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I dedicate this research work to my beloved parents, to my beloved wife, to my beloved daughters and to my siblings.

DECLARATION OF THESIS

Title of thesis	PERFORMANCE EVALUATION OF SINGLE-HOP PERIODIC SAFETY BEACONING FOR VEHICLE-TO-VEHICLE COMMUNICATION IN VANET

I, BILAL MUNIR MUGHAL

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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Date : 27/03/2012

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Dr. Halabi Bin Hasbullah

Date : 27/3/2012

PERFORMANCE EVALUATION OF SINGLE-HOP PERIODIC SAFETY BEACONING FOR VEHICLE-TO-VEHICLE COMMUNICATION IN VANET

By

BILAL MUNIR MUGHAL

A Thesis
Submitted to the Postgraduate Studies Programme
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perbandingan eksklusif antara parameter bolehlaras menunjukkan bahawa semata-mata menyesuaikan *BGI* boleh mencapai *PDR* yang lebih tinggi daripada parameter bolehlaras yang lain, manakala *SBS* kekal sebagai parameter yang kurang berkesan. Ia juga mengesahkan bahawa pelarasan dinamik *CR* dan *BGI* adalah perlu bagi keluaran optimum dari segi *PDR*. Tambahan pula, gabungan optimum parameter-parameter bolehlaras untuk tahap perkhidmatan lebuh raya yang berbeza dan berkaiatn dengan keperluan aplikasi keselamatan, juga turut dipersembahkan.

ABSTRAK

Menyelamatkan nyawa manusia di jalan raya telah menjadi matlamat utama *Vehicular Ad Hoc Network* (*VANET*). Untuk menyediakan keselamatan, kenderaan akan melakukan kesedaran kejiranan dengan bantuan mesej keselamatan. Bagaimanapun, menyediakan satu mekanisma mesej keselamatan yang cekap adalah satu tugas yang mencabar di dalam *VANET* kerana ciri-ciri tertentu *VANET*, iaitu mobiliti yang tinggi, lebar jalur saluran yang terhad, tempoh komunikasi yang sangat pendek, dan topologi sangat dinamik. Dalam kebanyakan skim mesej keselamatan yang telah dicadangkan setakat ini, *Periodic Safety Beacons* (*PSB*) pada amnya dianggap tidak diperlukan jika dibandingkan dengan mesej yang dipacu-peristiwa. Bagaimanapun, secara realiti, hubungan *PSB Vehicle-to-Vehicle* (*V2V*) digunakan untuk mengumpul maklumat kritikal yang diperlukan oleh semua mesej skim keselamatan dan tidak boleh diketepikan. Oleh itu, memastikan *QoS* yang optimum untuk satu-hop *PSB V2V* adalah penting demi mencapai tahap keselamatan yang boleh diterima. Walau bagaimanapun, penilaian prestasi yang menyeluruh terhadap *PSB* hop-tunggal akan dilakukan.

Kerja kajian ini menyelidik secara komprehensif terhadap keselamatan *V2V* hop-tunggal beacon berkala dengan menumpukan ke atas parameter bolehlaras, iaitu *Beacon Generation Interval* (*BGI*), *Safety Beacon Size* (*SBS*), dan *Communication Range* (*CR*) yang mengawal tingkah laku mereka. Keputusan dari simulasi menyeluruh menunjukkan bahawa semata-mata menyesuaikan parameter bolehlaras atau gabungannya, tidak sepenuhnya mampu memenuhi kriteria *QoS* ketat yang diperlukan untuk aplikasi keselamatan. Secara keseluruhan, tahap kelewatan hujung-ke-hujung yang boleh diterima boleh dicapai dengan secara dinamiknya menyesuaikan parameter bolehlaras dengan *BGI* > 100ms, tetapi *BGI* lebih rendah tidak sesuai dengan *SBS* yang lebih besar. Dalam keadaan lalu lintas yang padat, kriteria *PDR* ketat 99% tidak pernah mencapai sasaran *CR* melebihi 100m. Satu

ABSTRACT

Saving human lives on road has become the prime objective of Vehicular Ad hoc Network (VANET). In order to achieve safety, vehicles maintain neighborhood awareness with the help of safety messages. Providing an efficient safety messaging mechanism is a challenging task in VANET, due to particular characteristics of VANET, i.e. high mobility, limited channel bandwidth, very short communication duration, and highly dynamic topology. In most of the safety messaging schemes proposed so far, Periodic Safety Beacons (PSBs) are generally considered dispensable in comparison with event-driven messages. However in reality, vehicle-to-vehicle (V2V) PSBs are used to collect critical information required by all the safety messaging schemes and cannot be dispensed. Thus, ensuring optimum QoS for V2V single-hop PSBs is essential for achieving acceptable level of safety. However, thorough performance evaluation of V2V single-hop PSBs is yet to be carried out.

This research comprehensively investigates V2V single-hop periodic safety beaconing in the light of tunable parameters i.e. Beacon Generation Interval (BGI), Safety Beacon Size (SBS), and Communication Range (CR) that govern their behavior. Results from exhaustive simulations show that adjusting tunable parameters solely or combined does not fully satisfy the strict QoS criterion required for safety applications. Overall, an acceptable level of end-to-end delay can be achieved by dynamically adjusting tunable parameters with BGI > 100ms, but lower BGI is not suitable with larger SBS. In dense traffic conditions strict PDR criterion of 99% is never achieved beyond 100m target CR. An exclusive comparison between tunable parameters shows that solely adjusting BGI can attain relatively higher PDR than other tunable parameters while SBS remains the least effective parameter. It is also validated that dynamic adjustment of CR and BGI is necessary for optimal output in terms of PDR. Furthermore, optimal combinations of tunable parameters for different highway service levels with respect to safety application requirements are also presented.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC	Access Category
ACI	Access Category Index
ACK	Acknowledgment
AIFSN	Arbitration Inter-Frame Space Number
ATB	Adaptive Traffic Beacon
BGI	Beacon Generation Interval
BLR	Beacon Loss Ratio
BPSK	Binary Phase Shift Keying
BSM	Basic Safety Message
C2CC	Car Communication Consortium
CACC	Cooperative Adaptive Cruise Control
CAT	Channel Access Time
CBT	Channel Busy Time
CCH	Control Channel
CCW	Cooperative Collision Warning
CEN	The European Committee for Standardization
CR	Communication Range
CRC	Cyclic Redundancy Check
CS	Carrier Sense
CSMA	Carrier Sense Multiple Access
CTS	Clear to send
CVSSs	Cooperative Vehicle Safety Systems
CW	Contention Window
DCF	Distributed Coordination Function
D-FPAV	Distributed Fair transmit Power Adjustment for Vehicular ad hoc networks
DIFS	DCF InterFrame Space
DoT	Department of Transportation

DRCV	Distributed Rate Control Algorithm for VANETs
DSRC	Dedicated Short Range Communication
DVDE	Distributed vehicle Density Estimation
e2e	End-to-end (delay)
ECR	Effective Communication Range
EDCA	Enhanced Distributed Channel Access
EEBL	Emergency Electronic Break Lights
EIFS	Extended InterFrame Space
EMDV	Emergency Message Dissemination for Vehicular environment
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FCW	Forward Collision Warning
FPAV	Fair transmit Power Adjustment for Vehicular ad hoc networks
GHz	Gigahertz
GPS	Global Positioning System
GREP	global regular expression print
ICR	Intended Communication Range
IEEE	Institute of Electrical and Electronics Engineers
IRTAD	International Road Traffic and Accident Database
ISO	International Standardization Organization
ITS	Intelligent Transportation System
Kbps	Gigabits per second
LLC	Logical Link Control
LOS	Line Of Sight
MAC	Media Access Control
MANET	Mobile Ad hoc Network
MBL	Maximum Beaconing Load
Mbps	Megabits per second
MHz	Megahertz
MLME	MAC Layer Management Entity
MSDU	MAC Service Data Unit
NAM	Network Animator

NHTSA	National Highway Traffic Safety Administration
NoW	Network on Wheels
NS-2	Network Simulator - 2
OBU	Onboard Unit
OFDM	Orthogonal Frequency-division Multiplexing
OTcl	Object Oriented Tool Command Language
PDR	Packet Delivery Ratio
PHY	Physical (layer)
PLCP	Physical Layer Convergence Protocol/Procedure
PLME	Physical Layer Management Entity
PLR	Packet Loss Ratio
PMD	Physical Media Dependent
PSBs	Periodic Safety Beacons
PSID	Provider Service Identifier
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RCP	Resource Command Processor
RCPI	Received channel power indicator
RF	Radio Frequency
RM	Resource Manager
RMA	Resource Manager Applications
RSU	Roadside Unit
RTS	Request to send
SBS	Safety Beacon Size
SCH	Service Channel
SIFS	Short InterFrame Space
TCL	Tool Command Language
TCP	Transport Control Protocol
TR	Transmission Range
TRG	Two-Ray Ground
UBPFCC	Utility-Based Packet Forwarding and Congestion Control
UDP	User Datagram Protocol

V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad hoc Network
VMESH	Vehicular MESH Network
VSC	Vehicle Safety Communication
WAN	Wide Area Network
WAVE	Wireless Access in Vehicular Environment
WBSS	WAVE basic service set
WC	Worst Case
WME	WAVE Management Entity

CHAPTER 1

INTRODUCTION

This chapter presents the introduction of relevant research field and various related topics. Furthermore, research questions and research objectives are also defined in this chapter. At the end of the chapter, brief summary of all the remaining chapters is also provided.

1.1 Overview

Intelligent Transportation System (ITS) has long been envisaged to replace conventional driving paradigm. In order to help drivers make safer decisions, vehicles can make use of sensors and communication devices. One such example is Vehicular Ad hoc Network (VANET). Saving human lives is the prime concern of VANET; in addition it can also be used for commercial purposes.

VANET communication is anticipated to play a crucial role in Intelligent Transportation System (ITS) [1]. Furthermore, VANET inherits its technological features from Mobile Ad hoc Network (MANET). Apart from many similarities, i.e. ad hoc structure, mobility and wireless communication, MANETs and VANETs also have some distinct features. For example in MANETs, nodes move arbitrarily while in VANETs, primarily nodes follow a predefined path (roads), which makes their movement more predictable. VANET nodes move at much higher velocities than nodes in MANETs. Generally, VANET nodes (vehicles) are not affected by stringent energy constraints and can accommodate various types of equipment e.g. high performance processors, wireless transceivers, various types of sensors, GPS equipment, cameras etc [2]. On the other hand, energy is a scarce resource in MANET nodes. In essence, VANETs pose various new challenges that cannot be simply resolved by applying MANET strategies to them.

In VANET, vehicles form decentralized network(s) by communicating via On-Board-Units (OBUs) in a given geographical area. Generally two types of communication takes place in VANET i.e. vehicles communicate with roadside infrastructure, called Vehicle-to-Infrastructure (V2I) communication and vehicles communicating with nearby vehicles called Vehicle-to-Vehicle (V2V) communication. Both types of communication are sometimes collectively described as vehicle to all (V2X) communication.

Safety applications that make use of information exchange between neighboring vehicles and roadside infrastructure can help save lives on road. A comprehensive set of possible safety applications have been identified in Vehicle Safety Communications Project report [3]. VANET applications can be divided into two major categories, i.e. safety and non-safety applications. Applications that are critical to human life safety are placed under safety application category, e.g. pre-crash sensing, post-crash warning, pedestrian/children warning, etc. The rest of the applications, fall in non-safety category, which includes toll collection, mobile internet, infotainment and many more. To achieve a level of safety, VANET-equipped vehicles exchange messages (beacons), i.e. event-driven safety beacons and periodic safety beacons, to keep themselves aware of the neighborhood situation at all times. Both types of beacons are transmitted over single-hop or multi-hop distance.

Event-driven beacons are broadcast when a hazardous situation is detected on the road, e.g. accident. Examples of applications that can use event-driven beacons are post crash warning, Emergency Electronic Brake Lights (EEBL), etc. However, the focus of this study is on Periodic Safety Beacons (PSBs). PSBs are exchanged among neighboring vehicles several times per second and contain information (e.g. position, speed, direction, etc) that is useful for driver's awareness of the surrounding situation. Efficiency of many envisioned safety applications e.g. cooperative collision warning, lane change warning, wrong way driver warning and others, depends upon the information received via periodic beacons.

1.2 VANET Standardization

All over the globe, plenty of research work is being carried out to help refine the VANET standards, i.e. frequency allocation, routing algorithms, PHY and Link layer specifications, as well as security issues and new application [4]. Efforts to finalize VANET communication standards, i.e. Wireless Access in Vehicular Environment (WAVE), IEEE 1609.x and 802.11p are in progress by standardization organizations. WAVE is a trial layered architecture designed for V2X communication and is to be used by IEEE 802.11 devices operating within the DSRC band.

In USA, Federal Communications Commission (FCC) has allocated Dedicated Short-range Communications (DSRC) spectrum at 5.9 GHz, which is structured into seven of 10 MHz wide channels. Channel 178 (5.885-5.895GHz) is the control channel (CCH) and is primarily used for safety communications. The two extreme channels (Ch172 & Ch184) are reserved for future safety applications, e.g. advanced accident avoidance applications. The other service channels (SCH) are to be used for future safety as well as non-safety applications. At PHY level, the philosophy of IEEE 802.11p design is to make minimum necessary changes to IEEE PHY so that WAVE devices can communicate effectively among the fast moving vehicles in the roadway environment [5].

