDR is demonstrated so as to establish an interrelationship between the layers. In a further step, the impact of various network conditions on PDR is analyzed using a comprehensive simulation study that involves different scenarios and some of the main influencing factors. Furthermore, this research investigates the impact of network performance on mutual awareness and consequently on safety applications' performance. The obtained results provide insight on how network performance metrics address application requirements and contribute to enhancing the reliability of safety applications. In the end, this study examines the reliability of three representative safety-application requirements (after setting an assumption of their requirements in terms of required packets to be delivered per second). The goal is to try to identify the communication parameters necessary for these applications to run efficiently.

3.3 Beaconing and Mutual Awareness

The basic communication paradigm behind VANETs is the periodic exchange of information via broadcast messages known as Beacons or Basic Safety Messages. Essentially, beaconing mechanisms require each DSRC-equipped vehicle to periodically broadcast information about its status to neighboring vehicles (those located within a single hop distance).

The shared information is embedded inside BSMs and contains the vehicle's ID, location, velocity, and direction of movement. Upon the reception of such information, vehicles can calculate the trajectories of neighbors to compare them with its own trajectory and then evaluate whether any neighboring vehicle poses a safety threat that can cause a collision.

The successful reception of BSMs by all participating vehicles is crucial to gaining mutual awareness among vehicles. Mutual awareness is the foundation of vehicular safety applications, and it can be defined as the ability of vehicles to provide information on their presence, position, direction, as well as to gather information about the state of other vehicles. Fig. 3.1 illustrates how safety applications rely on mutual awareness in detecting potential threats and hazardous situations.

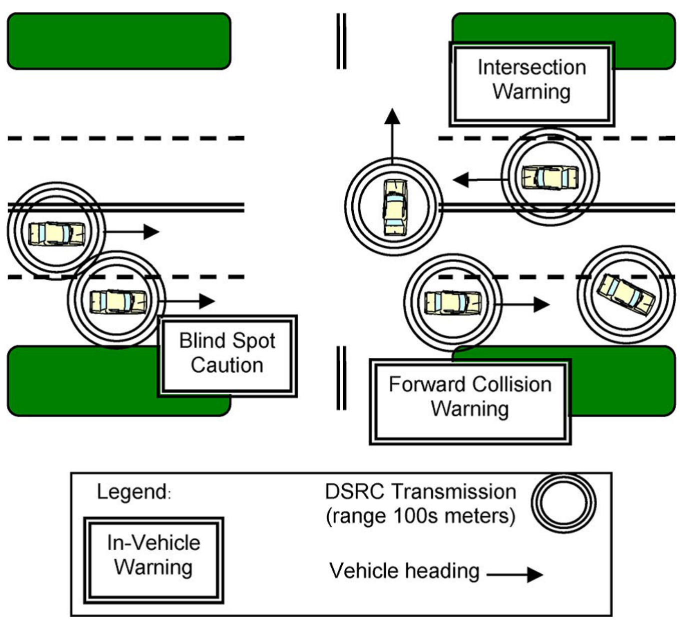

Figure 3.1: Vehicles sending safety messages, displaying in-vehicle warnings [45]

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Table 3.1: Active road safety application requirements

Use Case	Communication Mode	Minimum Transmission Frequency	Critical Latency
Intersection Collision Warning	Periodic message broadcasting	10 Hz	Less than 100 ms
Lane Change Assistance	Co-operation awareness between vehicles	10 Hz	Less than 100 ms
Overtaking Vehicle Warning	Broadcast of overtaking state	10 Hz	Less than 100 ms
Co-operative Forward Collision Warning (CFCW)	Co-operation awareness between vehicles	10 Hz	Less than 100 ms
Emergency Electronic Brake Lights (EEBL)	Time limited periodic messages broadcasting on event	10 Hz	Less than 100 ms
Safety function out of normal condition warning	Time limited periodic messages broadcasting on event	1 Hz	Less than 100 ms
Slow Vehicle Warning	Periodic triggered by vehicle mode	2 Hz	Less than 100 ms
Pre-crash Sensing Warning	Broadcast of pre-crash state in CAM associated with direct vehicle to vehicle communication	10 Hz	Less than 50 ms

Indeed, achieving mutual awareness in VANETs relies on the successful exchange of messages among all vehicles. According to the results obtained in [70] and [18], each safety application requires a different level of network communication performance in order to function reliably. Some of these requirements include the update rate, transmission mode, data to be transmitted or received, and the maximum required transmission range. Table 3.1 presents the requirements of some mission-critical safety applications.

3.4 The Relationship Between PDR and Awareness

This section demonstrates awareness as a metric that can be used to evaluate the reliability of VANETs. As stated earlier, awareness can be used to establish an understanding of how application reliability depends on network performance. For the purpose of this research, awareness is defined in a form that is influenced by network conditions and understood by application layer. The following sections present the definition of awareness using two relations that are dependent on network conditions: Probability of Awareness and Awareness Range.

3.4.1 Probability of Awareness

If safety applications are optimized to achieve mutual awareness by receiving updates at a certain rate such as 10Hz (i.e., an update rate of 10 beacons per second) as presented in Table 3.1, the Probability of Awareness can be defined as a probability of successfully receiving at least n beacons in the tolerance time window T. This definition is derived from [22] and is similar to the neighborhood awareness, defined in [56]. Using PDR (which indicates network performance), Awareness Probability (PA) evaluates the possibility of receiving n out of k beacons in a given time window and provides a means of measuring the effectiveness of vehicular safety applications. Formally, awareness probability can be expressed in a binomial probability formula, as given in 3.1:

$$P_A(n, k, PDR) = \sum_{n}^{k} \begin{pmatrix} k \\ n \end{pmatrix} PDR^n (1 - PDR)^{k-n}, \quad (3.1)$$

where PDR is the Packet Delivery Ratio indicating the network performance at distance d, between the sender and the receiver; k is the number of beacons sent in the time window T with the given transmission rate; and n is the number of beacons that are successfully delivered.

According to the above definition of awareness probability, safety applications that require the receipt of 8 out of 10 beacons per second demand higher network performance requirements than safety applications that can cope with the receipt of only 2 out of 10 beacons. When applications set their requirements on awareness probability and awareness range, as will be presented in the next section, these requirements can be translated to identify the communication parameters and network conditions that are required to satisfy awareness. Consequently, they can guarantee the reliability of vehicular safety applications.

3.4.2 Awareness Range

Awareness Range can be defined as the maximum distance from a transmitting vehicle within which a desired awareness probability is achievable. By first determining an awareness probability threshold, the network-level PDR required to achieve this threshold of PA can be determined. The distance from the transmitting vehicle at which the determined PDR can be achieved is defined as the effective awareness range. In other words, all vehicles within this identified range can achieve the PDR that satisfies the PA threshold. Awareness Range indicates whether sufficient space and time exist for safety applications to effectively support drivers or autonomous vehicles in maintaining safe operation conditions. Therefore, Awareness Range is considered a much more suitable metric for assessing the reliability of safety applications than network or application metrics.

3.5 Methodology

This section provides details on the methodology followed to assess the reliability of safety applications using awareness metrics. Given the performance criteria of safety applications, awareness range can be determined from PDR. Then, with a predefined safety reliability threshold, PDR and awareness probability can be used to determine an awareness range within which applications can function reliably.

First, simulation is used to determine the mean PDR for different scenarios under the impact of various communication parameters and network conditions, including transmission power, message generation rate, vehicular density, message size, as well as radio propagation and fading effects. Once all of these conditions have been accounted for, the results consider the impact of the two main aspects that influence PDR: concurrent transmissions and channel fading with path loss.

Second, each safety application is assumed to have its own requirements on awareness. These requirements are specified in terms of how many n out of k total beacons need to be delivered within time window T with desired awareness probability PA.

Third, the minimum $PDR_{required}$ is identified for the scenarios under consideration. This minimum is needed to achieve the desired PA specified by safety applications.

The final step is to determine the awareness range at which $PDR_{required}$ can be achieved and hence within which awareness can be assumed. Safety applications can then be claimed to reliably deliver assistance within this determined range.

3.6 Simulation Framework

Although outdoor real experiments can provide the best results in evaluating network performance, the expensive cost and other limitations associated with running such empirical experiments on VANET environments make doing so difficult and impractical. Such limitations include the massive number of vehicles and the different scenarios involved, as well as the complex environment of VANET and its dynamic topology. To overcome these limitations, several simulation packages have been developed and used extensively to evaluate VANET performance. Most of the simulation tools that are used to simulate VANETs provide separate architectural modules. These simulators address mobility, networking, and radio propagation [40]. However, few existing simulators merge two or more of these primary modules into one package [54].

3.6.1 Network and Mobility simulators

As background to the simulation framework used in this research, this section lists some of the common simulators currently in use by the VANET research community. Fig. 3.2 presents the taxonomy of VANET simulation software. According to this classification, VANET simulation packages can be divided into three categories: (1) vehicular traffic simulators, (2) network simulators, and (3) VANET simulators.

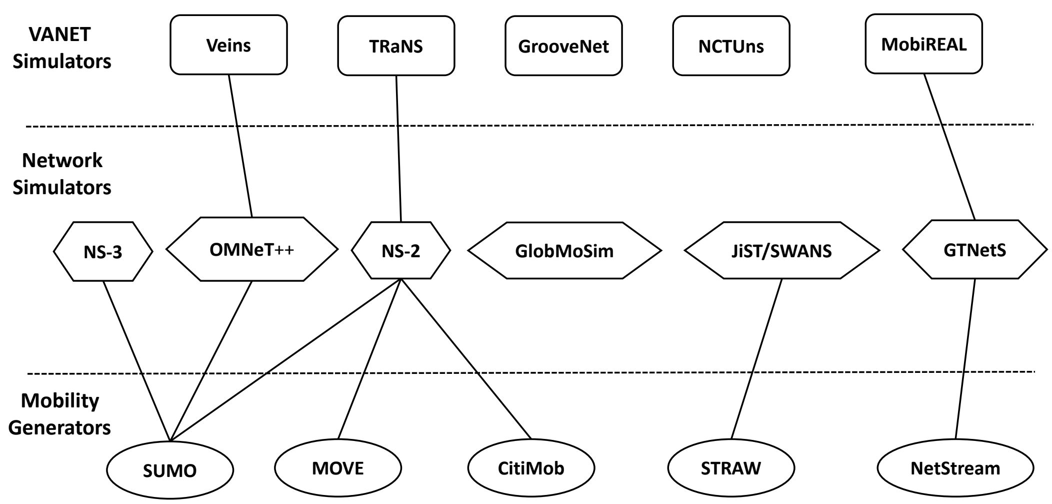

Figure 3.2: A taxonomy of VANET simulation software. Adapted from: [54]

To simulate vehicular traffic, a multitude of research work in ad hoc networks was performed using the simple random waypoint mobility model. In [67], Saha and Johnson claim that random waypoint model provides acceptable approximation of vehicle movements. Nevertheless, dedicated vehicular traffic simulators are required to handle advanced settings so as to increase the level of realism in VANET simulations. Such traffic simulators generate realistic vehicular mobility traces to be used as input for network simulators. Examples of vehicular traffic simulators include SUMO[46], MOVE[4], STRAW[7], VanetMobiSim[39], and CityMob[53]. Most of these listed mobility simulators require road models as an input along with scenario parameters (e.g., rates of vehicle arrivals and departures, maximum vehicular speed) so they can generate mobility traces that contain the location of each vehicle at every time instant for the entire simulation time.