Similar measures are taken in other parts of the world, for example in Europe, plans are on the way to allocate a spectrum of 30 MHz in the 5GHz band for vehicular safety communications [5]. Similar efforts are also taking place in Japan, Korea and Brazil.

1.3 Research Background

Providing efficient safety messaging scheme is a challenging task due to particular characteristics of VANET, i.e. high mobility, limited channel bandwidth, very short communication duration, and highly dynamic topology. Furthermore, the broadcast nature of communication in VANET, may lead to saturated/congested channel, which was identified as a major concern for efficient safety communication by [6] and [7].

However, it is possible to reduce these side effects by taking appropriate remedial actions. For example, according to [8], transmission powers and transmission rate are suitable methods for periodic messaging congestion control.

A comparison of ad hoc network broadcasting schemes is given in [9]. Multi-hop broadcast communication has been extensively studied in ad hoc networks [10–14]. Multi-hop communication and event-driven messaging has also been well studied in [15–23]. In VANETs, some studies partially address single-hop broadcast under different objectives, e.g. congestion control [24–30] and connectivity [31], [32]. As a common approach, in these studies single-hop periodic beaconing is mainly treated as background traffic and is considered dispensable, while event-driven messaging is given the prime importance. Event-driven messages are triggered by specific events, e.g. accidents, ensuring their delivery over single hop as well as over multi-hop distance is also important. On the other hand, event-driven messages are primarily a reactive safety mechanism to prevent further damage. While, periodic safety beacons (PSBs) are a proactive approach that can minimize the happening of such life threatening incidents in the first place. Therefore, treating PSBs as background traffic is not realistic, as many life safety applications are dependent upon periodic beaconing.

All the studies, considering single-hop PSBs as background traffic do not provide in-depth analysis of V2V single-hop periodic safety beaconing. Since, single-hop PSBs will predominantly occupy the control channel communication; it may have adverse effects on overall VANET communication i.e. channel congestion. On the other hand, successful and timely delivery of PSBs is also essential for saving lives, as they can proactively monitor potentially dangerous situations on the road and can help to prevent accidents from happening. Thus, there is a strong need to thoroughly analyze practicality of single-hop periodic safety beaconing. It is also important to evaluate parameters (such as transmission power/communication range, beacon generation interval, beacon size) used to control behavior of single-hop PSBs.

Only few studies focus on periodic beaconing, e.g. in [33–35], authors performed simulation based studies for exploring some predefined VANET message dissemination characteristics. However, these studies do not provide comprehensive analysis of V2V single-hop PSBs.

1.4 Research Spotlight

Smooth functionality of VANET and effectiveness of safety applications are highly dependent upon the safety messaging schemes. PSBs will predominantly occupy control channel communication as the heartbeat of VANET and are expected to provide fundamental information for message dissemination and geographic routing [36]. Thus, all safety applications and messaging schemes are inherently dependent upon the behavior of single-hop PSBs. Consequently, it becomes essential that effects of single-hop PSBs on overall VANET performance be known beforehand. Furthermore, it is also necessary to evaluate the parameters involved in controlling the behavior of periodic safety beacons, such as Beacon Generation Interval (BGI), Safety Beacon Size (SBS), and Communication/Transmission Range (CR/TR) or transmission power.

1.4.1 Research Questions

This research is focused on following research questions.

- What is the impact of single-hop periodic broadcast of safety beacons on the performance of vehicle-to-vehicle communication?
- Which method is the most effective in achieving higher QoS for vehicle-to-vehicle periodic safety beaconing?
- How to optimize the single-hop periodic beaconing in the context of vehicle-to-vehicle safety applications?

1.4.2 Research Objectives

The objectives of this research are:

a) To analyze the impact of single-hop periodic safety beacons and tunable parameters involved in controlling their behavior, i.e. Beacon Generation Interval (BGI), Safety Beacon Size (SBS) and Communication Range (CR).

b) To determine the effectiveness of communication range control and beacon generation interval control methods in improving V2V periodic safety beaconing performance.

c) To find optimal combinations for tunable parameters with reference to requirements of safety applications that depend upon V2V periodic safety beaconing.

1.4.3 Motivation

According to Annual Road Safety Report 2009 [37] issued by the International Road Traffic and Accident Database (IRTAD), on-road fatality rate in many countries has been reduced in recent years. However, the numbers are still quite high. For example, in 2008, 37,261 people died in road accidents in USA alone. In the same year, 6,527 on road deaths were recorded in Malaysia and 6,023 on road deaths in Japan. For the year 2007/08, among the IRTAD member countries, Malaysia has the highest on road fatality to population ratio, i.e. 23.5 fatalities per 100,000 inhabitants, followed by Poland (14.26) and Greece (13.84). A large portion of these fatalities occur outside urban areas, e.g. motorways.

VANET is a promising technology that can help reduce number of road accidents, consequently minimizing fatalities and injuries. Furthermore, a rapid growth in VANET implementation can make the system ubiquitous. Various regional and international organizations are participating in DSRC standardization at present, e.g. Institute of Electrical and Electronics Engineers (IEEE), The European Committee for

Standardization (CEN), International Standardization Organization (ISO). There are many ongoing projects focused on various aspects of VANET. Some of the major projects include, "Crash Avoidance Research Program" by National Highway Traffic Safety Administration (NHTSA), "Connected Vehicle Research" by Department of Transportation (DoT) in USA, Car to Car Communication Consortium (C2CC) and Network on Wheels (NoW) in Europe are some of the major programs.

Motivation of this study comes from the fact that Periodic Safety Beacons (PSBs) will provide the core information required to achieve safety through VANET. Hence, evaluating their performance under challenging environment is essential in order to determine their practical feasibility and to determine the parameters effective in improving their efficiency.

1.4.4 Scope and Limitations

This research specifically focuses on vehicle-to-vehicle single-hop periodic broadcast of safety beacons. Topics like vehicle-to-infrastructure communication, multi-hop communication, event driven messaging or congestion control are beyond the scope of this study. Assumptions and limitations of experimental setup used in this research are given in the following.

a. In all the simulations, it is assumed that all nodes are equipped with VANET supported equipment e.g. OBU, GPS devices. Furthermore, only IEEE WAVE architecture for safety communication is implemented, other trial architectures like C2C-CC are not considered.

b. According to USA FCC, safety communication will use control channel and a vehicle may optionally switch to other service channels for other types of communication e.g. non-safety applications. Since, the focus of the study is safety communication, channel switching is not considered in the simulations.

c. All road and traffic settings used for simulations are based on highway scenarios and urban scenarios are not considered. Furthermore, vehicle movement is not considered in order to maintain uniform worst case scenarios for highways.

1.5 Overview of Methodology

The main aim of this research is to appraise the performance of PSBs and to analyze the impact of parameters that govern them. In the foremost, parameters that can be tuned to control the behavior of periodic safety beacons are introduced. Choosing appropriate value ranges for these parameters is also a subject of great interest and is discussed in detail. Suitable Quality of Service (QoS) metrics used to evaluate the performance of PSBs under selected parameters are also given their due attention.

Proper performance evaluation of PSBs requires testing of all the involved parameters on large scale. However, implementing real world VANET is not practical due to lack of hardware standardization and availability. In addition, a large scale deployment of real world VANET system is extremely costly due to the large amount of required resources. The intrinsic complexity of real world VANET scenarios also makes it very difficult to analyze the performance of specific parameters as is the case in this research. It is also very difficult to reproduce the acquired results for such a complex and diverse system. Nonetheless, realistic modeling of the VANET system is also necessary for accurate performance evaluation of PSBs and the involved parameters.

Two of the traditional modeling approaches that can be used for implementing VANET system are analytical approach and simulation approach. For simple and small systems, analytical modeling is preferable, while for large and complex systems, simulation approach is more suited [38]. Furthermore, as compared to analytical modeling, simulations typically require fewer assumptions. With the help of detailed configurations of the system, one can avoid oversimplifications which can lead to inaccurate representation of the underlying system. Most importantly this can be achieved with little or no cost. Thus, for this research a simulation based approach is used for performance evaluation of V2V single-hop PSBs.

Research design is discussed with details in chapter 3. Research design consists of several components i.e. network simulator, system model, simulation setup, traffic scenarios and coding process. Several simulation tools are available for designing wireless networks. NS-2 is chosen as the most suitable choice based on its reliability and credibility among research community. The most imperative part of any simulation based research is the system model as it is used to depict the real world system. System model used in this research is based on VANET trial architecture and standards along with realistic road environment. Relevant simulation settings are also set to closely match vehicular safety communication. A new worst case scenario is introduced that justifies safety application requirement and also represents practically taxing situations under which VANET system has to operate in real world environment. Several programs and scripts are written to accomplish various tasks in order to achieve the objectives of this research. Sample codes are also provided in Appendix A and Appendix B.

Exhaustive simulations are carried out under deterministic and probabilistic (also called non-deterministic) propagation models with various combinations of tunable parameters to test their behavior and effectiveness. Results are analyzed and effectiveness of each tunable parameter is determined. Furthermore, a comparative analysis of results obtained from deterministic and probabilistic propagation models is also presented to determine the effectiveness of both models. Different set of simulations are performed using probabilistic propagation model to find optimal combinations of the tunable parameters for various highway service levels.

1.6 Research Contributions

In the light of the objectives stated in Section 1.4.2, following are the contributions of this research.

a. All the results were presented with high level of accuracy through appropriate implementation of PHY and MAC layer for VANET trial standards using latest NS-2 simulator. Furthermore, various result calculation methods were used for broader evaluation of the parameters involved.

b. It is validated that conventional dynamic power control and beacon generation interval schemes do not fully satisfy V2V safety application requirements. This leads to the conclusion that dynamic adjustment of both parameters is necessary for efficient V2V single-hop periodic beaconing.

c. To evaluate the performance of V2V single-hop periodic safety beaconing extensive simulations were carried out using a realistic system model and several findings are presented along with perceptive recommendations.

d. A new realistic worst case traffic scenario for highway is introduced. The scenario depicts challenging environment in which VANET has to operate and also considers life threatening situation, justifying the use of safety applications. Several worst case scenarios for different highway service levels are also presented.

e. Optimal range of each tunable parameter in worst case scenario and optimal combinations of BGI & CR for different highway service levels are presented. These optimal combination values can be used as lookup tables for efficient safety communication and can also facilitate development of new safety applications.

f. Micro level details of the simulation configurations for VANET implementation are provided along with sample codes for seamless reproduction of results. These settings can also be used by other researchers without going into preliminaries. More than 800+ GB of available trace data can be used for further analysis of different V2V communication aspects.

1.7 Thesis Organization

This dissertation is divided into six chapters. The following is the layout of the study along with brief details of the matter covered in each chapter.

Chapter 2: This chapter covers of the literature review related to the VANET trial standards, and safety communication. Related work to the current study is also discussed in detail. Furthermore, shortcomings and gaps in closely related works are also highlighted.

Chapter 3: This chapter presents the simulation based research methodology approach taken to accomplish the objectives of this study. The system model is also presented along with worst-case highway scenarios. The tunable parameters and performance metrics are also discussed. The coding and result handling process is also described in this chapter.

Chapter 4: In this chapter, the complete simulation setup is explained including simulation grid design, MAC&PHY configurations and radio propagation models. Furthermore, rational reasoning behind settings for various configuration parameters and their respective values is also provided. Particular attention is paid in describing all micro-level settings for convenient reproduction of results and scenarios.

Chapter 5: Detailed results and discussion of V2V single-hop periodic safety beaconing in deterministic and probabilistic propagation models under worst-case scenario are presented in this chapter. Comparative analysis between results from both propagation models is also given. Detailed insight into Beacon Loss Ratio (BLR) and its causes is also discussed. Through exhaustive simulation, optimal values of tunable parameter for worst case scenarios and several highway service levels are also presented.

Chapter 6: Final chapter contains the findings, recommendations and contributions of the present research. In the light of research findings, future direction of the research is determined and duly discussed.

CHAPTER 2

LITERATURE REVIEW

This chapter is abstractly divided into two parts. First part provides details of VANET architecture and its trial standards as a prerequisite to understand VANET communication and its fundamentals. The safety applications dependent on V2V periodic beaconing are also introduced. The second part contains analysis of partially and closely related work to current research area that was carried out over the period of time up till recently. Importantly, this chapter also highlights the gaps that remain unfulfilled by the previous studies thus providing essential reasoning behind the need to carry out this research work.

2.1 VANET Communication

Primarily there are two types of communication devices in VANETs. The first type called roadside unit (RSU), is usually permanently fixed along the roadside and is only active in stationery mode. The second type, called onboard unit (OBU), is usually mobile as it is mounted on vehicles. Figure 2.1 illustrates communication setup between VANET devices. V2V communication occurs between vehicles via OBUs, while V2I communication typically involves OBU/s and RSU.

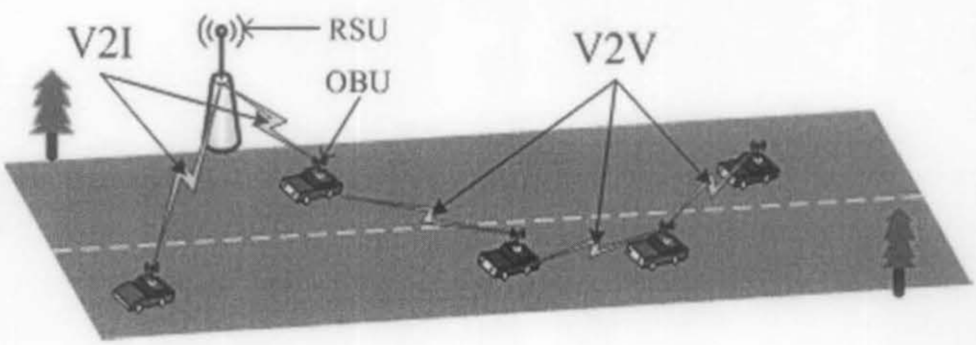


Figure 2.1: Communication in VANET

Since saving human lives is the prime objective of the VANETs, all necessary steps are to be taken before their full deployment. In fact trial use of some VANET safety applications has already begun in USA, while some non-safety applications e.g. toll collection are also implemented in Japan.

2.2 Standards and Protocols

VANET nodes communicate via Wireless Access in Vehicular Environment (WAVE) layered architecture and DSRC. Protocols defined for VANET work within this WAVE/DSRC system. Figure 2.2 shows communication setup of VANET devices within the DSRC/WAVE system.

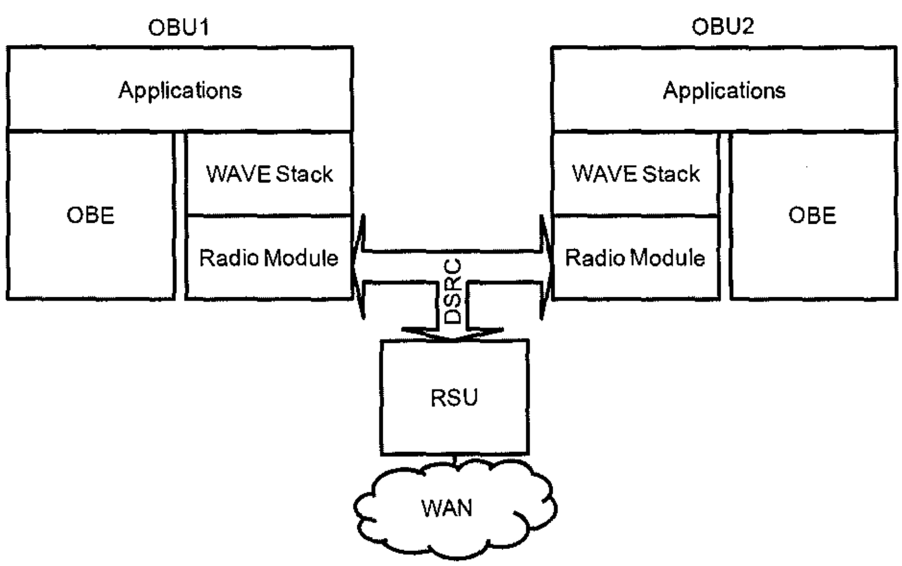


Figure 2.2: DSRC/WAVE system

DSRC/WAVE system is generally attributed to low latency (in milliseconds) communication. DSRC/WAVE system and relevant standards are introduced in the following.

2.2.1 Dedicated short-range communication (DSRC)

DSRC is short-to-medium range wireless communication channel exclusively planned for vehicular networks accompanied by specific standards and protocols. In the USA Federal Communications Commission (FCC) has allocated a 75MHz spectrum in

5.9GHz band to be used for DSRC within ITS. In Europe, the European Telecommunications Standards Institute (ETSI) has used a similar approach and has reserved a 30MHz spectrum in the 5.9GHz band for similar purposes. The selection of 5GHz band spectrum is based on its propagation characteristics and spectral environment, which are considered suitable for vehicular environments, i.e. radio propagation with high data rate over short-to-medium range distances with low weather dependence. DSRC systems in Europe and Japan are currently used for electronic toll collection only.

Previously, DSRC spectrum was only associated with lower frequency, i.e. 915MHz. The new 5.9GHz frequency enables higher data rates than the lower-frequency 915MHz band. The 915MHz range offers only 12MHz of shared spectrum with garage door openers, cordless telephones, and various other applications. In 5.9GHz band, other users in the range include military radars and satellite communication. Figure 2.3 shows USA DSRC allocation distribution of seven 10MHz channels.

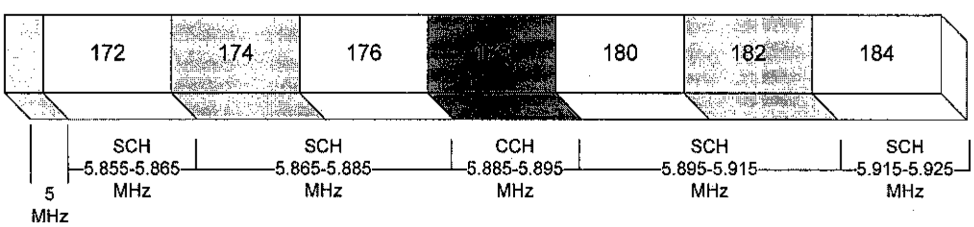


Figure 2.3: DSRC Spectrum allocated by FCC in USA

Central channel 178 with frequency allocation of 5.885MHz onwards is dedicated for safety communication along with control overhead and is known as control channel (CCH). Both extreme channels 172 and 184 are reserved for future applications, such as safety. The rest of the service channels (SCH) are allocated for non-safety applications. Two adjacent 10MHz non-safety channels can be combined into a single 20MHz channel if required by certain applications.

2.2.1 Wireless Access in Vehicular Environment (WAVE)

WAVE is a trial standard that defines management model, communication architecture, physical access, and security methods for short-to-medium range wireless communication in support of devices operating in multi-channel vehicular environment. The basic aim is to facilitate vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) wireless communications along with the safety and non-safety applications to the users.

A DSRC/WAVE system consists of Roadside Units (RSUs) and On-Board-Units (OBUs). RSUs are primarily static devices, in some cases they are portable but do not function while in transit, while OBUs are mounted on vehicles and are mostly mobile. By default, RSUs and OBUs operate independently and communicate over control channel (CCH). However, a set of only OBUs or OBUs and RSUs can form a small network called WAVE basic service set (WBSS). All the nodes associated with specific WBSS communicate through a service channels (SCH). A WBSS can connect to a Wide Area Network (WAN) with appropriate setup. Figure 2.4 shows WAVE services architecture loosely bonded to OSI reference model.

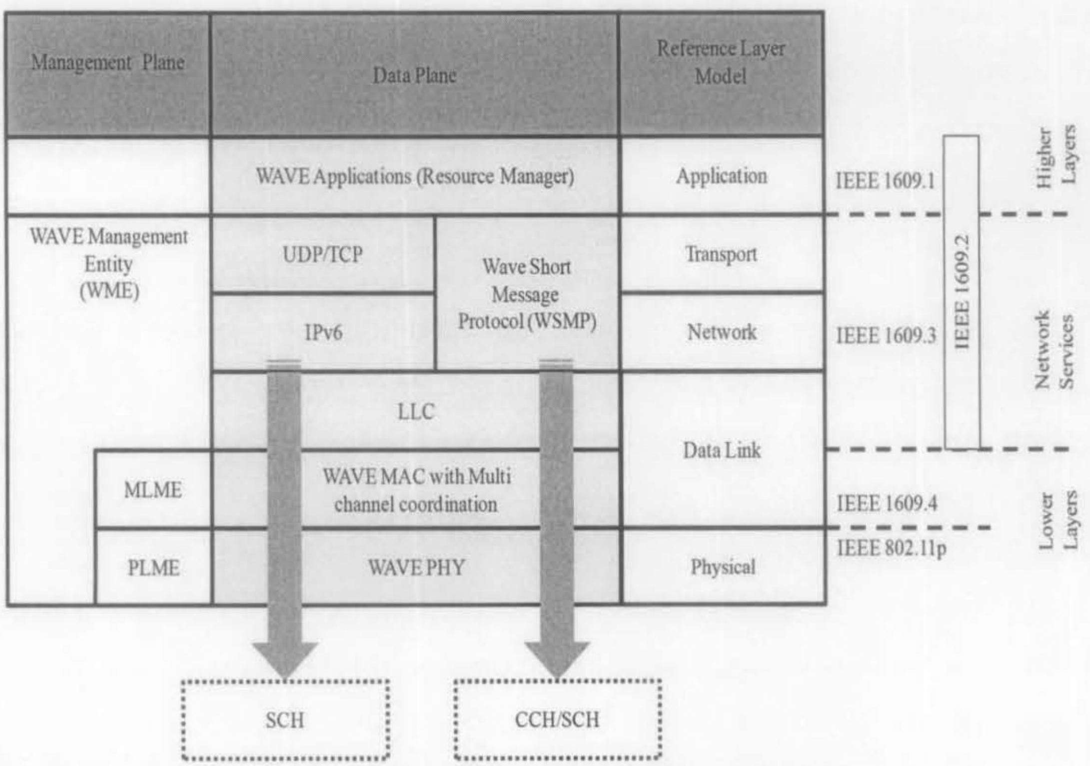


Figure 2.4: WAVE architecture with reference to respective OSI layers

The WAVE architecture basically consist of IEEE 802.11p and IEEE 1609.x set of trial-use standards under development. IEEE 1609.x is comprised of four documents, i.e. IEEE 1609.1, IEEE 1609.2, IEEE 1609.3 and IEEE 1609.4. A brief description of the each of these standards along some relevant protocols is given in the following.

2.2.2 IEEE 1609.1 (Resource Manager)

IEEE 1609.1 standard is documented in [39] and the objective of the standard is to facilitate a variety of applications handled by an On-Board-Unit in a cost effective manner within DSRC/WAVE system.

Usually, RSUs host applications that provide certain services, and the OBUs host peer applications that uses these services. In some situations, certain applications providing services to the OBUs may reside on devices remote from the static RSUs. This standard defines application called resource manager (RM) that resides on RSU or OBU and it also defines application called resource command processor that resides on OBU. The applications that reside on devices remote from RSU are known as resource manager applications (RMAs). RMAs communicate with Resource Command Processor (RCP) at OBU through RM. The objective of the communication is to provide ample resources such as memory, user interfaces and interfaces to the RCP equipment, to satisfy the requirements of RMAs.

The RM communication is based upon the concept of entities known as provider and user, the communication is initiated by the provider, which issues requests to a user, which responds only to requests received. Here the RM acts as the provider of a service (representing RMAs), and RCP is the user of the service (represents the resources to be managed). Either the RSU or OBU can host the RM, thus act as the provider. A system using RM concept is able to execute applications at remote devices, thus reducing the processing complexity at mobile devices, i.e. OBUs. This reduction in processing complexity is considered a simple way to reduce OBU manufacturing cost, while maintaining the reliability and ensuring compatibility between different manufacturer products. Furthermore, the concept allows future application development and deployment without modifying onboard hardware or software.

2.2.3 IEEE 1609.2 (Security Services)

IEEE 1609.2 standard is documented in [40] and defines formats and the processing of secure messages, within the scope of DSRC/WAVE system. Apart from vehicle-originating safety messages the standard covers methods for securing all WAVE management and application messages; however vehicle-originating safety messages are expected to be included later on.

Given the safety-critical nature of many applications, it is vital to specify methods against threats like eavesdropping, alteration, spoofing, and replay. Since the system usages involves individuals, it is also important to provide privacy to secure personal information. To satisfy these security constraints, cryptographic mechanisms are provided that mainly include symmetric algorithms or secret-key, asymmetric algorithms or public-key and hash functions.

Furthermore, safety applications require minimum latency in the delivery of information; therefore, it is also important to minimize overhead incurred by the processing while keeping the bandwidth usage in check.

2.2.4 IEEE 1609.3 (Networking Services)

IEEE 1609.3 standard as documented in [41] defines networking services across LLC, network, and transport layers of the OSI model, within DSRC/WAVE system. The protocol supports communication between portable, stationery and mobile WAVE devices. Based on the functionality networking services can be divided into two parts i.e. management services and data plane services.

Management plane services comprise of a set of services known as the WAVE Management Entity (WME). WME service set includes:

- Application registration
- WBSS management
- Channel usage monitoring
- IPv6 configuration

- Received channel power indicator (RCPI) monitoring
- Management information base (MIB) maintenance

All applications requiring networking services must get a unique Provider Service Identifier (PSID) that is registered with the WME. WBSS management service handles WBSS operations on behalf of applications that provide a service. Channel usage monitoring process is yet to be specified. However WME permits tracking of SCHs usage patterns. Channel usage information is used to select a less congested channel for establishing a WBSS. DSRC/WAVEE system supports IPv6 traffic on service channels only. Received Channel Power Indicator (RCPI) is used monitor received signal strength of a remote device. An application requiring the signal strength information sends a query via WME and remote device responds via MLME instead of WME. All the system and application related information is stored in a WME database called Management Information Base (MIB).

Data plane services are primarily comprised of IPv6: and WSMP protocol stacks, operating above LLC layer. The IPv6 stack handles traditional traffic (via service channels only) with the help of TCP/UDP protocols, while WSMP tackles high-priority, delay-sensitive traffic (mainly via control channel).