Network simulators are used to evaluate network protocols and applications under a variety of conditions. They are capable of performing detailed packet-level simulation of source, destinations, data transmission, reception, routing, links, and channels. Examples of network simulators include NS-2[36], NS-3[2], OPNET[1], GloMoSim[42] and GTNetS[8]. In fact, most of the existing network simulators were initially developed for MANETs and hence they require VANET extensions to adapt them for VANET simulation.

Finally, combinations of network and traffic simulators that can interact with each other have evolved into what can be called VANET simulators, such as MobiREAL[5], NCTUns[6], TraNS[65], and GrooveNet[51]

In this research, realistic mobility traces are used to evaluate VANET performance. These traces are obtained from a multi-agent microscopic traffic simulator (MMTS), which was developed by K. Nagel (at ETH Zurich, now at the Technical University in Berlin, Germany). This simulator is capable of simulating public and private traffic over real regional road maps of Switzerland with a high level of realism. The mobility traces offered by this simulator provide a 24-hour detailed car traffic trace file [59] that contains detailed simulation of the area in the canton of Zurich. This region includes the part where the main country highways connect to the city of Zurich, the largest city in Switzerland. Around 260,000 vehicles are involved in the simulation, with more than 25,000,000 vehicles' direction/speed changes, recorded in an area of around 250 km x 260 km. From these trace files, a small but substantial number were chosen for this research and modified to have shorter simulation times.

The obtained mobility traces are then used as inputs to the network simulator of our choice, which is NS-3. NS-3 is a discrete event simulator engine that can be used to conduct simulation experiments. In particular, for the purpose of networking research and education, it is developed to provide an open and extensible network simulation platform that offers models of how packet data networks work and perform. NS-3 is built as a system of software libraries that work together, where user programs can be written to link with (or import from) these libraries. User programs are written in either the C++ or Python programming languages. Fig. 3.3 presents the reference model of NS-3.

3.6.2 Radio Propagation Models

Radio Propagation Models (RPMs) are needed to add realism to the simulation of VANETs. These models handle the effect of signal attenuation, caused by many factors including

<table>
<tr><th colspan="6">Source Code Modules</th><th>Usage and examples</th></tr>
<tr><td colspan="6">Helpers</td><td>High-level wrappers that ease the creation of basic facilities and define their interrelationships.</td></tr>
<tr><td>Applications</td><td>Protocols</td><td>Devices</td><td>Propagation</td><td colspan="2">...</td><td></td></tr>
<tr><td colspan="3">Internet</td><td colspan="3">Mobility</td><td>Mobility modules (static, random walk, random waypoint, etc.)</td></tr>
<tr><td colspan="6">Network</td><td>Packets, Packet Tags, Packet Headers, Pcap/ASCII file writing.
Node class, NetDevice, Address types (Ipv4, MAC, etc.), Queues, Socket, and Packet sockets.</td></tr>
<tr><td colspan="6">Core</td><td>Smart pointers, Dynamic types, Attributes, Callbacks, Tracing, Logging, Random Variables, Events, Scheduler, Time arithmetic.</td></tr>
</table>

Figure 3.3: Current Modules in main NS-3 tree [2]

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the distance, multipath signal fading caused by reflectors, and shadowing which blocks the reception of radio waves due to obstacles such as buildings. In general, there are three main factors that degrade the strength of radio waves and attenuate the signal as it propagates through space:

1. Line-of-sight signal attenuation.

2. Fast fading effects such as strong signal reflections from the ground.

3. Slow fading due to scattering and shadowing effects.

The total path loss is modeled by accumulating the effects listed above. Therefore, the total path loss, L_{Total}, can be expressed as:

$$L_{Total} = L_{propagation} + L_{fading} + L_{shadowing}, \tag{3.2}$$

Several RPMs have been proposed for the purpose of VANET simulation. Of these different models, the unit-disk model is commonly used by the research community, due to its simplicity. In its basic form, this model as presented in [20] uses a threshold distance within which vehicles can communicate. Any other vehicles beyond this threshold will simply not receive any signal. In [55], the authors present a more flexible unit-disk model to handle complex shadow-fading environments. Even though the unit-disk model is popular and commonly used, it was shown in [20] that it does not realistically approximate path loss in communication channels. In many cases, other simple models such as the log normal model are preferred in simulating more-complex scenarios that involve obstacles.

The most commonly used RPM to model propagation loss in VANET simulations is the Two-ray model. To a great extent, this model can accurately approximate path loss in inter-vehicle communications by considering signal reflections from the road surface [74]. For the simulation of small-scale fast fading effects, different stochastic distributions have been proposed. Some of the commonly used models include Nakagami-m, Rice, Weibull and Rayleigh distributions [20]. According to the results in [66], large-scale fading in radio propagation channels at 5.3GHz was shown to be log-normally distributed, whereas the small-scale fading can be modeled using Weibull distribution.

The authors in [19] provide a normalized general gamma distribution that can be used to model multipath and shadow fading, as given in 3.3:

$$f_{gamma}(r;\alpha,\beta,\nu) = \frac{2\nu r^{2\nu\alpha-1}}{(\beta/\alpha)^{\alpha}\Gamma(\alpha)}e^{-\frac{\alpha r^{2}\nu}{\beta}}, \tag{3.3}$$

where α is the fading parameter, β is the power scaling parameter, ν is the shape parameter, and Γ is the gamma function.

The Nakagami-m fading model presented in [30] is a special case of gamma distribution where ν is set to 1 (i.e., $\nu = 1$). The Nakagami-m is a probabilistic model that employs various parameters to simulate fading levels and determine signal power reception. This model is described as shown in 3.4:

$$f_{Nakagami-m}(r;m,\Omega) = \frac{2m^{m}r^{2m-1}}{\Omega^{m}\Gamma(m)}e^{-\frac{mr^{2}}{\Omega}}, \tag{3.4}$$

where m is the Nakagami parameter which corresponds to the shape parameter in the gamma distribution, Ω controls the spread of the distribution and represents the average power of the multipath scatter field, and $\Gamma(m)$ is the gamma function.

In this thesis, NS-3 is used to simulate path loss due to propagation (i.e., the L_p component in Equation 3.2) utilizing the two-ray ground propagation-loss model. By applying this model, the received power, $P_{prop-loss}$, after considering the propagation loss can be expressed as given in 3.5:

$$P_{prop-loss} = P_t G_t G_r \frac{{h_t}^2 {h_r}^2}{d^4}, \tag{3.5}$$

where P_t is the initial transmission power, d is the distance between the sender and the receiver, G_t and h_t are the gain and height of the transmitter, respectively, and G_r and h_r are the gain and height of the receiver, respectively.

Furthermore, the simulation conducted in this research utilizes the Nakagami-m fading model to add the effects of path loss due to fast fading (i.e., the L_f component in 3.2). These effects lead to further reduction of the received power. Because the multiple path loss effects are cumulative, the effects of fast fading are applied to the received signal after considering the propagation path loss (i.e., $P_{r,prop-loss}$) previously calculated in 3.5. Accordingly, the output power, P_{out}, can be expressed using the Nakagami-m distribution as given in 3.6:

$$P_{out} = f_{gamma}(m_{Nak}, \frac{P_{prop-loss}}{m_{Nak}}, 1), \tag{3.6}$$

where f_{gamma} is the gamma distribution defined in 3.3 with the Nakagami-m shape parameter, m_{Nak}, replacing α; $\beta = P_{r,prop-loss}/m_{Nak}$, and $\nu = 1$.

Chapter 4

Experimental Work and Results

4.1 Introduction

In this chapter, simulation experiments are conducted to assess the reliability of safety applications under various network conditions, following the methodology described in Section 3.5 (i.e., based on the achievable awareness probability and awareness range in the different simulation scenarios).

4.2 Experimental Setup and Simulation Approach

To maintain realism, this simulation study employes the IEEE WAVE and 802.11p modules and devices provided by NS-3 to simulate communication among vehicles. In their default settings, all vehicles transmit 200-byte BSMs at a 10Hz transmission rate, with a transmission power of 20dBm. It is assumed that vehicles have continuous access to a single 10MHz channel in the spectrum range of 5.9GHz, which is dedicated for the DSRC. As described previously in Section 3.6.2 , path loss due to propagation is modeled using the two-ray ground propagation loss model, while Nakagami-m fading model is used to add the effects of path loss due to fast fading. The rest of the controllable simulation parameters are presented in Table 4.1.

Realistic mobility traces are obtained from the multi-agent microscopic traffic simulator described in [59]. These traces contain 300 detailed simulation seconds of mobility patterns for various vehicular densities within the Unterstrass section of Zurich, Switzerland. Fig. 4.1 shows satellite imagery views from GoogleEarth™ along with corresponding views of NS-2 vehicular movement files visualized using the NS-3 network simulator.