2.2.5 IEEE 1609.4 (Multi-channel Operations)

IEEE 1609.4 standard is documented in [42] and specifies multi-channel operation within WAVE/DSRC system. It is an innate requirement of WAVE/DSRC system that a WAVE device must support multichannel architecture consisting of a control channel and multiple service channels. The channel switching or channel coordination is an augmentation to IEEE 802.11 MAC and is bound to interact with IEEE 802.2 LLC and IEEE 802.11 PHY.

The standard describes the MAC and PHY layer functionalities that handle the Control Channel (CCH) and Service Channel (SCH) operations. The functionalities include but are not limited to management services, priority access mechanism, channel routing, channel coordination, and data transmission. Figure 2.5 shows the reference architecture of the MAC with channel coordination as shown in [42].

Based upon Enhanced Distributed Channel Access (EDCA) function of IEEE 802.11e, the priority access mechanism is used for contention to access the medium on control and service channels (details in section 2.2.8).

The purpose of the channel router function is to route data traffic from LLC to the selected channel within channel coordination process at MAC layer. To choose a suitable channel for MAC Service Data Unit (MSDU) transmission, the channel coordination process adjusts the channel intervals accordingly.

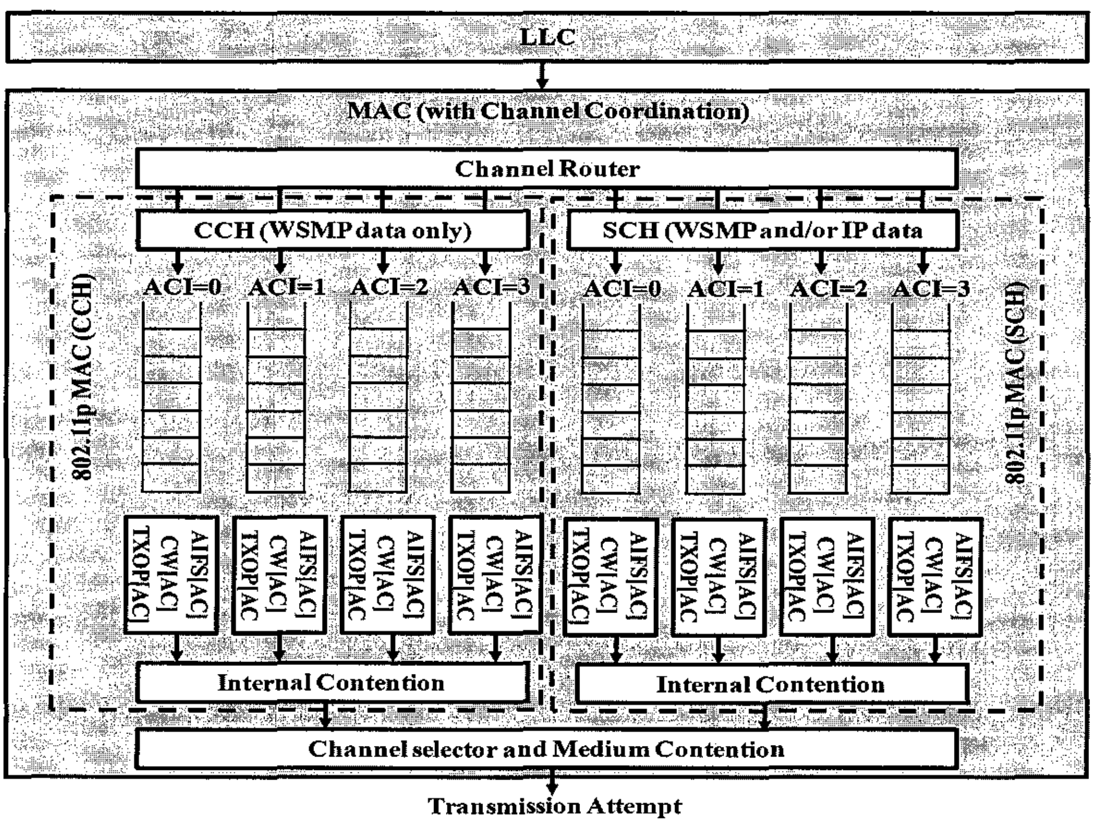


Figure 2.5: Reference architecture of the MAC with channel coordination and EDCA, as in[42]

Three services handle the data transmission of MSDU, the services are; service channel data transfer, control channel data transfer, and data transfer services. The primary concerns of these services are providing higher priority and direct access to the WSMP. Information regarding the type of data packet WSMP or IP is provided by its EtherType as in IEEE 802.2 header.

2.2.6 IEEE 802.11p

IEEE 802.11p handles functions at physical layer and portion of layer two in the protocol stack. IEEE 802.11p standard is an enhanced form of IEEE 802.11a standard. The enhancements have been incorporated due to the different operating environments of wireless LAN and vehicular networks as described before. The enhancements include changes in protocols of data transmission section as well as inclusion of new management entities at layer one and two i.e. the physical layer management entity (PLME) and the MAC layer management entity (MLME). Some differences between IEEE 802.11a & 802.11p are given in Table 2.1. A detailed comparison between the two standards can be found in [43] and [44].

Table 2.1: 802.11a vs 802.11p

Parameters	IEEE 802.11a	IEEE 802.11p
Operating frequency	5180–5825 MHz	5850-5925MHz
Channel bandwidth	20MHz	10MHz, 20MHz (optional on SCHs)
Payload data rate (Mbps)	6, 9, 12, 18, 24, 36, 48, 54	3, 4.5, 6, 9, 12, 18. 24. 27
Basic data rate	6Mbps	3Mbps
OFDM symbol duration	4μs	8μs
Preamble duration	16μs	32μs
Communication range	250m	1000m
Slot time	9 μs	13 μs
SIFS	16 μs	32 μs

WAVE architecture was based on 802.11 due to stability, reliability reasons as well as to support interoperability between VANET equipment made by different manufacturers. This also ensures the maximum mutual benefit from the future developments in the 802.11 family.

2.2.7 Enhanced Distributed Channel Access (EDCA)

Message prioritization is an important part of VANET communication, in which safety related messages are assigned priority over the messages that are not directly related to safety. For quality of service (QoS) support IEEE 802.11p makes use of Enhanced Distributed Channel Access (EDCA) mechanism from IEEE 802.11e. Basically EDCA replaces DCF functions at MAC level. EDCA defines four access categories (AC).

Application generating the message assigns each frame an access category according to the importance of message's content. The importance of the traffic is identified by the access category index (ACI). Each AC has exclusive frame queue and related set of parameters for prioritization implementation. CCH and SCH are assigned exclusive set of queues; ACI and related parameter settings for each channel are given in Table 2.2.

Table 2.2: EDCA parameter settings for CCH and SCH [42]

Channel Type	ACI	AC	CWmin	CWmax	AIFSN
CCH	1	Background	aCWmin	aCWmax	9
	0	Best effort	(aCWmin+1)/2-1	aCWmin	6
	2	Video	(aCWmin+1)/4-1	(aCWmin+1)/2-1	3
	3	Voice	(aCWmin+1)/4-1	(aCWmin+1)/2-1	2
SCH	1	Background	aCWmin	aCWmax	7
	0	Best effort	aCWmin	aCWmax	3
	2	Video	(aCWmin+1)/2-1	aCWmin	2
	3	Voice	(aCWmin+1)/4-1	(aCWmin+1)/2-1	2

Figure 2.5 shows EDCA implementation at MAC level. Each AC is allocated minimum/maximum Contention Window (CW) boundaries. DCF fixed Distributed Inter-frame Space (DIFS) time is replaced by the arbitration inter-frame space number (AIFSN). Having a higher ACI means lower contention window borders as well as lower AIFSN and thus a higher probabilistic priority e.g. ACI=3 has the CWmin=3 & CWmax=7 and AIFSN=2, consequently is assigned to highest priority frame.

Furthermore, Transmit Opportunity (TXOP) mechanism is used to provide contention free period to a node, meaning a node can continuously transmit frames for a period known as TXOP limit (in milliseconds). A TXOP limit of 0 allows a single MSDU to be transmitted. By default all ACs are assigned 0 TXOP limit. Overall the whole system provides a probabilistic prioritization mechanism rather than strict prioritization.

2.2.8 SAE J2735 DSRC Message Sets

As of [45], SAE J2735 standard is expressed as *DSRC message set dictionary* and in terms of the standard, a *message set* is a set of message types. The structure of the *message type* is generic while its specific instantiation is the actual message. Each message type consists of constituent data structures i.e. *data frames* and *elements*. A data frame is a complex data structure and is composed of data element/s or other data frames while a *data element* is the most fundamental structure. The semantics and syntax of (format, length) of each *data frame* and *data element* are also defined in SAE J2735 standard.

2.2.9 Basic Safety Message (BSM)

Among many of the J2735 standard message sets, one of the most important message sets is Basic Safety Message (BSM). Basic Safety Message or as we call it periodic safety beacon is used to convey core state information i.e. position, dynamics, size and system status, about the sender. Additional information may be added to the messages if desired by the sender. The BSM is the key part of many vehicle-to-vehicle safety applications described in next section.

2.3 V2V Safety Applications Relying on Single-hop Periodic Beaconing

In the past vehicle safety applications were limited to single-vehicle-based technologies e.g. car parking sensors and vehicles were unable to share information with each other. The advent of VANET has brought new dimensions in on-road safety applications. Nodes use V2V and V2I communication to share important information that will be helpful to reduce safety risks.

A broad range of DSRC-enabled intelligent applications were identified in Vehicle Safety Communication Project (VSC) report [3]. Identified applications include safety as well as non-safety applications. Although VANET application designing is an on-going area of research, nonetheless VSC report provides important insight into safety applications and their requirements. Table 2.3 shows a brief summary of communication requirements regarding these applications.

Table 2.3: V2V safety applications relying on single-hop periodic beaconing

Application	Types of communication	Tx mode	BGI	Allowable Latency (ms)	Max. range (m)
Wrong way driver warning	V2V One way One-to-many	Periodic	100	100	500
Cooperative forward collision warning	V2V One way One-to-many	Periodic	100	100	150
Lane change warning	V2V One way One-to-many	Periodic	100	100	150
Blind spot warning	V2V One way One-to-many	Periodic	100	100	150
Highway merge assistant	V2V One way One-to-many	Periodic	100	100	250
Visibility enhancer	V2V One way One-to-many	Periodic	500	100	300
Cooperative collision warning	V2V One way One-to-many	Periodic	100	100	150
Cooperative vehicle-highway automation system (Platoon)	V2V and I2V One way and two way One-to-one and one-to-many	Periodic	20	20	100
Cooperative adaptive cruise control	V2V and I2V One way One-to-many	Periodic	100	100	150
Highway/rail collision warning	I2V or V2V One way One-to-many	Periodic or Event-driven	1000	1000	300

2.3.1 Cooperative Forward Collision Warning (FCW)

The cooperative forward collision warning application is intended to aid drivers avoid crash into rear-end of vehicles in front. The message will be sent to all vehicles in surrounding area (single-hop) and over multi-hop distance. Each vehicle receives velocity, position, yaw rate, heading, and acceleration information of all the neighboring vehicles. Then, this data along with road map data is used by the vehicle to ascertain a possible rear-end crash with the front vehicle. Vehicle will also resend the beacon along including its data to other neighbors. FCW is one of the eight high priority applications identified by VSC.

2.3.2 Lane Change Warning

Lane changing maneuvers are prone to be hazardous. This application helps avoid collisions when the driver is in the process of making a risky lane change. Whenever a lane change signals is used, the application will process the information it has and then determine if the space between vehicles is sufficient for the maneuver. If the space is not sufficient the application will notify the driver about the danger of changing the lane. This application is also included in the list of high priority applications by VSC.

2.3.3 Wrong Way Driver Warning

As the name indicates the wrong way warning system is designed to warn drivers when they are driving in opposite direction to the flow of driving and if so, the driver will be warned. The wrong-way vehicle will also broadcast this information to other neighboring vehicles to warn them about the problem.

2.3.4 Blind Spot Warning

Blind spot warning application works in the similar way as the lane change warning. It is designed to evade collisions by informing the driver with the existence or nonexistence of vehicles in the blind spot while trying to change the lane.

2.3.5 Highway Merge Assistant

The highway merge assistant is intended to warn drivers regarding any merging vehicles. Through its navigation system the merging vehicle determines if it is on a highway on-ramp. If on an on-ramp, it alerts the other vehicles by broadcasting periodic beacons.

2.3.6 Visibility Enhancer

As the name implies it is designed to enhance visibility in different situations e.g. fog, heavy rain, snow storm etc. The system either detects such situations automatically or is triggered manually by the driver. The application uses obtained heading, velocity and position of neighboring vehicles with vehicle's own information taken from GPS and map database for enhancing visibility.

2.3.7 Cooperative Collision Warning (CCW)

CCW is designed to warn drivers if an accident is about to occur. The warning is issued based on the information collected from nearby vehicles. Information like position, heading, acceleration and yaw rate of other nearby vehicles are compared with the similar information of the vehicle itself. If an accident is about to happen, the driver will be warned.

2.3.8 Cooperative Vehicle-highway Automation System (Platoon)

This application enables cooperative vehicle-highway automation system for vehicles on the highway, e.g. for convoys. It makes use of vehicular data and position information along with map data to make vehicle platoon/s which is helpful in improving road service i.e. traffic flow and capacity. It also helps reduce the amount of time a driver controls the vehicle thus minimizing human error rate.