In order to apply the methodology described in Section 3.5 in assessing the reliability of safety applications, these applications need to set their requirements on awareness by specifying the minimum number of BSMs that need to be delivered successfully in a time window T (such requirements are presented in Table 3.1). These requirements can be used as a criteria to evaluate the reliability of safety-applications. For instance, the Stationary

Table 4.1: Network simulation parameters

Parameter	**Value**
BSM size	*200 Bytes*
BSM rate	*10 Hz*
Tx power	*20 dBm*
Frequency	*5.9 GHz*
Channel bandwidth	*10 MHz*
Channel access	*802.11p OCB*
Tx range	*50 – 1500 m*
Encoding	*OFDM*
Rate	*6 Mbps*
Propagation loss Model	*Two-ray ground*
Fading model	*Nakagami-1*
Simulation time	*300 seconds*

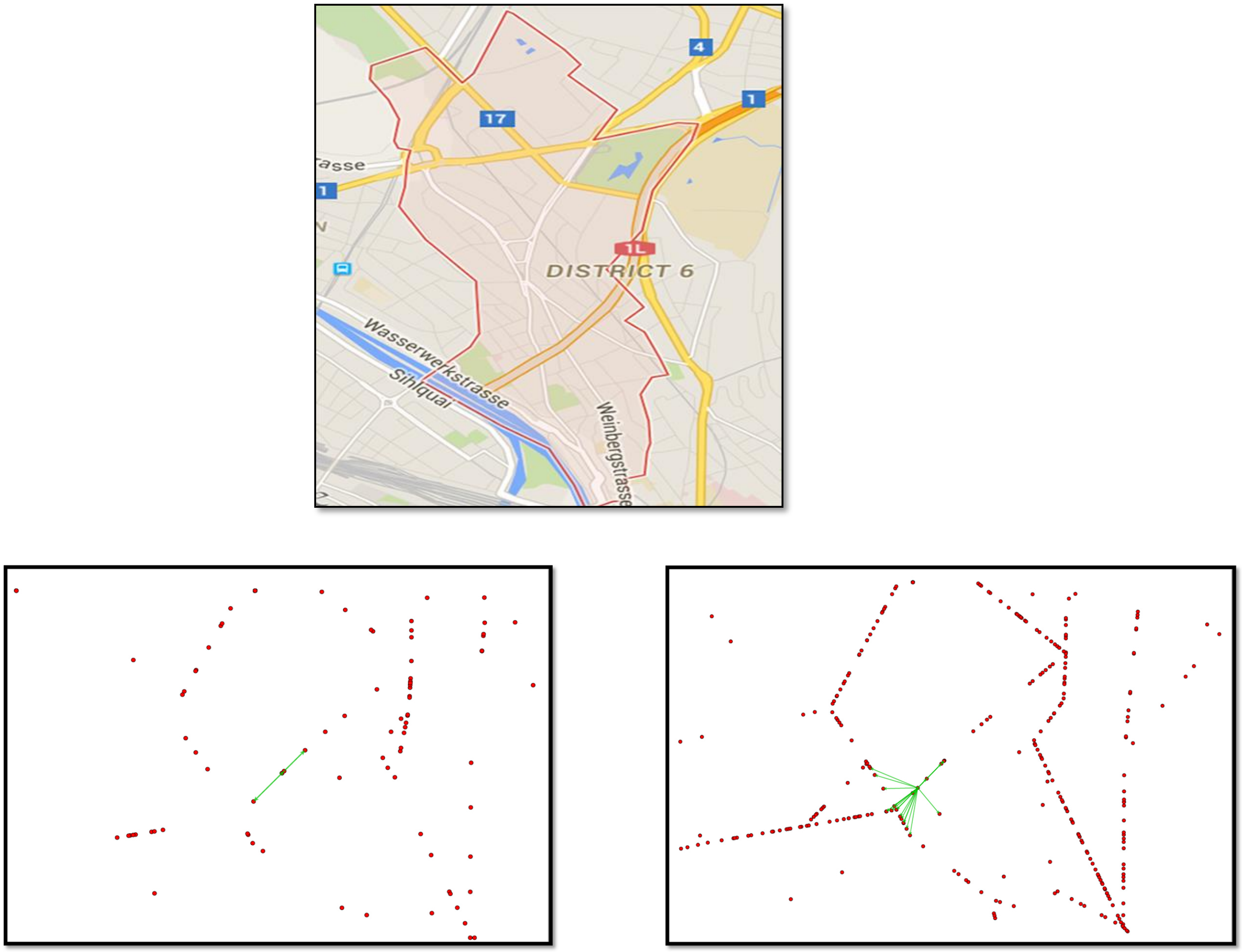

Figure 4.1: City scenario within the Unterstrass section of Zurich, Switzerland: (a) GoogleEarth™ view, (b) vehicular traffic of 210 vehicles, and (c) vehicular traffic of 635 vehicles

Vehicle Warning application assumes the receipt of one BSM per second (i.e., n = 1) to be sufficient to alert drivers and achieve awareness, as one such warning message can contain complete information about any immobilized vehicle on the road [18]. In contrast, for the Lane Change Warning application to assist drivers reliably, it requires the successful delivery of at least two BSMs in one second (i.e., n $\geqslant$ 2) in order to maintain up-to-date real-time information about the high-dynamic movement of vehicles driving on neighboring lanes.

Additionally, safety effectiveness thresholds need to be defined under the evaluation criteria so as to refer to these thresholds in evaluating the level of reliability that safety applications can offer. Three levels of reliability are defined in this simulation study; the performance of safety applications is evaluated in "*Level-1*" of the reliability band when network conditions can offer at least 95% of awareness probability (i.e., PA $\geqslant$ 95%), whereas safety applications running under network conditions that can offer 85% or more of awareness probability (i.e., PA $\geqslant$ 85%) are evaluated in "*Level-2*" of the reliability band. Furthermore, as network performance degrades to offer only 80% of awareness probability (i.e., PA $\geqslant$ 80%), the reliability of safety applications falls into "*Level-3*" of the reliability band. Finally, safety applications running under network conditions that fail to provide at least 80% of awareness probability are considered unreliable. Table 4.2 summarizes the reliability criteria.

According to the simulation approach, network performance is simulated first under the impact of various communication parameters and network conditions, including the

Table 4.2: Reliability criteria

Reliability Level	Awareness Probability	Notation
Level-1	>= 95%	Bold italic
Level-2	85% - 95%	Green color
Level-3	80% - 85%	Blue color
Unreliable	<= 80%	Red color

transmission power, message generation rate, vehicular density, and message size. For each simulation scenario, PDR is measured within a coverage radius of the transmitter at 50m, 100m, 200m, 300m, 500m, 700m, 900m, 1100m, 1300m, and 1500m. Using the relationship described in Section 3.4 along with the evaluation criteria presented in the previous paragraphs, the reliability of safety applications is assessed for each scenario through the calculation of awareness probability and range based on the achievable PDR.

4.3 Sensitivity Analysis: network conditions and system parameters

This section investigates the influence of different configuration parameters and network conditions on the reliability of safety-applications. For each parameter, a brief introduction is provided, then the results, followed by a discussion of the impact of this parameter on the reliability of safety applications.

4.3.1 Transmission Power

In principle, varying transmission power determines the transmission range of vehicles, and influences the packet reception capabilities either positively or negatively. Intuitively, increasing the transmission power would enable nodes within farther ranges to receive the transmitted packets. However, in reality this can increase interference effects in areas close to the transmitting node, thus degrading packet reception capabilities. In fact, there is no simple way to accurately predict these positive and negative influences. Therefore, the adaptation of transmission power is a challenging topic. In the literature, most of the Transmit Power Control (TPC) techniques proposed for VANETs have been adopted from MANETs. Nevertheless, the objectives and requirements of both networks are different. Unlike MANETs, whereas the focus is on minimizing power consumption, TPC in VANETs is used to adapt the transmission power to a target range for cooperative safety applications

[37], while minimizing the consequent interference. The impact of transmission power on the reliability of safety applications is analyzed in the following.

Experiment Settings

To quantify the impact of transmission power, a set of controlled experiments is conducted by varying transmission power while fixing other factors. Following this approach, the transmission power was set to three values: 10dBm; 20dBm which is the default value used in industrial tests [3]; and 40dBm, respectively. The rest of the configuration parameters of the three simulation scenarios are set as in Table 4.1, with a vehicular density of 60 vehicles and simulation time of 300 seconds.

Experiment Results

The results are presented in Table 4.3 and depicted in Fig. 4.2. These results show how PDR and hence PA vary with different settings of transmission power.

It can be seen from the results that higher transmission power leads to improved reception probabilities at far distances. However, for a vehicular density of 60 vehicles, increasing the transmission power degrades reception within ranges that are close to the transmitting vehicle. Increasing the transmission power from 10dBm to 20dBm does not significantly improve the PDR within distances close to the transmitting vehicle. For farther distances, beyond the 700m range, increasing the transmission power to 20dBm does provide better reception. On the other hand, the significant increment in transmission power to 40dBm

Table 4.3: The impact of transmission power on safety-application reliability

Parameter	Network Performance		Awareness Probability n out of k=10 messages sent per T = 1 sec					
Tx Power (dBm)	Distance (meters)	$PDR_{TxP}(d)$		1	3	6	9	
10	50	89.68%		**100.00%**	**100.00%**	**99.81%**	72.38%	
10	100	89.70%		**100.00%**	**100.00%**	**99.81%**	72.43%	
10	200	89.47%		**100.00%**	**100.00%**	**99.79%**	71.53%	
10	300	88.97%		**100.00%**	**100.00%**	**99.74%**	69.59%	
10	500	86.03%		**100.00%**	**100.00%**	**99.28%**	58.28%	
10	700	81.26%		**100.00%**	**100.00%**	**97.48%**	41.49%	
10	900	70.22%		**100.00%**	**99.85%**	85.35%	15.27%	
10	1100	62.50%		**99.99%**	**99.21%**	69.42%	6.36%	
10	1300	58.47%		**99.98%**	**98.41%**	59.42%	3.78%	
10	1500	51.16%		**99.92%**	**95.30%**	40.58%	1.30%	
20	50	87.58%		**100.00%**	**100.00%**	**99.57%**	64.21%	
20	100	87.60%		**100.00%**	**100.00%**	**99.57%**	64.29%	
20	200	87.57%		**100.00%**	**100.00%**	**99.57%**	64.16%	
20	300	87.46%		**100.00%**	**100.00%**	**99.55%**	63.74%	
20	500	86.65%		**100.00%**	**100.00%**	**99.40%**	60.61%	
20	700	84.78%		**100.00%**	**100.00%**	**98.95%**	53.63%	
20	900	78.32%		**100.00%**	**99.99%**	**95.48%**	32.73%	
20	1100	71.69%		**100.00%**	**99.90%**	87.72%	17.74%	
20	1300	67.43%		**100.00%**	**99.71%**	80.23%	11.33%	
20	1500	59.11%		**99.99%**	**98.57%**	61.06%	4.12%	
40	50	68.38%		**100.00%**	**99.77%**	82.06%	12.58%	
40	100	68.49%		**100.00%**	**99.77%**	82.25%	12.71%	
40	200	68.61%		**100.00%**	**99.78%**	82.49%	12.89%	
40	300	68.61%		**100.00%**	**99.78%**	82.48%	12.88%	
40	500	68.60%		**100.00%**	**99.78%**	82.48%	12.88%	
40	700	68.42%		**100.00%**	**99.77%**	82.13%	12.63%	
40	900	67.03%		**100.00%**	**99.69%**	79.42%	10.84%	
40	1100	65.62%		**100.00%**	**99.58%**	76.49%	9.24%	
40	1300	64.75%		**100.00%**	**99.49%**	74.60%	8.35%	
40	1500	62.29%		**99.99%**	**99.18%**	68.93%	6.20%	

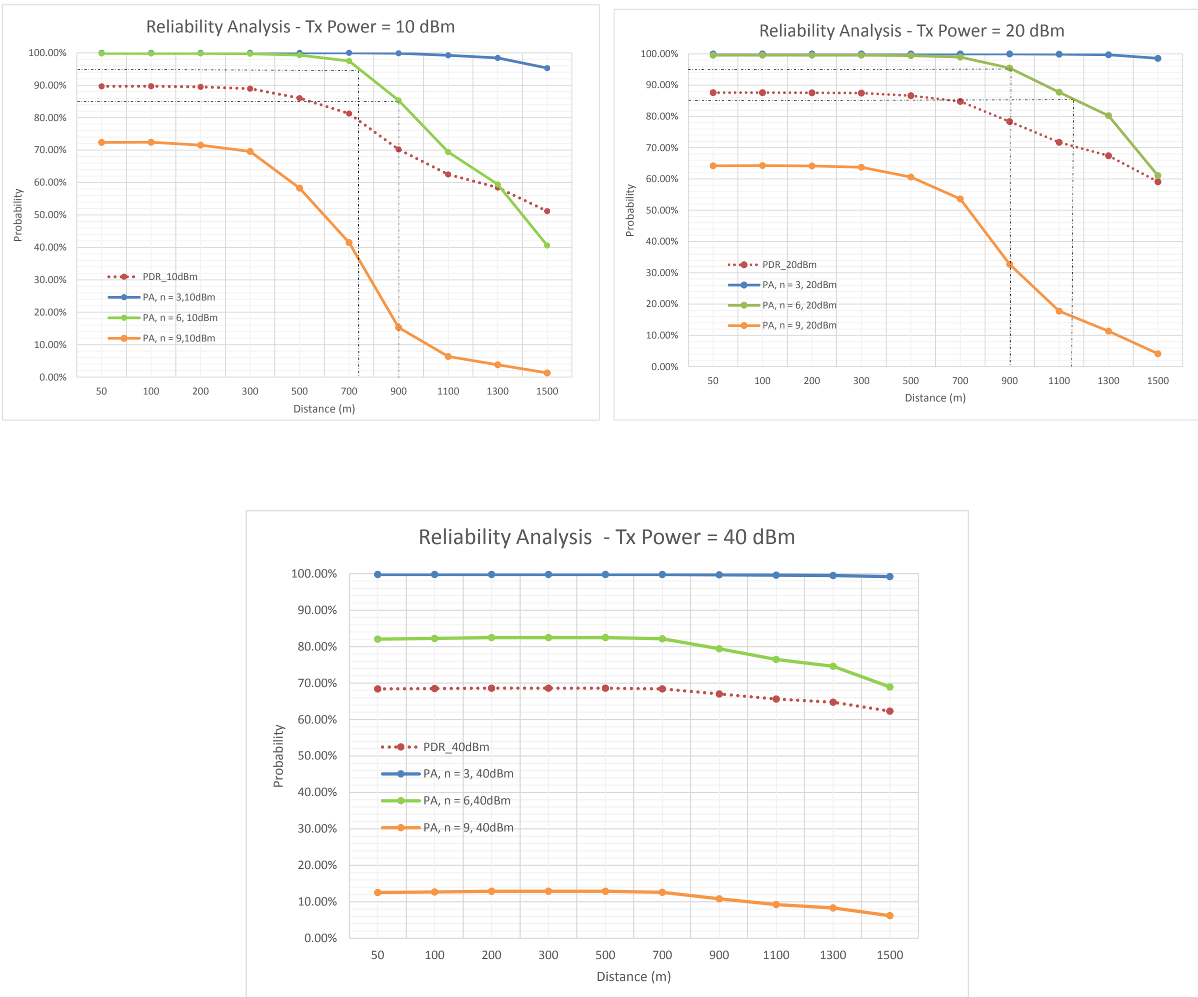

Figure 4.2: The impact of transmission power on safety-application reliability

(i.e., double increment) severely reduces the PDR at distances less than 1200m; however, it provides better performance beyond this range. This observed behavior can be attributed to the fact that high powers induce high energy on the wireless channel, leading to interference and failed receptions at close distances, whereas it combats signal attenuation due to fading effects at farther distances, leading to better performance.

The charts shown in Fig. 4.2 depict the probability of awareness calculated using Equation 3.1 for three representative safety-application requirements, with n = 3, n = 6, and n = 9, respectively, where n represents the number of desired packets received in one second. Based on the evaluation criteria presented in Section 4.2, the values of PDR and their corresponding PA values that provide "*Level-1*" reliability of safety performance are indicated in bold italic, whereas the values that provide "*Level-2*" reliability of safety performance are indicated with green. Finally, the values that provide "*Level-3*" reliability are indicated with blue. The rest of the values do not meet the reliability requirements and hence are indicated by red.

Using the awareness range metric as defined in Section 3.4.2, communication ranges that provide safe conditions can be determined for each scenario; for safety applications that require the successful delivery of one to three packets per second, setting the transmission power to 10dBm, 20dBm, or 40dBm can provide "*Level-1*" reliability up to a communication range of 1400m. In other words, despite the settings of transmission power, such applications with flexible requirements can assist drivers reliably within a safe range of 1400m, far from the transmitting vehicle.

As the requirements of safety applications increase, the influence of transmission power settings becomes more relevant. It can be seen in Fig. 4.2 that for safety applications that require the successful delivery of six packets per second (i.e., n = 6), setting the transmission power to 10dBm can provide "*Level-1*" reliability up to a communication range of 750m, whereas for ranges between 750m and 900m, only "*Level-2*" reliability can be offered, and no reliability can be guaranteed beyond 900m. Increasing the transmission power to 20dBm extends the safety range within which "*Level-1*" reliability can be offered, up to 900m. In addition, with this increase in transmission power, "*Level-2*" reliability can be offered up to 1150m. This setting of transmission power (i.e., 20dBm) seems to be the best among the three trials conducted in this experiment, as the last trial, which sets the power to 40dBm, can only provide "*Level-3*" reliability within a limited range for safety applications that require successful delivery of six packets in one second.

4.3.2 Message Generation Rate

The message generation rate (packets per second) is one of the main parameters that directly influence the network performance, as it determines the amount of transmitted messages and hence controls the load on the wireless channel. Intuitively, halving the transmit rate is supposed to halve the channel load. However, this would double the inter-arrival time between subsequent transmissions, probably leading to significant impact on awareness quality. The influence of message generation rate on the reliability of safety applications is investigated in the following experiment.

Experiment Settings

A set of controlled experiments is conducted by varying the message generation rate, while fixing the other factors. In each scenario, the message generation rate was set to one of the three values: 10Hz, 6Hz , and 4Hz, respectively. The rest of the configuration parameters of the three simulation scenarios are set as in Table 4.1, with a vehicular density of 60 vehicles and simulation time of 300 seconds.

Experiment Results

The results are presented in Table 4.4 and depicted in Fig. 4.3. These results show how PDR and hence PA vary with different settings of message generation rate.

Referring to the results of the achievable PA under the three different scenarios, the awareness range metric determines the communication ranges that provide safe conditions for each scenario. For safety applications that require the successful delivery of one to three packets per second, it can be noticed that setting the message generation rate to a high value such as 10Hz can guarantee "*Level-1*" reliability along the whole transmission range up to 1500m, whereas lowering the message generation rate to 6Hz can only guarantee such high level of reliability up to 1000m and can afford "*Level-2*" reliability for the remaining transmission range beyond the 1000m. Further decrement of the message generation rate to 4Hz cannot afford "*Level-1*" reliability at all, instead it can only provide "*Level-2*"

Table 4.4: The impact of message generation rate on safety-application reliability

Parameter	Network Performance		Awareness Probability n out of TxRate messages sent per T = 1 sec					
Tx Rate (Hz)	Distance (meters)	$PDR_{TxR}(d)$		1	3	6	9	
10	50	87.58%		***100.00%***	***100.00%***	***99.57%***	64.21%	
10	100	87.60%		***100.00%***	***100.00%***	***99.57%***	64.29%	
10	200	87.57%		***100.00%***	***100.00%***	***99.57%***	64.16%	
10	300	87.46%		***100.00%***	***100.00%***	***99.55%***	63.74%	
10	500	86.65%		***100.00%***	***100.00%***	***99.40%***	60.61%	
10	700	84.78%		***100.00%***	***100.00%***	***98.95%***	53.63%	
10	900	78.32%		***100.00%***	***99.99%***	***95.48%***	32.73%	
10	1100	71.69%		***100.00%***	***99.90%***	87.72%	17.74%	
10	1300	67.43%		***100.00%***	***99.71%***	80.23%	11.33%	
10	1500	59.11%		***99.99%***	***98.57%***	61.06%	4.12%	
6	50	86.51%		***100.00%***	***99.60%***	41.90%	0.00%	
6	100	86.54%		***100.00%***	***99.61%***	41.99%	0.00%	
6	200	86.49%		***100.00%***	***99.60%***	41.86%	0.00%	
6	300	86.39%		***100.00%***	***99.59%***	41.56%	0.00%	
6	500	85.62%		***100.00%***	***99.50%***	39.39%	0.00%	
6	700	83.73%		***100.00%***	***99.20%***	34.46%	0.00%	
6	900	77.29%		***99.99%***	***97.32%***	21.32%	0.00%	
6	1100	70.75%		***99.94%***	93.53%	12.54%	0.00%	
6	1300	66.56%		***99.86%***	89.88%	8.70%	0.00%	
6	1500	58.34%		***99.48%***	79.71%	3.94%	0.00%	
4	50	87.38%		***99.97%***	91.97%	0.00%	0.00%	
4	100	87.40%		***99.97%***	92.00%	0.00%	0.00%	
4	200	87.36%		***99.97%***	91.96%	0.00%	0.00%	
4	300	87.27%		***99.97%***	91.85%	0.00%	0.00%	
4	500	86.48%		***99.97%***	90.91%	0.00%	0.00%	
4	700	84.63%		***99.94%***	88.56%	0.00%	0.00%	
4	900	78.21%		***99.77%***	79.12%	0.00%	0.00%	
4	1100	71.65%		***99.35%***	68.07%	0.00%	0.00%	
4	1300	67.42%		***98.87%***	60.60%	0.00%	0.00%	
4	1500	59.10%		***97.20%***	45.98%	0.00%	0.00%	