2.3.9 Cooperative Adaptive Cruise Control (CACC)

CACC is an enhancement to Adaptive Cruise Control (ACC) it helps to achieve safety by dynamically adjusting the speed of the vehicle by using the speed information obtained from the vehicle in front. The application makes use of V2V messaging between leading and following vehicles. In low-speed-limit zones, e.g. school zones, work zones, off-ramps, etc it can also make use of I2V communication to maintain speed limit.

2.3.10 Highway/rail Collision Warning

This application is designed to provide safety at highway/rail intersections. RSU will be deployed near such intersections that can alert vehicles in the vicinity of approaching train/s (I2V communication). Alternately train can send messages to other approaching vehicles (V2V communication).

2.4 Anticipated Range of Tunable Parameters

All of the applications discussed in the previous section are few examples of currently envisaged V2V safety applications that rely on information received via single-hop periodic safety beacons. Exploring new VANET applications is currently an active area of research and there is no shortage of ideas for new applications. Thus, safety application parameters like target communication range and beacon generation interval are not restricted to only specifications given in Table 2.3. However, the maximum single-hop communication range is restricted by maximum supported range by VANET which is 1000m. Similarly, maximum beacon generation interval is also restricted by average human reaction time and maximum allowable latency. Considering these factors, maximum upper limit of beacon generation interval is usually set to 500 ms. Maximum supported beacon payload size in VANET is 1400 bytes, however according to [46], beacon size will remain between 284 bytes to 791 bytes including the security overhead. A practical range of safety applications parameters is given in Table 2.4.

Table 2.4: Practical range of safety application parameters

Parameter	Range
Communication range	up to 1000m
Beacon generation interval	up to 500ms
Beacon payload size	284 - 791 bytes [46] (max supported 1400 bytes)

It is important to mention that providing detailed information of all V2V safety applications is subject to continuing research and is beyond the extent of this study. However, the parameter requirements of these applications are directly related to this research and are duly addressed.

2.5 Related Work

VANET primarily uses broadcasting as the basic communication mechanism. Periodic V2V safety beacons are generally broadcasted in single hop range. Periodic beacons or WAVE Short Messages (WSM) are of core importance to safety applications, as these beacons are used to exchange critical information regarding the current state of all the vehicles in the vicinity. The information exchanged includes but is not limited to vehicle size, position, dynamics, velocity, acceleration, heading, yaw rate, and others.

Since the primary mode of communication in VANET is broadcast, a comparative analysis of broadcast techniques in ad hoc networks is given in [9]. Most of the previous works in ad hoc networks are focused on multi-hop broadcast communication [10–14]. Multi-hop communication and event-driven messaging has also been well studied in [15–23]. In VANETs, single-hop periodic beaconing broadcast has received little attention. Some VANET studies partially, address single-hop broadcast under different objectives, e.g. congestion control [24–29] and connectivity [31], [32]. Furthermore, these studies use various schemes for dynamic adaption of transmission power/communication range or beacon generation interval to control beaconing behavior. Most of these studies have either partially explored the periodic safety beaconing effects on VANET or simply proposed performance enhancement schemes based on general assumptions regarding broadcast communication behavior. In addition, single-hop V2V periodic beaconing is primarily treated as background traffic. Thus, these studies do not perform in-depth analysis of single-hop periodic safety beaconing and its impact on VANET performance. All in all, V2V single-hop broadcast of periodic beaconing remains a less explored area.

This section provides analysis of the previous research work related to V2V single-hop periodic beaconing. For convenience, this section is divided into three parts. The first two parts consist of the research work that is carried out under various objectives but also partly addresses periodic beaconing. Most of the work that partly addresses periodic beaconing is done under a wide range of objectives and it is not feasible to categorize it objectively. However, here it is divided on the basis of different techniques used to monitor or control the behavior of beaconing, i.e. communication range studies /transmission power, beacon generation interval studies. Furthermore, closely related work that directly focuses on periodic safety beaconing is addressed in the last part.

2.5.1 Communication Range Schemes

Many researchers rely on the power control (communication range) techniques to enhance packet delivery ratio and mitigate channel congestion by scheming periodic beaconing behavior. The power control schemes that setup messaging environment similar to beaconing but do not explicitly consider the V2V beaconing behavior and beaconing safety applications, are analyzed in the following.

Authors of [31] present a power control scheme based on estimation of surrounding traffic density concerning a particular node. However, the main focus is to maintain connectivity using dynamic transmission range assignment. Another power control technique is introduced in [32] which is based upon a Delay-Bounded Dynamic Interactive Power Control module that makes use of eight directional and is also focused on 1-hop neighbor connectivity. Authors in [47] and [48] proposed a power adaptive algorithm based on an analytical model to maximize 1-hop broadcast area using CSMA. However, this protocol requires same transmission power for all nodes, which is not suitable to accommodate varying density, wide range application requirements and dynamic environment of VANET.

In [49], a feedback-based power control algorithm is devised to satisfy the transmission range requirements of safety applications. However, the algorithm performance is greatly dependent upon the proper reception of feedback beacons. If the feedback beacons are not received due to some reason e.g. collisions, the higher transmission powers are assigned to the nodes. Without a mechanism to ensure the delivery of feedback beacons, the algorithm can converge into an unstable equilibrium. Adding feedback mechanism also increases the congestion in dense traffic environment. Furthermore, only fixed packet size is used in simulations.

Among communication range schemes the most extensive simulations of periodic safety communication are carried out by Marc Torrent-Moreno et al. in a series of publications on congestion control schemes. In [25], Marc Torrent-Moreno et al. present Fair Power adjustment for Vehicular environment (FPAV) algorithm for controlling channel congestion level. Conceptually, in FPAV, vehicles have to adjust their transmission power using power control techniques in such a way that bandwidth utilized by periodic beacons does not exceed a predefined threshold known as Maximum Beaconing Load (MBL). The idea behind defining MBL is to reserve a chunk of bandwidth for event-driven message so that communication of event-drive messages is not hindered by channel saturation. In addition, an approach to attain max-min fairness transmit power is given that relies on global knowledge assumption. The centralized nature of the scheme makes it unrealistic in VANET environment due to lack of central entity presence at all locations, e.g. V2V communication.

Considering the drawbacks of FPAV, an enhanced and fully distributed version called D-FPAV was presented in [26]. D-FPAV was also formally proven to follow the max-min fairness criterion. Its effectiveness was proved through simulations under different radio propagation models such as Two-Ray Ground, Nakagami and log normal shadowing. The enhancements in D-FPAV come at the cost of reduced beaconing range and control message overhead. In [27], it is argued that per packet transmit power control is very hard to implement. On the other hand, simulations results in [8][28] indicate that actual rate of change in network traffic load conditions is likely to remain lower than the rate of information update, which supports calculation of transmission power/range assignment on per packet basis. Like its predecessor, D-FPAV also requires global knowledge, which is not easy to obtain in VANET. Furthermore, efficient bandwidth usage with D-PAV is not always possible as event-driven messages are supposed to be rare, thus reserved bandwidth is not utilized at all, most of the time. Besides, in a fully converged Distributed Fair transmit Power Adjustment for Vehicular ad hoc networks (D-FPAV) based VANET, all nodes should have a minimum common power level which may not be a suitable choice in diverse traffic densities and high mobility. From the perspective of periodic safety beacon analysis, the simulations were carried out with fixed packet size and fixed BGI. Measurements were taken by varying communication range only, for providing a ground to compare the efficiency of D-FPAV. Since the objective of the study is congestion control, it lacks various other aspects to present any viable picture of V2V single-hop communication performance and its broad range effects. For example, the study does not consider the vehicle safety application requirements, which were probably being developed in parallel with the study itself. In addition, safety beacon size and BGI were fixed throughout the simulations and only low traffic density environment was setup. Furthermore, data rate used in simulations is 3Mbps, which may not be an optimal choice for varying vehicular environments as explained by [50].

A contention-based forwarding scheme, namely EMDV (Emergency Message Dissemination for Vehicular environment) [28] works along customized algorithm of [26] and is used to improve propagation of event-driven messages in the network. However, as the name suggests, the study is focused on event-driven messaging and does not provide comprehensive analysis of periodic beaconing. Similar simulation set up is used in [29], in which Jens Mittag et al. introduced Distributed vehicle Density Estimation (DVDE) and Segment-based Power Adjustment for Vehicular environments (SPAV) strategies to reduce communication overhead generated by D-FPAV. Simulation results of DVDE/SPAV also confirm less control overhead as compared to D-FPAV. However, the presented scheme does not strictly follow the MBL threshold and beaconing range remains limited.

Another power control scheme is presented in [51]. However, this scheme does not incur any communication overhead, as in D-FPAV. Communication overhead is reduced by gathering neighborhood information via 12-bit sequence number and 4-bit fragment number, which are already part of 802.11 MAC header and are consequently present in beacon. Analytical modeling and simulations are used to evaluate the proposed schemes; however the focus remains similar to other power control schemes, i.e. congestion control.

Generally, the communication range control schemes try to limit available resources for periodic safety beacons as they are treated as background traffic. However, in reality safety mechanism is dependent upon the information received through periodic safety beacons and thus cannot be treated as background traffic.

2.5.2 Beacon Generation Interval Control Schemes

As an alternate to power control (communication range) techniques researchers have also used Beacon Generation Interval (BGI) control schemes. The BGI schemes that setup messaging environment similar to beaconing but do not explicitly consider the V2V beaconing behavior and beaconing safety applications are reviewed as under.

Lars Wischhof and Hermann Rohling provide a Utility-Based Packet Forwarding and Congestion Control scheme (UBPFCC) scheme [24] that works on top of IEEE 802.11 MAC protocol. Furthermore, this approach needs the road to be segmented into sections, thus it cannot be used directly in the context of safety applications. In [52][53], researchers also make use of adaptive BGI for traffic information distribution and priority-based QoS provisioning respectively. Varying traffic density scenarios on freeway were simulated in [54] with 802.11a MAC layer at 27Mbps data rate and the focus of the study is to explore decentralized traffic information system. Most importantly, all the studies described in this paragraph are only focused on non-safety applications.

A detailed theoretical analysis of adaptive beaconing in safety communication is given in [36]. In [55], another adaptive beacon generation architecture is presented for VANET, however architecture is not validated by simulation or analytical means.

Distributed Rate Control Algorithm for VANETs (DRCV) [56] uses bandwidth reservation concept for event-driven messages by limiting the periodic beaconing generation interval within a min-max threshold. Similar concept is used in [57][58], where authors introduce Vehicular MESH Network (VMESH) protocol. However, unlike DRCV, VMESH is focused on bandwidth reservation on Service Channels (SCH), and is primarily focused on non-safety V2I communication.

A congestion control scheme in [27] exploits dynamic contention window (CW) size to control the message transmission rate. Larger CW size means lower channel access thus lower transmission rate and vice versa. Adaption of CW size is based on the channel usage measurement. If the channel usage level exceeds set value of 95% all output queues are blocked except for event-driven safety messages. In case of 70% channel usage or higher, CW size is doubled, and 30% or lower channel usage results in reduction of CW size to half till it reaches predefined minimum CW size. Stochastic simulations were performed using Wireless Access Radio Protocol II (WARP2). Emergency Electric Brake Light with Forwarding (EEBL-F) safety application which is also recognized as cooperative forward collision warning (CCW) is used as test case. Periodic beaconing is considered as background traffic in this study and no performance evaluation is provided.

Adaptive Traffic Beacon (ATB) protocol is detailed in [59] and is able to take advantage of Road Side Units in addition to V2V communication. ATB performance is evaluated via OMNeT++ simulator [60]. However, no DSRC, 802.11p MAC/PHY settings are incorporated in communication setup. Furthermore, all simulations are carried out using free space propagation model which does not reflect realistic vehicular environment.

Most of the studies discussed in Section 2.4.1 and Section 2.4.2, either partially explore the periodic safety beaconing effects on VANET or simply propose performance enhancement schemes based on general assumptions regarding broadcast communication behavior. Generally, the proposed congestion control schemes are based on the same fundamental concept, i.e. limiting resource allocation (e.g. bandwidth, channel access) to periodic beacons in such a way that sufficient resources are always available for efficient event-driven safety messaging. Being the core safety information carrier, limiting network resources for periodic safety beacons can adversely affect safety communication. Thus, these studies do not provide a detailed and realistic analysis of single-hop periodic safety beaconing. Furthermore, the objectives of these studies are different from that of the current and providing a comparative analysis of these studies is beyond the scope of this study. Besides, researchers have used diverse set of QoS metrics under various scenarios to achieve different objectives; therefore, it is not convenient to present a comprehensive comparison of the proposed schemes.

2.5.3 The Closely Related Work

In this section, research work that is focused on single-hop V2V periodic beaconing is critically reviewed. First part of this section presents the analytical research work while later part covers the simulation based research work.

a) Analytical Research Work

Alexey Vinel et al. present an analytical model based on Markov chain and extensively examined the influence of only beacon generation interval on successful PDR in [61–63]. In [61] they present a simple analytical model for evaluating periodic broadcasting. The analytical model is extended in [62][63] and is compared to a saturated as well as unsaturated simulation environment in a custom built simulation model. The details of the simulation model validation are not discussed. Naturally, the analytical model is based on many simplified assumption e.g. considering 1D (one dimensional) VANET, CS range is considered as equal to CR, fixed number of stations in the CR of each station and a simplified fading model. Furthermore, the comparison of the analytical model results and simulation results demonstrate that the analytical model underestimates the performance of the system as compared to simulations.

In [64], firstly an analytical model that quantifies network performance parameters as function of Cooperative Vehicle Safety Systems (CVSSs) parameters (i.e. communication range and rate) is developed, secondly, different performance measures are analyzed that provide the analytical reasoning behind transmission range control concept and lastly different aspects of designing a robust control scheme is studied. However, only first part of the study is directly related to this work and is discussed here accordingly. The analytical model is also based on 1D VANET assumption which is unrealistic. Results for CR of only 20-400m for different scenarios are shown. A fixed beacon size of only 212 bytes is used. Beacon transmission rate of 4 to 256 pkts/sec is also not justified. MAC parameters are set according to DSRC and a customized PHY layer is employed. MAC and PHY layer designs are tested using ricean fading model only.

Another analytical analysis of periodic beaconing is presented in [65]. The presented model is tested with strict reliability criterion for failure rate i.e. 0.01 (PDR 0.99) and a delay of <500ms is considered acceptable. However, many assumptions in the model fail to account for the DSRC standard and realistic environmental conditions. For example, it is assumed that an optimal data rate of 24Mbps is available with a 10MHz channel bandwidth for a CR of up to 500m. Similarly, for 20MHz (does not represent CCH) channel, data rate of 54Mbps is assumed. Furthermore, beacon size only 200 bytes and BGI of only 100ms are considered. The model validation is done using only 802.11a wireless standard.

Another analytical approach using Convex Hull framework is used in [66] to compare the beaconing and beaconless approaches in VANET communication. Authors argue in favor of using beaconless approach instead of periodic beaconing. However, authors do not recognize the importance of V2V single-hop periodic beaconing for safety application such as given in Section 2.3. Many safety applications that use multi-hop communication are also dependent on the information gained via periodic beaconing. Furthermore, beacon size of 20 bytes and generation interval of above 500 ms are not suitable assumption to test beaconing behavior. The Beaconing behavior is also tested with a custom built simulator and no validation of the simulator itself is given.

Authors in [67] explore the communication requirements for Co-operative Adaptive Cruise Control (C-ACC) and present the theoretical beaconing boundaries for the application. Since C-ACC is a non-safety application, the study does not take the safety application requirements into consideration.

A summary of analytical studies on periodic safety beaconing is given in Table 2.5. The analytical modeling of complex real world scenarios such as VANET is extremely difficult. All of the analytical studies presented above are based on various simplified assumptions, such as considering VANET as a 1-Dimensional network, which in reality is quite different. Furthermore, the representation of VANET environmental conditions is also over simplified in most cases. Consequently, such simplified assumptions are prone to generate inaccurate results. Thus, for a complex system like VANET, a simulation-based approach is more suited. Currently known simulation-based studies on periodic safety beaconing are discussed in the following.

b) Simulation Based Research Work

In [68], researchers conduct a performance assessment of Cooperative Collision Warning (CCW) using QualNet™ [69] simulation tool. In addition to the CCW communication requirements, communication range evaluation is performed up to 350 m. No details are presented of the propagation models used. Furthermore, 100 bytes of packet size is used throughout the simulations, which is not realistic as in reality it is likely to be between 280 bytes to 800 bytes range.

Probably, the most closely related works to current research are [33–35] and [70], in which the researchers have conducted simulation based studies for exploring some predefined VANET communication characteristics. The main focus of [33] is priority access. The evaluation parameter used is rate of message reception within one hop broadcast range. As the focus is to evaluate priority access, simulations are carried out with limited configurations i.e. communication range of 100 m and 200 m with packet size of 200 bytes and 500 bytes only. Somewhat similar communication range packet size and simulation settings with the exception of data rates are used by the authors in

[34], which is also one the earliest works in this area. Furthermore, evaluation parameters used are probability of reception failure and channel busy time. Furthermore, in both these studies, the base wireless standard used for simulations is 802.11a with some customization to meet DSRC settings. Simulations are performed using an earlier version of NS-2 available at that time which had several shortcomings in 802.11 MAC and PHY layers, e.g. the inability to handle collisions, path loss calculations, and interferences. A detailed analysis on the shortcomings of 802.11 in previous versions of NS-2 is provided in [44] and comparison of 802.11a/802.11p is already given in Table 2.1.

Yousefi et al. use different adjustable network parameters in [35], i.e. transmission power (communication range), packet size, and packet dissemination interval, which is similar to current study. However, their choice of values for these parameters is an important factor to look into. For example, simulating packet size of 100 bytes and 200 bytes only is not practical, according to [46] actual message size will be rather large, i.e. between 280 to 800 bytes due the incurred security overhead. Furthermore, a communication range of up to 300 m is a reasonable choice in jammed traffic scenarios but does not cover highway traffic situations, where a wider range is required. Similarly 100 ms and 200 ms packet dissemination intervals do not provide significant insight into the overall behavior of the parameter, which we find to be very important factor for enhancing the performance of VANET in terms of packet reception. Although TRG propagation model used in this study is commonly applied in network studies, it does not accommodate real environmental factors such as fading and multipath effects.

Extensive simulations are performed in [70] to analyze the performance of periodic communication. Many features from the simulation framework used in this study are also adopted in the current work. However, there are many limitations and shortcomings of this work that are duly addressed in current research. For example, this study does not provide optimal combinations of the tunable parameters suitable for safety applications. Although, this study analyzes beacon generation rate and transmission range performance, affect of beacon generation interval is measured with a communication range of only up to 400 m which does not cover the maximum

DSRC communication range. Furthermore, beacon size is fixed for all simulations and performance evaluation with varying beacons payload is not considered. Number of nodes used for simulations are 66 vehicles per kilometer (veh/km) and 36 veh/km that corresponds to relatively light traffic density, while in reality it can go up to hundreds of nodes per kilometer. To ensure successful implementation of VANET safety applications, the worst possible scenarios should be considered for evaluating periodic safety beaconing. Besides, only a sufficiently dense traffic scenario justifies the use of safety communication.

There are several inadequacies in the simulation setup regarding implementation of VANET standards and realistic vehicular environment. For example, EDCA parameters for periodic beacons are not set according to the standard as described in Table 2.2. Instead, the CW parameter is set to 127 which results in limited available time slots and greatly increases the probability of collisions in a broadcast environment for dense traffic scenarios. This can cause inaccuracies in the measurement of performance evaluation metrics like PDR, throughput, and channel busy time. According to [50], 6Mbps is the optimal data rate for heterogeneous VANET environment and is also expected to be the default data rate for VANET communication. Whereas a data rate of 3Mbps is used in this study which is suboptimal. Choice of data rate not only affects performance evaluation metrics but also the configuration parameters like reception threshold and transmission power. According to FCC allocation of exact frequency for DSRC control channel is 5.885-5.895GHz whereas in this study it is set to 5.9GHz. Empirical studies show that for appropriate modeling of highway propagation environment in simulations, the Nakagami fading parameter m has to be configured for severe fading i.e. from 0.5 to 1.0 [71]. However, in this work the intensity of m is set to medium fading (m=3.0) for measuring the impact of communication range and beacon generation rate. Choosing performance evaluation metrics is also important for meaningful interpretations of the results. Primarily, the evaluation metric like Channel Busy Time (CBT) and Channel Access Time (CAT) are used, which are difficult to measure in real world scenarios. This work does not provide end-to-end delay measurements which is a key factor considering the latency requirements of safety applications. Furthermore, various code bugs have been fixed in the NS-2 802.11 module since, which raises many concerns regarding the accuracy of the presented results. A complete detail of the bug fixes can be found in[72]. Most important fixes include, correct calculations of cumulative power of received packets and carrier sense distance; correction in backoff handling process, fixes in basic data rate and capture affect implementations.

A comparative summary of simulation-based evaluation studies on periodic safety beaconing is given in Table 2.6. None of the studies mentioned in this table thoroughly evaluates the full range of the three tunable parameters. Furthermore, the simulation setup used in these studies is not fully compliant with VANET standards and highway environmental conditions. Relative effectiveness of each tunable parameter is also yet to be determined. Optimal combinations of tunable parameters also need to be established and are required to determine the efficiency of V2V single-hop PSBs. Limitations of these studies provide the motivation for this research. In this research, results from extensive set of simulations are presented to broadly analyze the impact of adjustable parameters that notably impact the performance of VANETs. For accurate results, all micro level parameter settings available in NS-2 simulator are carefully configured to match VANET standards and environment. Moreover, simulations in this study are performed using latest version of NS-2 v2.34 [44]. This version has the most enhanced 802.11 MAC and PHY modules with no known bugs for our implementation scenario at present, which strengthens the accuracy of the obtained results.

Table 2.5: Comparative analysis of analytical studies

Ref.	Thoroughly investigated parameters as per Table 2.4			Node Density	DSRC PHY/MAC	Propagation environment	Evaluation parameters
	CR (m)	BGI (ms)	Beacon payload size (bytes)				
[61][62][63]	X	✓	X	25-75, 10 In CR	802.11p	customized	Probability of successful reception, mean delay
[64]	X	X	X	NA	DSRC-MAC Custom-PHY	Ricean fading model	Probability of successful reception
[65]	X	X	X	NA	802.11a	customized	Probability of successful reception, delay
[66]	X	X	X	40v/km	NA	customized	Probability of successful reception, delay
[67]	X	X	✓	15/200m/l 120v in CR	NA	NA	Probability of successful reception

NA=Not Available, ✓=yes, X=No

Table 2.6: Comparative analysis of simulation studies

	Thoroughly investigated parameters as per Table 2.4			Optimal tunable parameter values and combinations	Node Density (veh/km)	Simulation environment			Evaluation parameters
	CR (m)	BGI (ms)	Beacon payload size (bytes)			Simulator	DSRC PHY/MAC	Propagation environment	
[33]	X	X	X	X	≈267	NS-2	Modified 802.11a	TRG, NAK	Probability of successful reception
[34]	X	X	X	X	NA	PATH (SHIFT+NS-2)	802.11a at 5.4GHz	Friis-TRG	Probability of reception failure, CBT
[35]	X	X	X	X	400	GloMoSim	802.11	TRG	Average PDR
[68]	X	✓	X	X	130, 1200	QualNet™	Modified 802.11a	Customized	Delay(IRT)& latency, Probability of successful reception,
[70]	✓	✓	X	X	24, 66	NS-2	PHY 802.11p MAC custom	TRG, NAK	CBT, CAT, Probability of successful reception

NA=Not Available, ✓=yes, X=No

2.6 Chapter Summary

In this chapter, VANET communication architecture and relevant trial standards were introduced. The V2V safety applications that rely on periodic beaconing were also discussed. The critical analysis of related work is also presented. It was observed that research studies that make use of communication range control and BGI control methods to achieve certain objectives e.g. congestion control, connectivity and event-driven message dissemination, generally treat periodic beaconing as background traffic, which is unrealistic. Thus, these studies do not fulfill the requirements for comprehensive evaluation of periodic safety beaconing. The research work that is focused on single-hop periodic safety beaconing was also critically analyzed. The limitations and shortcomings highlighted in closely related research work provide the rational reasoning for conducting current research work.

CHAPTER 3

RESEARCH METHODOLOGY

Research methodology is key aspect of any research work. A simulation based research design used to accomplish the objectives of this research is introduced in this chapter. Research design components like system model, network simulator, tunable parameters, traffic scenarios, coding process and performance evaluation metrics are discussed in detail.

3.1 Research Design

The goal of this study is to appraise the performance of V2V single-hop periodic safety beaconing and parameters that govern them by analyzing their behavior and also by finding their optimal operating values and combinations. The performance evaluation can be done through different methods such as experiments, analytical modeling or simulations. In case of this research, simulation based approach is more suitable for performance evaluation of V2V single-hop PSBs (as discussed in Section 1.5).

The research design presented in this chapter is tightly coupled with the research flow. Brief description of the research process flow is given in this section while research design components are individually discussed with details in the rest of the sections in this chapter. The process flow chart of the research design is illustrated in Figure 3.1.

First and the foremost, simulation software has to be selected carefully and according to the underlying system design. This is a tedious task due to the fact that a large number of network simulators are available for wireless ad hoc communication. After careful analysis, Network Simulator -2 (NS-2) came up as a strong candidate for

VANET implementation. Rational reasoning behind the NS-2 choice and its architecture are discussed in next section.