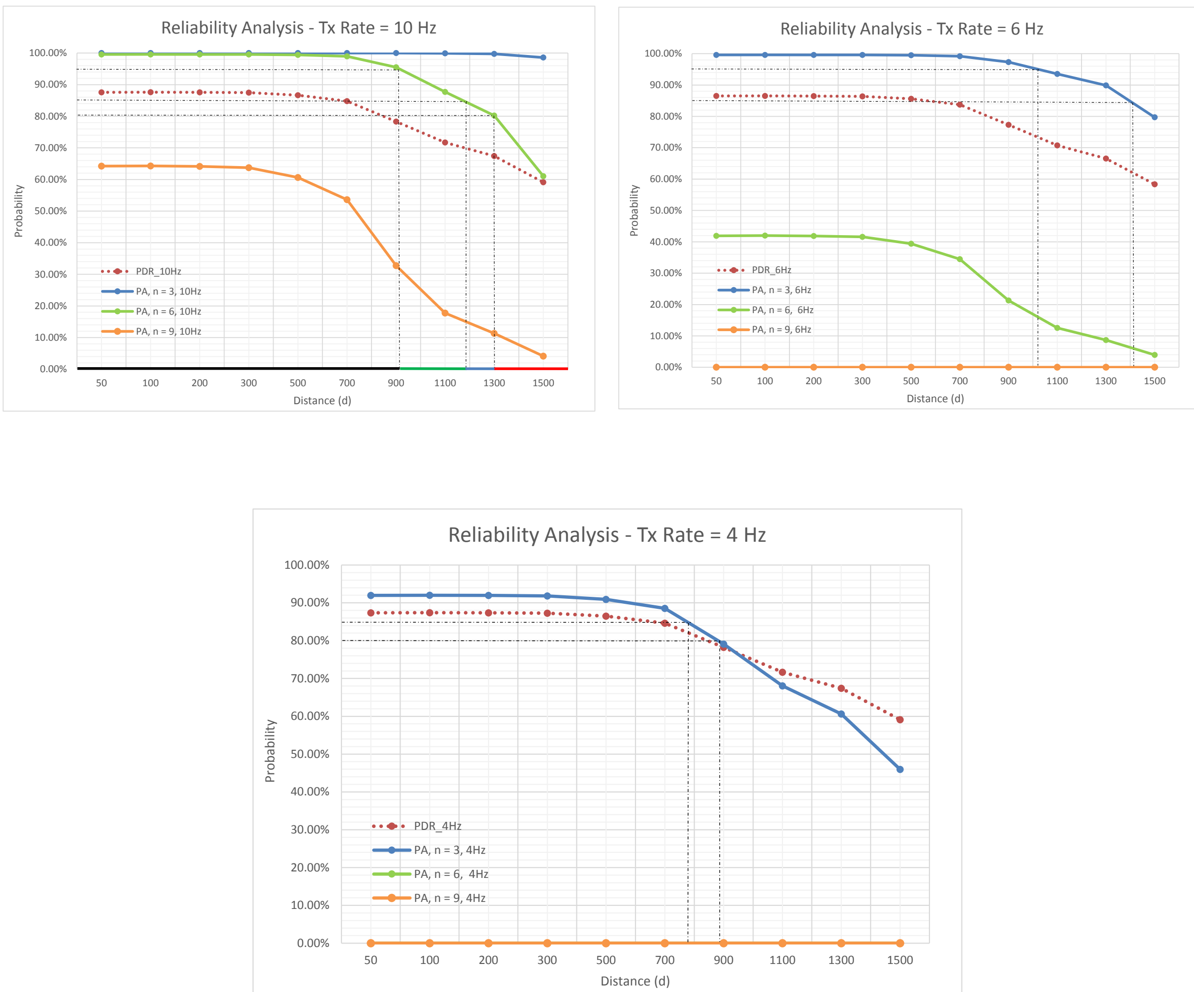

Figure 4.3: The impact of message generation rate on safety-application reliability

reliability up to 800m, and it cannot guarantee any level of reliability beyond 900m.

As the requirements of safety applications increase, the use of high message generation rates becomes mandatory. It can be seen in Fig. 4.3 that no reliability can be offered to safety applications that require the successful delivery of six packets per second (i.e., n = 6), when the message generation rate is set to 6Hz. Furthermore, it is not possible to deliver 6 packets per second when the rate is set to 4Hz. In contrast, setting the message generation rate to 10Hz can provide safety applications with "*Level-1*" reliability up to the communication range of 900m, and can offer them "*Level-2*" reliability for ranges between 900m and 1200m. With this relatively high message generation rate, further communication ranges up to 1300m can be guaranteed reliability at "*Level-3*".

In conclusion, lower transmission rates cannot satisfy the requirements of high-rate demands (e.g, n=6, or n=9). However, they can reliably meet the requirements of safety applications that have flexible requirements (e.g, n=1, or n=3), while saving the channel from overloading. Therefore, it is important to consider using adaptable (application-dependent) message generation rates that satisfy the reliability requirements of safety applications without overloading the wireless channel.

4.3.3 Vehicular Density

The number of vehicles participating in the network is another important factor that directly influences the load on the wireless channel and hence the overall performance of the network and the quality of awareness. In fact, as the number of neighboring nodes increases, the probability that two or more nodes will select the same slot to access the channel increases. Therefore, the probability of packet loss due to collisions increases too. The impact of the vehicular density on the reliability of safety applications is studied in the following experiment.

Experiment Settings

In order to assess the reliability of different safety applications under various vehicular density environments, controlled simulations are conducted by examining different densities of vehicles, while fixing the other simulation factors. Three different densities of vehicles are examined; in the first scenario, 28 vehicles are configured to exchange messages at a 10Hz rate over a duration of 300 seconds. In the second scenario, all the simulation configurations are kept the same, but the number of vehicles is increased to 60. In the last scenario, the number of vehicles is increased to 210 vehicles and the rest of the configurations are kept at their default values.

Experiment Results

The results are presented in Table 4.5 and depicted in Fig. 4.4. These results show how PDR and hence PA vary under different vehicular densities.

As shown in Fig. 4.4, the awareness range metric identifies the communication ranges that provide safe conditions for each scenario. With only 28 vehicles participating in the

Table 4.5: The impact of vehicular density on safety-application reliability

Parameter	Network Performance		Awareness Probability n out of 10 messages sent per T = 1 sec					
Vehicular Density (# vehicles)	Distance (meters)	$PDR_{Density}(d)$		1	3	6	9	
28	50	97.87%		**100.00%**	**100.00%**	**100.00%**	**98.18%**	
28	100	97.83%		**100.00%**	**100.00%**	**100.00%**	**98.12%**	
28	200	97.78%		**100.00%**	**100.00%**	**100.00%**	**98.04%**	
28	300	97.71%		**100.00%**	**100.00%**	**100.00%**	**97.91%**	
28	500	97.52%		**100.00%**	**100.00%**	**100.00%**	**97.57%**	
28	700	97.32%		**100.00%**	**100.00%**	**100.00%**	**97.20%**	
28	900	97.06%		**100.00%**	**100.00%**	**100.00%**	**96.68%**	
28	1100	96.85%		**100.00%**	**100.00%**	**100.00%**	**96.23%**	
28	1300	96.48%		**100.00%**	**100.00%**	**100.00%**	**95.38%**	
28	1500	96.10%		**100.00%**	**100.00%**	**100.00%**	94.45%	
60	50	87.58%		**100.00%**	**100.00%**	**99.57%**	64.21%	
60	100	87.60%		**100.00%**	**100.00%**	**99.57%**	64.29%	
60	200	87.57%		**100.00%**	**100.00%**	**99.57%**	64.16%	
60	300	87.46%		**100.00%**	**100.00%**	**99.55%**	63.74%	
60	500	86.65%		**100.00%**	**100.00%**	**99.40%**	60.61%	
60	700	84.78%		**100.00%**	**100.00%**	**98.95%**	53.63%	
60	900	78.32%		**100.00%**	**99.99%**	**95.48%**	32.73%	
60	1100	71.69%		**100.00%**	**99.90%**	87.72%	17.74%	
60	1300	67.43%		**100.00%**	**99.71%**	80.23%	11.33%	
60	1500	59.11%		**99.99%**	**98.57%**	61.06%	4.12%	
210	50	44.85%		**99.74%**	89.87%	25.83%	0.44%	
210	100	45.21%		**99.76%**	90.27%	26.60%	0.47%	
210	200	45.72%		**99.78%**	90.82%	27.70%	0.51%	
210	300	46.26%		**99.80%**	91.37%	28.90%	0.57%	
210	500	45.73%		**99.78%**	90.83%	27.73%	0.51%	
210	700	43.81%		**99.69%**	88.66%	23.69%	0.36%	
210	900	40.07%		**99.40%**	83.38%	16.74%	0.17%	
210	1100	35.84%		**98.82%**	75.61%	10.51%	0.07%	
210	1300	32.04%		**97.90%**	66.97%	6.41%	0.03%	
210	1500	28.35%		**96.43%**	57.20%	3.63%	0.01%	

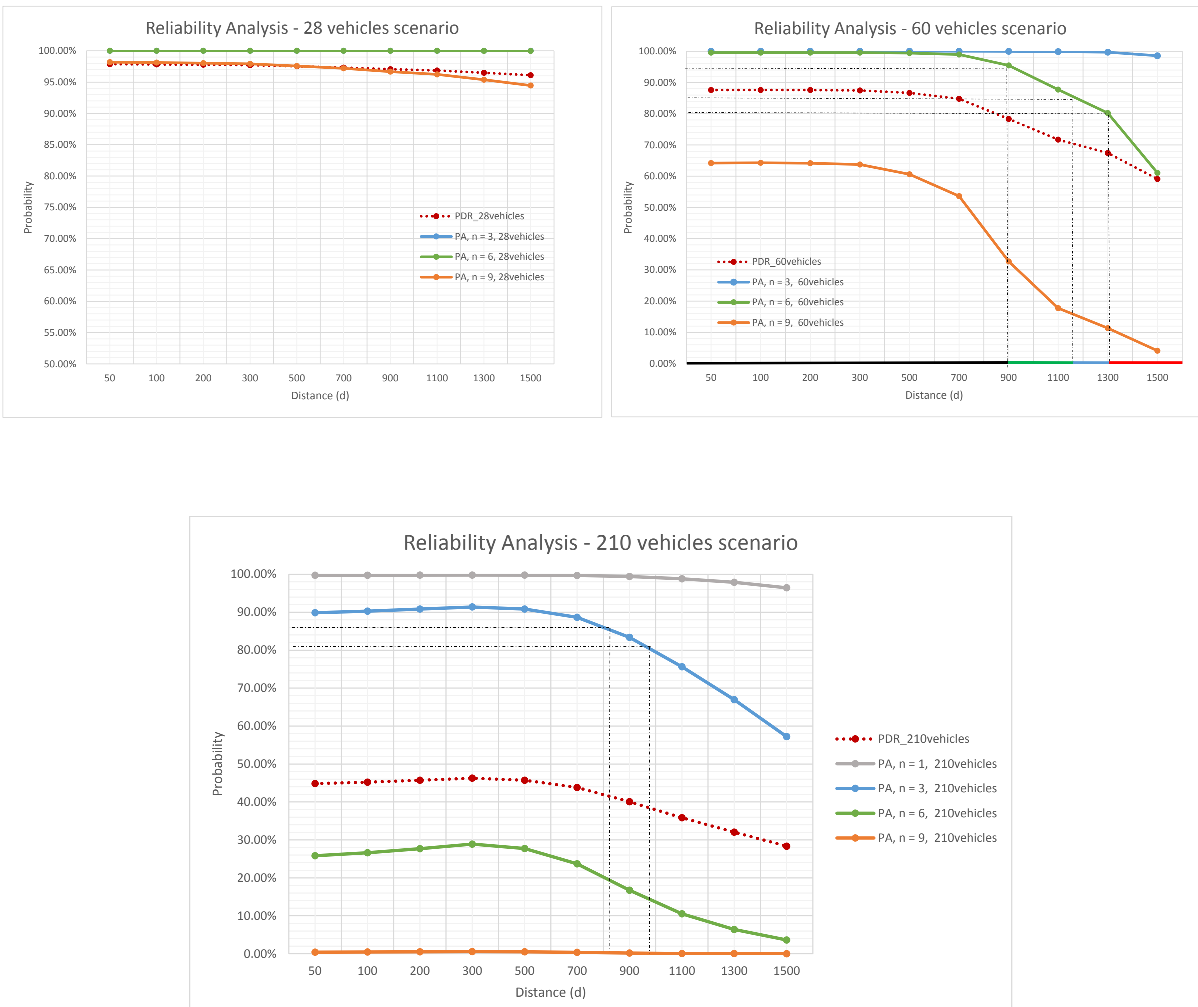

Figure 4.4: The impact of vehicular density on safety-application reliability

network as in the first scenario, high values of PDR can be achieved consistently over the whole range of communication, up to 1500m. Such high network performance provides high probabilities of awareness among vehicles, and hence high levels of reliability can be offered to safety applications. It can be seen from the presented charts that under this scenario, reliability at "*Level-1*" can be offered to almost all the considered requirements, ranging from applications that require the delivery of one packet (i.e., n = 1) to the applications that require the delivery of 9 packets per second (i.e., n = 9).

In comparison with the first scenario, in the second, increasing the vehicular density to 60 vehicles degrades the levels of reliability that can be offered to safety applications requiring the successful delivery of six packets per second. Safety applications with such requirements are offered "*Level-1*" reliability only up to communication range of 900m. Beyond this range, "*Level-2*" reliability can be provided for ranges between 900m and 1200m, whereas further communication ranges up to 1300m can only be guaranteed reliability at "*Level-3*".

Increasing the vehicular density to 210 vehicles in the third scenario maintains the trend of degrading network performance and hence lowers the levels of reliability that can be offered to safety applications. It is obvious from the presented charts that under this vehicular density, even safety applications with low requirements, such as the delivery of three packets per second, can at maximum be offered "*Level-2*" of reliability up to 850m. Moreover, no reliability can be offered to safety applications with higher requirements (e.g., $n \geqslant 6$).

In conclusion, for low vehicular density scenarios, the probability that two or more nodes will select the same slot to transmit after a busy period is not significant, resulting in lower load on the wireless channel and hence better network performance can be achieved. Higher network performance implies better awareness quality and higher reliability of safety applications. On the other hand, increasing the number of vehicles participating in the network degrades coordination among vehicles accessing the channel, which increases the probability of packet loss. As a result, lower probabilities of awareness are achieved and hence only lower levels of reliability can be offered to safety applications.

4.3.4 Message Size

This part of the simulation investigates the influence of the BSM size. In fact, this parameter directly impacts the load that vehicles contribute to the data traffic on the wireless channel. Logically, the larger the BSMs transmitted, the more intense the usage imposed on the communication channel. Moreover, large BSMs are subject to transmission errors; therefore, they need to be retransmitted more often than small BSMs. The impact of BSM size on the reliability of safety applications is studied in the following.

Experiment Settings

Two scenarios are investigated in this experiment in order to study the impact of BSM size on the reliability of three requirements of safety applications. In these two scenarios, the simulation configurations are set to their defaults as per Table 4.1, except for the BSM size, which is set to 200 bytes in one scenario, and to 400 bytes in the other. In both scenarios, vehicular density is configured to 60 vehicles and the simulation time is set to 300 seconds.

Experiment Results

The results are presented in Table 4.6 and depicted in Fig. 4.5. These results illustrate how PDR and hence PA vary with different settings of BSM size. The impact on the reliability of safety applications is also presented.

From the figures, it can be noticed that increasing the packet size from 200 bytes to 400 bytes deteriorates the level of reliability that can be offered to safety applications that demand the successful delivery of six packets per second. In the second scenario, this influence is obvious for communication ranges beyond 500m, where only "*Level-2*" reliability can be offered up to 900m, whereas in the first scenario "*Level-1*" reliability was applicable up to the same range when small BSMs of 200 bytes were used. On the other hand, it can be seen that the impact of increasing the BSM size is not significant for less-demanding applications (e.g., $n \geqslant 3$), as in both scenarios the same level of reliability – "*Level-1*" – can be offered.

4.4 Summary

This chapter has studied the impact of various network conditions on the PDR and mutual awareness, using a comprehensive simulation approach that involved different scenarios and some of the main influencing factors. The results provide insight on how network performance metrics address application requirements and enhance the reliability of safety applications. Three representative safety-application requirements were examined to identify the level of reliability that can be offered to these applications under the effect of various communication parameters and network conditions. Table 4.7 summarizes the results of all the examined scenarios and presents the level of reliability that can be maintained in each scenario.

Table 4.6: The impact of BSM size on safety-application reliability

Parameter	Network Performance		Awareness Probability n out of 10 messages sent per T = 1 sec				
BSM Size (Bytes)	Distance (meters)	$PDR_{BSMsize}(d)$		1	3	6	9
200	50	87.58%		**100.00%**	**100.00%**	**99.57%**	64.21%
200	100	87.60%		**100.00%**	**100.00%**	**99.57%**	64.29%
200	200	87.57%		**100.00%**	**100.00%**	**99.57%**	64.16%
200	300	87.46%		**100.00%**	**100.00%**	**99.55%**	63.74%
200	500	86.65%		**100.00%**	**100.00%**	**99.40%**	60.61%
200	700	84.78%		**100.00%**	**100.00%**	**98.95%**	53.63%
200	900	78.32%		**100.00%**	**99.99%**	**95.48%**	32.73%
200	1100	71.69%		**100.00%**	**99.90%**	87.72%	17.74%
200	1300	67.43%		**100.00%**	**99.71%**	80.23%	11.33%
200	1500	59.11%		**99.99%**	**98.57%**	61.06%	4.12%
400	50	79.00%		**100.00%**	**99.99%**	**96.02%**	34.65%
400	100	79.08%		**100.00%**	**99.99%**	**96.07%**	34.86%
400	200	79.12%		**100.00%**	**99.99%**	**96.10%**	34.98%
400	300	79.07%		**100.00%**	**99.99%**	**96.06%**	34.83%
400	500	78.40%		**100.00%**	**99.99%**	**95.55%**	32.95%
400	700	76.60%		**100.00%**	**99.97%**	93.92%	28.20%
400	900	70.27%		**100.00%**	**99.85%**	85.44%	15.36%
400	1100	64.03%		**100.00%**	**99.41%**	72.97%	7.66%
400	1300	60.15%		**99.99%**	**98.80%**	63.69%	4.73%
400	1500	52.70%		**99.94%**	**96.19%**	44.49%	1.65%