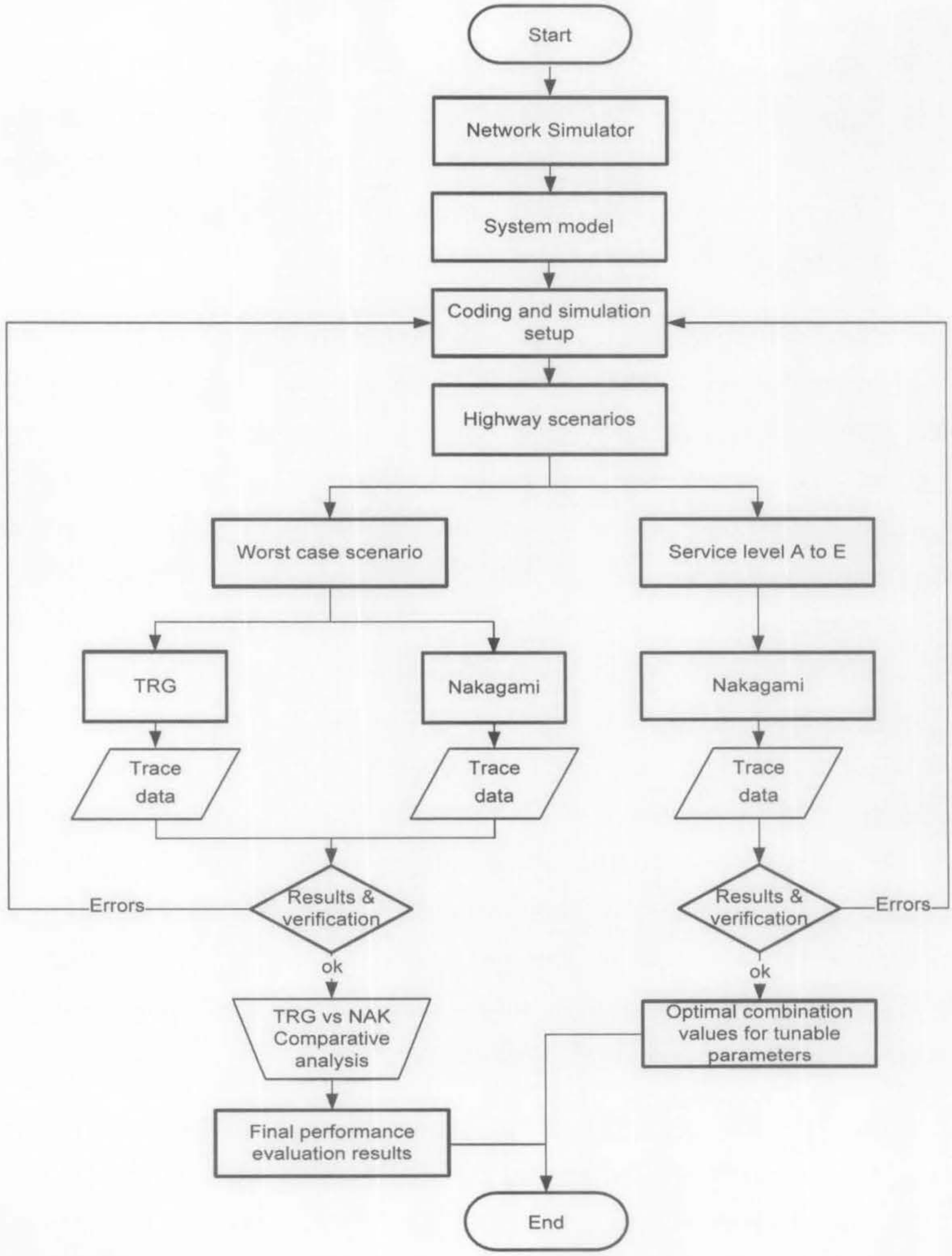


Figure 3.1: Process flow chart

The most imperative part of any simulation based research is the system model. The system model implemented in NS-2 demonstrates a fairly accurate representation of VANET system. Major VANET system model components are safety application parameters, DSRC-enabled node, road environmental conditions and traffic scenarios. Within the scope of system model, all simulation configuration parameters are set to match required VANET trial standards. Special emphasis is given to PHY and MAC layer implementation of IEEE 802.11p. In coding phase, several codes were required to design a number of scenarios. For appropriate implementation of system model in NS-2, the main program code was written in Object Tool Command Language (OTcl). A sample OTcL code is provided in Appendix A.

Designing realistic traffic scenarios is also a fundamental requirement for obtaining accurate and meaningful results. A new worst case scenario is introduced that justifies safety application requirement and also represents practically taxing situations under which VANET system has to operate in real world environment. Using the worst case scenario, numerous simulations are carried out under deterministic propagation model, i.e. TRG while adjusting tunable parameters to test their impact and behavior on VANET communication. The similar set of simulations is carried out using probabilistic (also called non-deterministic) radio propagation model i.e. Nakagami. Results are analyzed and effectiveness of each tunable parameter is determined under both propagation models. Furthermore, a comparative analysis of results obtained from the deterministic and probabilistic propagation models is also presented to determine the usefulness of both models. To find the optimal operating values for tunable parameters and their combinations, the simulations are carried out on different highway service levels. The Nakagami propagation model is used for these simulations as empirical studies have shown its close resemblance with highway environment [71].

Huge trace data was generated from the exhaustive simulations. To extract meaningful results from these simulations, several scripts were written in AWK (abbreviated from names of the designers, Alfred Aho, Peter Weinberger, and Brian Kernighan) programming language (Appendix B). Results for all simulations scenarios were manually verified with the help of AWK and grep command utility. In case of errors, appropriate rectifications were made in main program wherever required. The process was repeated unless no further errors were found.

3.2 Network Simulator

Selecting a suitable simulator for VANET implementation is a strenuous job as quite a few simulation tools are available for simulating wireless ad hoc communication. A survey of ACM VANET (2004-2007) reveals NS-2 as the most frequently used simulation tool in VANET studies [73]. Other popular simulators like OMNeT++, QualNet™ are frequently used in wireless communication and are also used for VANET simulations in some studies. These well known network simulation tools OMNeT++, QualNet™ and NS-2 (also popular for VANET) were compared with a real test-bed including wired and wireless networks[74] in a recent study. According to this study, in the overall rating the results of QualNet™ were considered to be realistic in 76% of the cases, while NS-2 provided realistic results in 81% of the cases. Furthermore, OMNeT++ was not recommended due to lack of certain features that lead to most scenarios not being implemented. Above studies strongly suggest the applicability of NS-2 in networks field, moreover its credibility among VANET research community is also well established. Thus, NS-2 is our final choice for conducting this research.

NS-2 is an open-source simulator with multiple platform support. Basically NS-2 was enhanced from REAL network simulator in 1989[75]. NS-2 supports multiple platforms i.e. Linux, FreeBSD, SunOS, Solaris and Windows with Cygwin. Primarily NS-2 is written in C++, with OTcl (Object Tool Command Language) at the front-end. Depending on the nature of the object it can be fully implemented in either C++ or OTcl, or both. Latest available NS-2 version 2.34 [76] comes with overhauled 802.11 PHY and MAC layers. This latest version is used to carry out simulations in order to accomplish the objectives of this study. A frequently used generic operational design for wireless (802.11) implementation in NS-2 is shown in Figure 3.2.

Simulations may require plenty of computer hardware resources like processing, memory and storage. Requirements of hardware resources are dependent upon the simulation scenario. System specifications of the machine used to perform simulations for this research are given in Table 3.1.

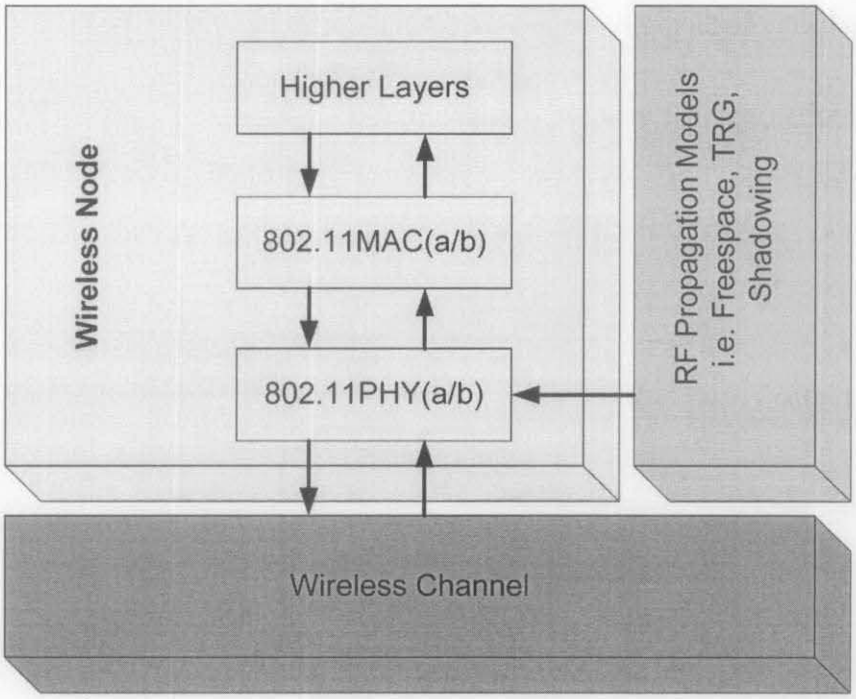


Figure 3.2: 802.11operational design in NS-2 (v2.34)

To make, maximum computational resources available to NS-2, all simulations are carried out in a controlled environment with a minimum set of services running in the background and no parallel applications running.

Table 3.1: Specification of the computer hardware used for the simulations

Item	Specification
CPU Clock Speed	2.0GHz
CPU Type	Intel Core 2 Duo
Memory	3 GB
Operating System	Fedora Core 10

3.3 System Model

Depending on the research requirements, a system model should incorporate features of WAVE architecture and the relevant standards (see Section 2.2) in order to represent a real VANET system. Moreover, designing a full-fledged VANET system model is a matter of ongoing research and is out of scope of this study. Nonetheless, it is still very important that the used system model provides sufficient level of realism for the underlying scenario.

The NS-2 conventional wireless operational design shown in Figure 3.2 is relatively easier to implement but not sufficient to model VANET system. Instead, we make use of an overhauled 802.11 model [72] introduce by Karlsruhe Institute of Technology (University of Karlsruhe, Germany) and Mercedes-Benz Research & Development North America. In addition to many enhancements in conventional NS-2 802.11 model, this model also facilitates the integration of many MAC and PHY layer features in accordance with IEEE 802.11p trial standard for VANET. For current research, several parameter settings are customized in accordance with the latest research and findings. The system model used for evaluating V2V single-hop periodic safety beaconing is presented with reference to conventional layered architecture in Figure 3.3.

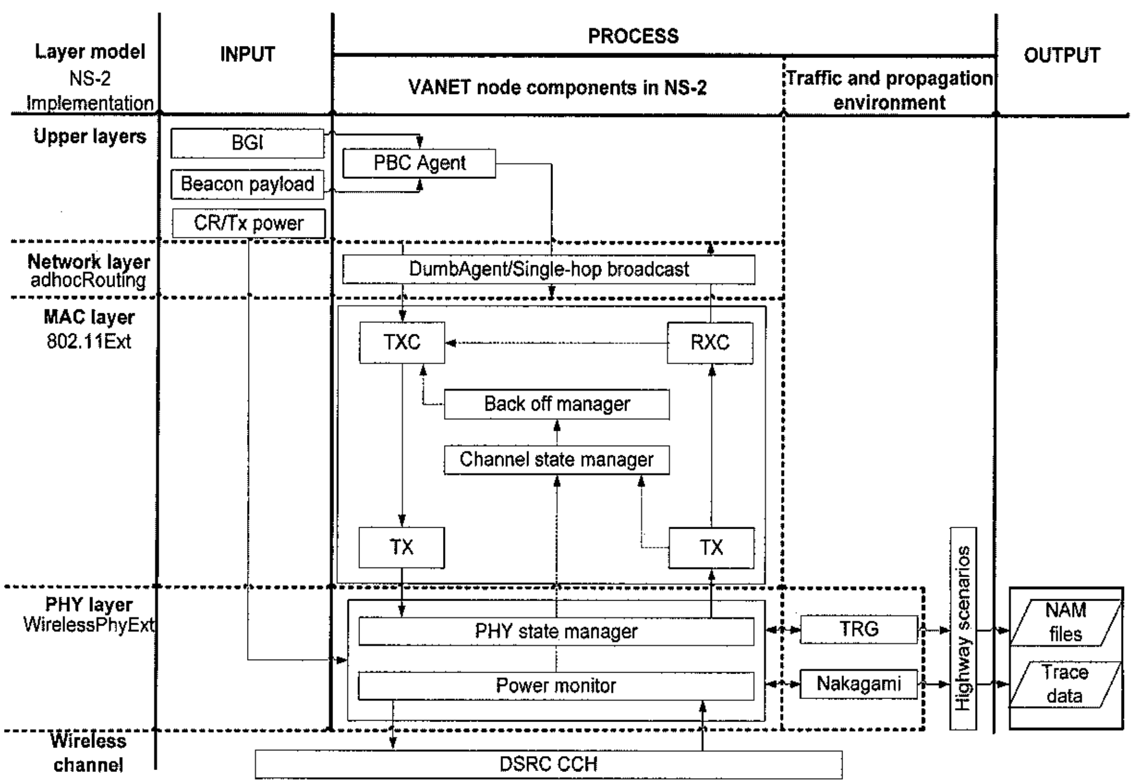


Figure 3.3: System model

To handle adjustable parameters at application layer, i.e. BGI and beacon payload size, in the context of VANET safety applications, a special message generator agent called *PBCAgent* is used. To generate periodic beacons the *PeriodicBroadcast* switch of *PBCAgent* is turned ON (details in Section 4.5). At network layer, to ensure a V2V communication, *adhocRouting* is enabled and *DumbAgent* is used for single-hop broadcast. At MAC layer, *802.11_Ext* module is used and all the given parameters are configured to match IEEE WAVE/DSRC standard. MAC layer functions and parameter settings are thoroughly discussed in Section 4.2. *WirlessPhyExt* module is configured to match physical layer settings of IEEE 802.11p draft standard. Details of NS-2 physical layer functionality and parameters are given in Section 4.3. Wireless channel is set according to the DSRC control channel with no channel switching.