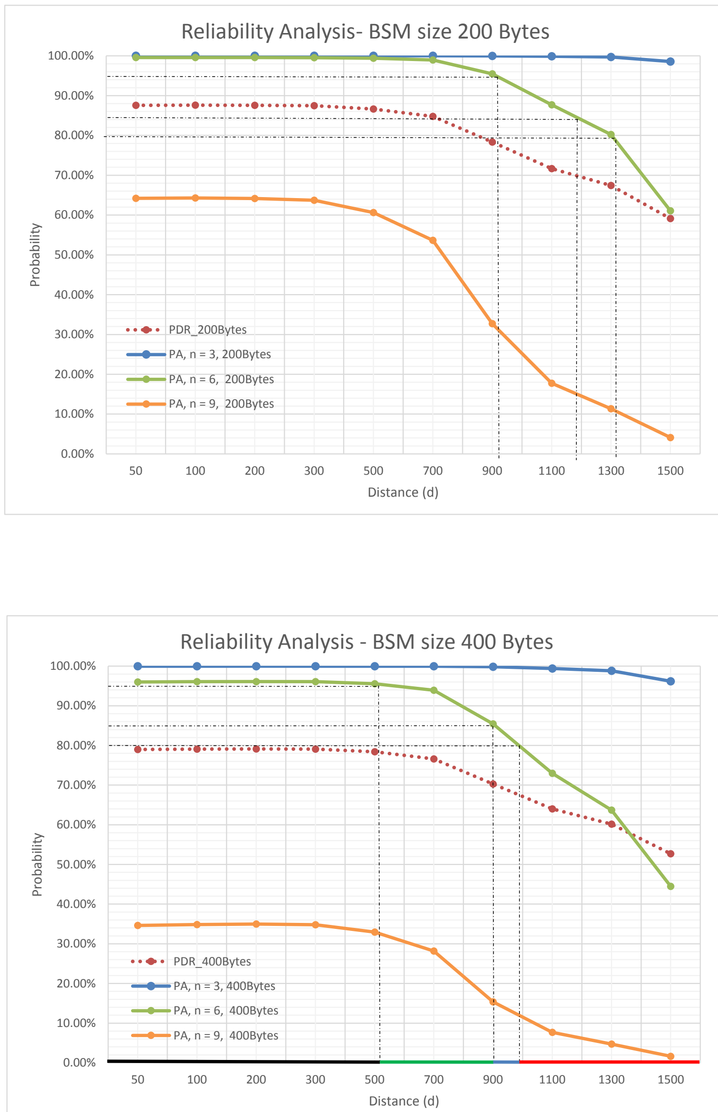

Figure 4.5: The impact of BSM size on safety-application reliability

Table 4.7: Summary of the results

Influencing Factor	Variable parameter	Achievable level of reliability for different requirements of safety applications								
		Requirement of (n <= 3)			Requirement of (n = 6)			Requirement of (n = 9)		
		Level-1	Level-2	Level-3	Level-1	Level-2	Level-3	Level-1	Level-2	Level-3
Transmission Power	10 dBm	***Up to 1500m***			***Up to 750m***	Up to 900m	Up to 1000	x	x	x
	20 dBm	***Up to 1500m***			***Up to 900m***	Up to 1150m	Up to 1300m	x	x	x
	40 dBm	***Up to 1500m***			x	x	Up to 900m	x	x	x
Message Generation Rate	4 Hz	x	Up to 800m	Up to 900m	x	x	x	x	x	x
	6 Hz	***Up to 900m***	Up to 1400m	Up to 1500m	x	x	x	x	x	x
	10 Hz	***Up to 1500m***			***Up to 900m***	Up to 1150m	Up to 1300m	x	x	x
Vehicular Density	28 vehicles	***Up to 1500m***			***Up to 1500m***			***Up to 900m***	Up to 1500m	
	60 vehicles	***Up to 1500m***			***Up to 900m***	Up to 1150m	Up to 1300m	x	x	x
	210 vehicles		Up to 850m	Up to 980m	x	x	x	x	x	x
Message Size	200 Bytes	***Up to 1500m***			***Up to 900m***	Up to 1150m	Up to 1300m	x	x	x
	400 Bytes	***Up to 1500m***			***Up to 500m***	Up to 900m	Up to 1000m	x	x	x

Chapter 5

Conclusion and Future Work

This chapter summarizes the research conducted for this thesis. A discussion on the work along with conclusions and suggestions for future study are also provided.

5.1 Conclusions

Assessing the reliability of safety applications is essential to evaluating the contribution of VANETs to improved safety and driving conditions. Reliability metrics that express the requirements of safety applications in terms of network performance are much more suitable than network-level metrics, as standalone network-level metrics do not indicate whether the requirements of safety applications can be met.

To identify different levels of reliability that can be offered to safety applications, this work employed awareness metrics as an intermediate step between application and network layers, in a form that is influenced by the network conditions and understood by the application layer. The relationship between awareness probability and PDR is used to establish an interrelationship between the network and application layers.

First, through a comprehensive simulation study that involved different scenarios and some of the main influencing factors, this work analyzed the level of awareness that networks can offer under the impact of various operational conditions, including transmission power, message generation rate, vehicular density, message size, as well as radio propagation and fading effects. Then, insights are provided on how network performance metrics address application requirements and contribute to enhancing the reliability of safety applications. Finally, this work has attempted to identify the communication parameters necessary to offer high levels of reliability for three representative safety-application requirements.

5.2 Future Work

Due to time constraints and resource limitations, some scenarios were not included and have been left for future work. Additionally, many research ideas can be built on the results obtained in this work. The following list suggests some areas for extending the work of this thesis:

1. Study more network conditions and scenarios, including the use of higher vehicular densities, the effects of shadowing in urban areas to improve the level of realism in simulations, and the the impact of different road topologies and longer simulation times.

2. Investigate the possibility of providing levels of reliability acceptable to safety applications with high requirements (e.g., n=9).

3. Conduct real experiments which would provide more realistic results than simulations.

4. Develop adaptable safety-applications that can adapt their mechanisms in acquiring awareness based on the available network performance. For example, as opposed to the situation when the network is capable of delivering 10 packets per second, such adaptable safety-applications would need to use sophisticated algorithms to build awareness when the network is capable of delivering only 3 packets per second.

5. Investigate how quantifying the level of reliability offered to users can facilitate the resolution of some of the legal and liability issues. Based on the available network performance, it might be feasible to define the scope of the role that safety applications can provide in assisting drivers. Accordingly, drivers would be able to rely on applications 100% in situations when high reliability levels can be offered, but would be warned not to completely rely on applications and to use other available aids when only low levels of reliability prevail. This flexibility might facilitate the

initial deployment of safety applications.

References

[1] OPNET Technologies, 2008. Available at: http://www.opnet.com/.

[2] Network Simulator 3 - NS-3. https://www.nsnam.org/.

[3] Vehicle safety communications project final report. Technical report. CAMP IVI Light Vehicle Enabling Research Program, US Dept of Transportation HS 810 591, April 2006.

[4] MOVE (MObility model generator for VEhicular networks): Rapid Generation of Realistic Simulation for VANET, 2007. Available at: http://lens1.csie.ncku.edu.tw/MOVE/download.php.

[5] MobiREAL, 2008. Available at: http://www.mobireal.net/.

[6] NCTUns 5.0, 2008. Available at: http://nsl10.csie.nctu.edu.tw/.

[7] STRAW - STreet RAndom Waypoint - vehicular mobility model for network simulations (e.g., car networks), 2008. Available at: http://www.aqualab.cs.

[8] The Georgia Tech Network Simulator (GTNetS), 2008. Available at: http://www.ece.gatech.edu/research/labs/MANIACS/GTNetS/.

[9] SAE. J2735 dedicated short range communications (DSRC) message set dictionary, 2009.

[10] A European FP6 IP project. , 2010. [Online; accessed 19-July-2015].

[11] IEEE Standard for Wireless Access in Vehicular Environments (WAVE)–Multi-channel Operation. *IEEE Std 1609.4-2010 (Revision of IEEE Std 1609.4-2006)*, pages 1–89, Feb 2011.

[12] IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. *IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007)*, pages 1–2793, March 2012.

[13] IEEE Standard for Wireless Access in Vehicular Environments (WAVE)–Networking Services Corrigendum 1: Miscellaneous Corrections. *IEEE Std 1609.3-2010/Cor 1-2012 (Corrigendum to IEEE Std 1609.3-2010)*, pages 1–19, July 2012.

[14] A European FP6 IP project. http://www.its.dot.gov/connected_vehicle/connected_vehicle_policy.htm, 2013.

[15] IEEE Draft Guide for Wireless Access in Vehicular Environments (WAVE) - Architecture. *IEEE P1609.0/D6.0, June 2013*, pages 1–96, Aug 2013.

[16] IEEE Standard for Wireless Access in Vehicular Environments Security Services for Applications and Management Messages. *IEEE Std 1609.2-2013 (Revision of IEEE Std 1609.2-2006)*, pages 1–289, April 2013.

[17] IEEE Guide for Wireless Access in Vehicular Environments (WAVE) - Architecture. *IEEE Std 1609.0-2013*, pages 1–78, March 2014.

[18] ETSI TR 102 638. Intelligent transport system (its); vehicular communications; basic set of applications; definition. Technical report, ETSI, June 2009. ETSI specification TR 102 638, v.1.1.1.

[19] V.A. Aalo, T. Piboongungon, and C.-D. Iskander. Bit-error rate of binary digital modulation schemes in generalized gamma fading channels. *Communications Letters, IEEE*, 9(2):139–141, Feb 2005.

[20] N. Akhtar, O. Ozkasap, and S.C. Ergen. Vanet topology characteristics under realistic mobility and channel models. In *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, pages 1774–1779, April 2013.

[21] N. An, T. Gaugel, and H. Hartenstein. Vanet: Is 95 In *ITS Telecommunications (ITST), 2011 11th International Conference on*, pages 113–119, Aug 2011.

[22] Fan Bai and H. Krishnan. Reliability analysis of dsrc wireless communication for vehicle safety applications. In *Intelligent Transportation Systems Conference, 2006. ITSC '06. IEEE*, pages 355–362, Sept 2006.

[23] Fan Bai, Hariharan Krishnan, Tamer Elbatt, and Gavin Holland. Towards characterising and classifying communication-based automotive applications from a wireless networking perspective. *International Journal of Vehicle Autonomous Systems*, 10(3):165–197, 2012.

[24] Fan Bai, Daniel D. Stancil, and Hariharan Krishnan. Toward understanding characteristics of dedicated short range communications (dsrc) from a perspective of vehicular network engineers. In *Proceedings of the Sixteenth Annual International Conference on Mobile Computing and Networking*, MobiCom '10, pages 329–340, New York, NY, USA, 2010. ACM.

[25] Saeed Bastani, Bjorn Landfeldt, and Lavy Libman. On the reliability of safety message broadcastin urban vehicular ad hoc networks. In *Proceedings of the 14th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, MSWiM '11, pages 307–316, New York, NY, USA, 2011. ACM.

[26] G. Bianchi, L. Fratta, and M. Oliveri. for 802.11 wireless lans. In *Personal, Indoor and Mobile Radio Communications, 1996. PIMRC'96., Seventh IEEE International Symposium on*, volume 2, pages 392–396 vol.2, Oct 1996.

[27] Mate Boban, Wantanee Viriyasitavat, and Ozan K. Tonguz. Modeling vehicle-to-vehicle line of sight channels and its impact on application-layer performance. In *Proceeding of the Tenth ACM International Workshop on Vehicular Inter-networking, Systems, and Applications*, VANET '13, pages 91–94, New York, NY, USA, 2013. ACM.

[28] S.E. Carpenter. Inter-vehicle communications (IVC): Current standards and supporting organizations. North Carolina State University, 2013.

[29] S.E. Carpenter. Obstacle shadowing influences in vanet safety. In *Network Protocols (ICNP), 2014 IEEE 22nd International Conference on*, pages 480–482, Oct 2014.

[30] Qianbin Chen, Hongling Li, Bin Yang, and Rong Chai. A utility based relay vehicle selection algorithm for vanet. In *Wireless Communications Signal Processing (WCSP), 2012 International Conference on*, pages 1–6, Oct 2012.

[31] Federal Communications Commission. Intelligent transportation services report and order. Technical report, FCC, Oct. 1998. R & O FCC 99-305.

[32] Federal Communications Commission. Dedicated short range communications report and order. Technical report, FCC, Dec. 2003. R & O FCC 03-324.

[33] P.M. d'Orey and M. Boban. Empirical evaluation of cooperative awareness in vehicular communications. In *Vehicular Technology Conference (VTC Spring), 2014 IEEE 79th*, pages 1–5, May 2014.

[34] S. Eichler. Performance evaluation of the ieee 802.11p wave communication standard. In *Vehicular Technology Conference, 2007. VTC-2007 Fall. 2007 IEEE 66th*, pages 2199–2203, Sept 2007.

[35] Tamer ElBatt, Siddhartha K. Goel, Gavin Holland, Hariharan Krishnan, and Jayendra Parikh. Cooperative collision warning using dedicated short range wireless communications. In *Proceedings of the 3rd International Workshop on Vehicular Ad Hoc Networks*, VANET '06, pages 1–9, New York, NY, USA, 2006. ACM.

[36] K. Fall and K. Varadhan. ns notes and documents. The VINT Project, UC Berkeley, LBL, USC/ISI, and Xerox PARC. February 2000. Available at: http://www.isi.edu/nsnam/ns/ns-documentation.html.

[37] Xu Guan, Raja Sengupta, H. Krishnan, and Fan Bai. A feedback-based power control algorithm design for vanet. In *2007 Mobile Networking for Vehicular Environments*, pages 67–72, May 2007.

[38] Maurizio Guida, Maurizio Longo, Fabio Postiglione, Kishor S Trivedi, and Xiaoyan Yin. Semi-markov models for performance evaluation of failure-prone ip multimedia subsystem core networks. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 227(3):290–301, 2013.

[39] J. Haerri, M. Fiore, F. Fethi, and C. Bonnet. VanetMobiSim: generating realistic mobility patterns for VANETs. Institut Eurcom and Politecnico Di Torino, 2006. Available at: http://vanet.eurecom.fr/.

[40] J. Harri, F. Filali, and C. Bonnet. Mobility models for vehicular ad hoc networks: a survey and taxonomy. *Communications Surveys Tutorials, IEEE*, 11(4):19–41, Fourth 2009.

[41] H. Hartenstein and K.P. Laberteaux. A tutorial survey on vehicular ad hoc networks. *Communications Magazine, IEEE*, 46(6):164–171, June 2008.

[42] Martin J. Global mobile information systems simulation library. UCLA Parallel Computing Laboratory, 2001. Available at: http://pcl.cs.ucla.edu/projects/glomosim/.

[43] Daniel Jiang, Qi Chen, and Luca Delgrossi. Optimal data rate selection for vehicle safety communications. In *Proceedings of the Fifth ACM International Workshop on VehiculAr Inter-NETworking*, VANET '08, pages 30–38, New York, NY, USA, 2008. ACM.

[44] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, and T. Weil. Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions. *Communications Surveys Tutorials, IEEE*, 13(4):584–616, Fourth 2011.

[45] J.B. Kenney. Dedicated short-range communications (dsrc) standards in the united states. *Proceedings of the IEEE*, 99(7):1162–1182, July 2011.

[46] D. Krajzewicz and C. Rossel. Simulation of Urban Mobility (SUMO). German Aerospace Centre, 2007. Available at: http://sourceforge.net/projects/sumo/.

[47] Anurag Kumar, D. Manjunath, and Joy Kuri. *Wireless Networking*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 2008.

[48] Jia-Chin Lin, Chi-Sheng Lin, Chih-Neng Liang, and Bo-Chiuan Chen. Wireless communication performance based on ieee 802.11p r2v field trials. *Communications Magazine, IEEE*, 50(5):184–191, May 2012.

[49] Hongsheng Lu and Christian Poellabauer. Analysis of application-specific broadcast reliability for vehicle safety communications. In *Proceedings of the Eighth ACM International Workshop on Vehicular Inter-networking*, VANET '11, pages 67–72, New York, NY, USA, 2011. ACM.

[50] Xiaomin Ma, Xianbo Chen, and Hazem H. Refai. Performance and reliability of dsrc vehicular safety communication: A formal analysis. *EURASIP J. Wirel. Commun. Netw.*, 2009:3:1–3:13, January 2009.

[51] R. Mangharam, D. Weller, R. Rajkumar, P. Mudalige, and F. Bai. GrooveNet: A Hybrid Simulator for Vehicle-to-Vehicle Networks. Carnegie Mellon University, 2006. Available at: http://www.seas.upenn.edu/rahulm/Research/GrooveNet/.

[52] F. Martelli, M. Elena Renda, G. Resta, and P. Santi. A measurement-based study of beaconing performance in ieee 802.11p vehicular networks. In *INFOCOM, 2012 Proceedings IEEE*, pages 1503–1511, March 2012.

[53] F.J. Martinez, J.-C. Cano, C.T. Calafate, and P. Manzoni. Citymob: A mobility model pattern generator for vanets. In *Communications Workshops, 2008. ICC Workshops '08. IEEE International Conference on*, pages 370–374, May 2008.

[54] Francisco J. Martinez, Chai Keong Toh, Juan-Carlos Cano, Carlos T. Calafate, and Pietro Manzoni. A survey and comparative study of simulators for vehicular ad hoc networks (vanets). *Wireless Communications and Mobile Computing*, 11(7):813–828, 2011.

[55] R. Meireles, M. Ferreira, and J. Barros. Vehicular connectivity models: From single-hop links to large-scale behavior. In *Vehicular Technology Conference Fall (VTC 2009-Fall), 2009 IEEE 70th*, pages 1–5, Sept 2009.

[56] Jens Mittag, Felix Schmidt-Eisenlohr, Moritz Killat, Jérôme Härri, and Hannes Hartenstein. Analysis and design of effective and low-overhead transmission power control for vanets. In *Proceedings of the Fifth ACM International Workshop on VehiculAr Inter-NETworking*, VANET '08, pages 39–48, New York, NY, USA, 2008. ACM.

[57] Jens Mittag, Florian Thomas, Jérôme Härri, and Hannes Hartenstein. A comparison of single- and multi-hop beaconing in vanets. In *Proceedings of the Sixth ACM Inter-*

national Workshop on VehiculAr InterNETworking, VANET '09, pages 69–78, New York, NY, USA, 2009. ACM.

[58] Moustafa, Hassnaa, and Yan Zhang. Vehicular networks techniques, standards, and applications. Boca Raton: CRC Press, 2009. Available at: http://www.engnetbase.com/ejournals/books/book%5Fsummary/summary.asp?id=7569.

[59] K. Nagel, B. Raney, and H. Spindler. Realistic vehicular traces. Available at: http://www.lst.inf.ethz.ch/research/ad-hoc/car-traces/.

[60] Valery Naumov, Rainer Baumann, and Thomas Gross. An evaluation of inter-vehicle ad hoc networks based on realistic vehicular traces. In *Proceedings of the 7th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, MobiHoc '06, pages 108–119, New York, NY, USA, 2006. ACM.

[61] NHTSA. Fatality analysis reporting system (fars) encyclopedia. http://www-fars.nhtsa.dot.gov/Trends/TrendsGeneral.aspx, 2015. [Online; accessed 19-July-2015].

[62] NHTSA. Press release. http://www.nhtsa.gov/About+NHTSA/Press+Releases/2014/USDOT+to+Move+Forward+with+Vehicle-to-Vehicle+Communication+Technology+for+Light+Vehicles, 2015. [Online; accessed 19-July-2015].

[63] H. Noori and B.B. Olyaei. A novel study on beaconing for vanet-based vehicle to vehicle communication: Probability of beacon delivery in realistic large-scale urban

area using 802.11p. In *Smart Communications in Network Technologies (SaCoNeT), 2013 International Conference on*, volume 01, pages 1–6, June 2013.

[64] World Health Organization. World report on road traffic injury prevention (2004). [Who.int. 2010-12-12. Retrieved 2011-09-20].

[65] M. Piorkowski, M. Raya, AL. Lugo, P. Papadimitratos, M. Grossglauser, and J-P. Hubaux. TraNS (Traffic and Network Simulation Environment). Ecole Polytechnique Fdrale de Lausanne, EPFL, Switzerland, 2007. Available at: http://trans.epfl.ch/.

[66] O. Renaudin, V. Kolmonen, P. Vainikainen, and C. Oestges. Non-stationary narrowband mimo inter-vehicle channel characterization in the 5-ghz band. *Vehicular Technology, IEEE Transactions on*, 59(4):2007–2015, May 2010.

[67] Amit Kumar Saha and David B. Johnson. Modeling mobility for vehicular ad-hoc networks. In *Proceedings of the 1st ACM International Workshop on Vehicular Ad Hoc Networks*, VANET '04, pages 91–92, New York, NY, USA, 2004. ACM.

[68] M. Sepulcre and J. Gozalvez. On the importance of application requirements in cooperative vehicular communications. In *Wireless On-Demand Network Systems and Services (WONS), 2011 Eighth International Conference on*, pages 124–131, Jan 2011.

[69] M. Torrent-Moreno. *Inter-vehicle communications: achieving safety in a distributed wireless environment: challenges, systems and protocols*. PhD thesis, Karlsruhe, 2007.

[70] NHTSA USDOT. Vehicle safety communications applications (VSC-A). Technical report, NHTSA, Sep. 2011. DOT HS 811 492A.

[71] M. van Eenennaam, A. Remke, and G. Heijenk. An analytical model for beaconing in vanets. In *Vehicular Networking Conference (VNC), 2012 IEEE*, pages 9–16, Nov 2012.

[72] A. Vinel, V.M. Vishnevsky, and Y. Koucheryavy. A simple analytical model for the periodic broadcasting in vehicular ad-hoc networks. In *GLOBECOM Workshops, 2008 IEEE*, pages 1–5, Nov 2008.

[73] A. Vlavianos, L.K. Law, I. Broustis, S.V. Krishnamurthy, and Michalis Faloutsos. Assessing link quality in ieee 802.11 wireless networks: Which is the right metric? In *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on*, pages 1–6, Sept 2008.

[74] Gongjun Yan and S. Olariu. A probabilistic analysis of link duration in vehicular ad hoc networks. *Intelligent Transportation Systems, IEEE Transactions on*, 12(4):1227–1236, Dec 2011.

[75] Saleh Yousefi, Mahmood Fathy, and Abderrahim Benslimane. Performance of beacon safety message dissemination in vehicular ad hoc networks (vanets). *Journal of Zhejiang University SCIENCE A*, 8(12):1990–2004, 2007.