Actual communication range is highly dependent upon the road environment due to natural phenomenon like temperature fluctuation, reflection, refraction, scattering. In simulations, radio propagation models are used to represent different environmental conditions. Two of the popular propagation models, used for VANET are Two-Ray Ground (TRG) and Nakagami. Two-ray ground propagation model is a widely used radio model due to its simplicity. However, this model does not represent realistic highway environmental phenomenon i.e. fading, multipath effect. On the other hand, Nakagami propagation model provides more configurable parameters. In [71], DSRC channel characteristics for V2V communication were empirically determined and it was shown that Nakgami fading parameter m lies between 0.5 to 1.0 for highway scenario. Initially, simulations are carried out using TRG model, then same set of simulations are performed with Nakgami propagation model. A comparative analysis of results from both models is also provided. NS-2 implementation of both propagation models is discussed in Section 4.4.

To gain fruitful insight into behavior of adaptable parameters, it is very important to design a realistic road layout and vehicles need to be carefully deployed along the road. Various highway scenarios are used for different experiments. To evaluate the performance of tunable parameters, a special worst case scenario is designed. Optimal values for adaptable parameters for different highway service levels are also presented. Details of highway scenarios are presented in (Section 3.5 & 4.1). Over 800 gigabytes of trace data was generated from extensive simulations. Extracting meaningful information from these traces is also a daunting task and requires expertise in certain scripting languages and utilities. The complete coding process is given in Section 3.6.

3.4 Tunable Parameters for Periodic Safety Beaconing

Parameters explored in this study are beacon generation interval, communication range, and beacon payload size that can significantly influence overall performance of the network. Details of these parameters are given as under.

3.4.1 Communication Range

It is the most commonly used parameter in the literature for performance optimization of broadcast communication. In practical scenarios communication range attained by mobile nodes is largely dependent on their transmission power, receiver sensitivity and surrounding environmental conditions. Given fixed environmental conditions, a node's transmission power can be directly interpreted as the attainable communication range. Thus, here onwards, the term communication range implicitly implies the resultant range from a corresponding transmission power calculated under deterministic conditions without any interference from other nodes.

Decreasing the communication range (CR) essentially means reducing the number of nodes competing for a shared channel and vice versa. Thus it is understood that CR can be increased or decreased to reduce collisions by minimizing numbers of hidden nodes. In typical road situations node distribution is unpredictable and is mostly heterogeneous in nature thus having a common CR among the nodes at broader level is not practical. Consequently it is more useful for each node to adjust its CR according to immediate neighborhood situation. For example setting minimum or maximum common CR for a road segment of certain length having higher node density at the centre and lower node density at the edges, may result in isolation of farther nodes or higher collisions at the centre.

For VANET, maximum transmission power of 44.8 dBm [77] is supported at the control channel. However, to a given scenario a maximum transmission power equivalent to a communication range of 1000 m is desirable. Lower bounds vary according to underlying application requirements in different circumstances. To calculate transmission power for communication range of up to 1000 m we setup a simulation test environment with zero interference from other nodes. Two nodes are deployed on the highway and various transmission power values for different communication ranges are calculated via TRG model. Power values obtained from these tests are shown in Figure 3.4 and range from -17.18 dBm for 50 meters to 13.96 dBm for 1000 meters.

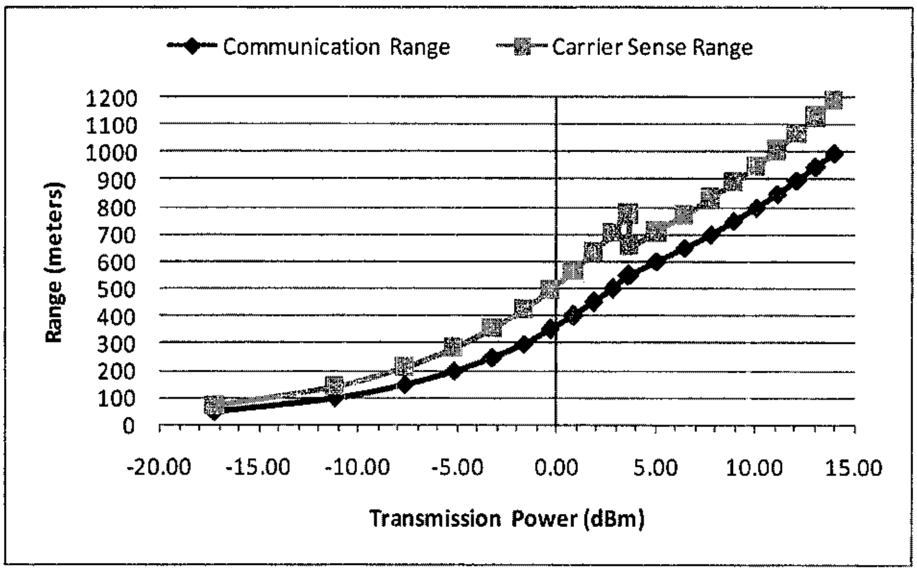


Figure 3.4: Transmission power values obtained for communication and carrier sense ranges using Two-Ray Ground propagation model

Obtained carrier sense range is taken with carrier sense threshold of -94 dBm and corresponding transmission power is taken with reception threshold of -91 dBm. A subtle dip in the CR and CS ranges is caused by the cross over distance phenomenon of TRG propagation model.

3.4.2 Beacon Generation Interval (BGI)

The time interval after which a node generates a periodic beacon is known as Beacon Generation Interval (BGI). BGI remains a relatively less explored parameter mainly because of the considerations that longer BGI may cause higher communication delays which can lead to ineffectiveness of safety applications. Generally, it is assumed that DSRC supported vehicles will exchange safety beacons every 100 ms. However, a realistic BGI should account for human reaction time, vehicle speed/acceleration, positioning update frequency of Global Positioning System (GPS) equipment and propagation delay.

According to [78], mean human reaction time for close encounters is 700ms or higher. Thus, considering the human reaction time, and network latency, an acceptable upper limit for BGI is 500ms. Beacons generated beyond this point may have no practical use as the driver is likely to react faster than the VANET safety system.

VANETs are expected to support vehicle speed of up to 120 mph or approx. 193 km/h. At this maximum speed a vehicle can travel 53.61 m in one second which seems a considerable change of position. However when sending the periodic SB at every 100 ms the actual distance covered by the sender in the mean time is only 5.36 m which is less significant considering the speed it is traveling at. Similarly decreasing speeds means that there will be even smaller variations in senders traveled distance between two consecutive safety beacons. Consequently at lower speed it becomes feasible to increase the time delay between two consecutive safety beacons. Majority of vehicles equipped with VANET technology are expected to get their positioning information though low cost GPS equipment. The positioning update frequency of such low cost devices is usually 200 ms or less. However, GPS devices with faster positioning update rate are available at relatively higher prices.

Taking the factors discussed above into consideration we can safely assume that an upper bound of 500 ms for BGI is sufficient to provide practical assistance to the driver. Furthermore, lower BGI is desired for provision of maximum reaction time for drivers. However, excessive beacon generation may cause adverse effects e.g. channel congestion.

3.4.3 Beacon Payload Size

Payload is the amount of actual information in a beacon excluding the headers. Size of the beacons to be exchanged in any network is of great importance. In VANET beacons may carry various types of information including velocity, position and hazard information. As a general concept more information carried by a beacon means a well informed neighborhood with higher safety level. However, increasing beacon size contributes towards channel saturation which is certainly not a desired feature in any network especially in CSAM/CA based VANETs.

According to IEEE 802.11 specifications the maximum payload size of a frame is 2304 bytes and maximum supported WAVE short message (periodic beacon) payload is 1400 bytes [67]. However majority of VANET communication is expected to operate within much smaller range of packet size for example, according to [46], message size in VANET would remain between 284 and 791 bytes including the security overhead.

3.5 Highway Layout and Node Deployment

To obtain realistic results, it is imperative to design a traffic scenario that resembles the real world. Appropriate node placement in a road traffic scenario is also of core importance to achieve meaningful results from the simulations. Node placement setup is divided into two parts i.e. worst case scenario and highway service levels.

3.5.1 Worst Case Scenario

For appropriate node deployment, important factors like node density, safety distance and node speed have to be taken into consideration. In addition, the scenario should also consider a life threatening situation for justifying the requirement for safety applications.

In real world, it is extremely difficult to predict precise node density at a highway-section at all times. It is possible that two vehicles present in the same highway-segment may experience totally different communication environment. For example, a slow moving vehicle in traffic jam near an intersection is experiencing a stressed channel, while only a few hundred meters away another vehicle leaving the intersection is accelerating fast with a relatively collision free channel. Another scenario could be that, a node is present near the center of a herd of cars, all cars in the herd are moving at close distances with similar velocities and there is another node that just left the herd by accelerating faster or by considerably slowing down but is still only a few hundred meters away from the herd. Despite being within the same highway-segment, both nodes experience different communication environments. Assuming that all nodes have equal probability of being the stressed node, any node on a highway can be in a stressed state at any given time. Furthermore, a fully stressed node is an ideal candidate for testing the performance evaluation of single-hop safety communication.

A scenario where all nodes represent a stressed node state can be described as worst case scenario. Several factors (like safety distance, node speed, causality risk factor) need to be taken into account for creating a realistic worst case scenario on highways. The safety distance is a distance that is required by a driver to completely stop the vehicle. As a general reference safety distance can be measured in meters as the half of the vehicle speed in km/h e.g. a vehicle traveling at the speed of 100km/h has a safety distance of approximately 50 meters. Therefore, in addition to the safety application requirements, a minimum safety distance needs to be maintained between deployed vehicles to avoid vehicle collisions.

Speed limits tend to vary greatly in highways due to various reasons e.g. terrain, government laws etc. On US highways minimum upper bound for speed limit is 60 mph (≈96 km/h) [79], as compared to freeways with no speed limit in Germany. Given the countless possibilities of highway scenarios, it is difficult to predict a life threatening situation, however according to [80] a study reveals that a relative risk of involving in a causality crash doubles after every increase of 5 km/h in speed from 60 km/h onwards.

Taking all of the above factors into consideration, following guidelines for node deployment are set in order to design a realistic worst case scenario.

- To create stressed environment for all nodes, maximum number of nodes should be deployed.

- Minimum safety distance between nodes should be enforced according to the respective speeds of vehicles.

- To achieve maximum practical density on a highway, all vehicles should be placed within the respective minimum safety distances.

- Average vehicle speed should consider a relative risk of casualty crash i.e. ≥ 1 (60 km/h or greater)

Within the prescribed guidelines, there are two possibilities for node placement. As a much simpler strategy, all nodes depicting an equal speed of 60 to 65 km/h can be placed at equal safety distance of 30 to 32.5 m distance. However, this is not the case in reality. Generally, outermost lanes of the highways are populated with slower vehicles while the fastest vehicles travel in innermost lanes. Therefore, a more realistic approach would be to place slower cars in outer-most lanes, while faster cars in middle lanes and the fastest vehicles in inner-most lanes.

3.5.2 Highways with Different Service Levels

Vehicle density tends to vary on different types of roads like highways or freeways. Thus, it is not viable to propose generic optimal combination values of tunable parameter for all types of roads. However, if maximum number of expected vehicles on a road is known beforehand, predicting optimal combination values for tunable parameters becomes much simpler. Highway capacity manual [81], provides an overview for different levels of service for highways in terms of maximum traffic flow or vehicle density and the average speed of the vehicles. Table 3.2 shows different service levels for a three lane highway with reference to [81].

Higher service level means lower vehicle density and relatively higher average vehicle speeds. For example, maximum density and average speed for a three lane highway with service level "E" are 25veh/km/lane and 88.0 km/h respectively. Whereas, a highway with service level "E" supports a maximum of 7 veh/km/lane at an average speed of 100km/h. With these specifications a highway with service level "E" with three lanes in each direction can have a maximum of 150 veh/km or 300 vehicles within the maximum VANET communication range of 1000 m.

Table 3.2: Different highway service level parameters

Service Level	Maximum vehicle density (veh/km/lane)	Average speed (km/h)	Vehicles in a 3-lane highway	
			Max. density (veh/km)	within 1000m CR
A	7	100.0	42	84
B	11	100.0	66	132
C	16	98.4	96	192
D	22	91.5	132	264
E	25	88.0	150	300

3.6 Coding Process and Results Handling

A step by step coding and result handling process is illustrated in Figure 3.5. At the very beginning some modifications are made to NS-2 defaults settings to accommodate VANET parameter settings. All simulation scenarios were designed through OTcl language of NS-2 (sample code in Appendix A).

More than 332 simulations were carried out with a 21 seconds simulation time for each. Simulation results for 1st second are truncated to observe steady network conditions. Overall 800+ gigabytes of trace data was generated and analyzed. NAM files were also generated in some cases to verify the correct node positioning on the grid. Size of trace data files, generated from different scenarios varies from a few hundred megabytes to approx. 17 GBs. Generating this much amount of trace files can take from a few minutes to a few days on the computer used for simulations.

To extract results from such huge text files, special scripting languages are used. We write scripts in a Linux built-in scripting language called AWK. Before final result extractions, the correct functionality of the scripts needs to be verified manually. In the manual verification process, data for randomly selected nodes is extracted for manual computation and the computed results are crossed matched with the results generated by the AWK scripts.

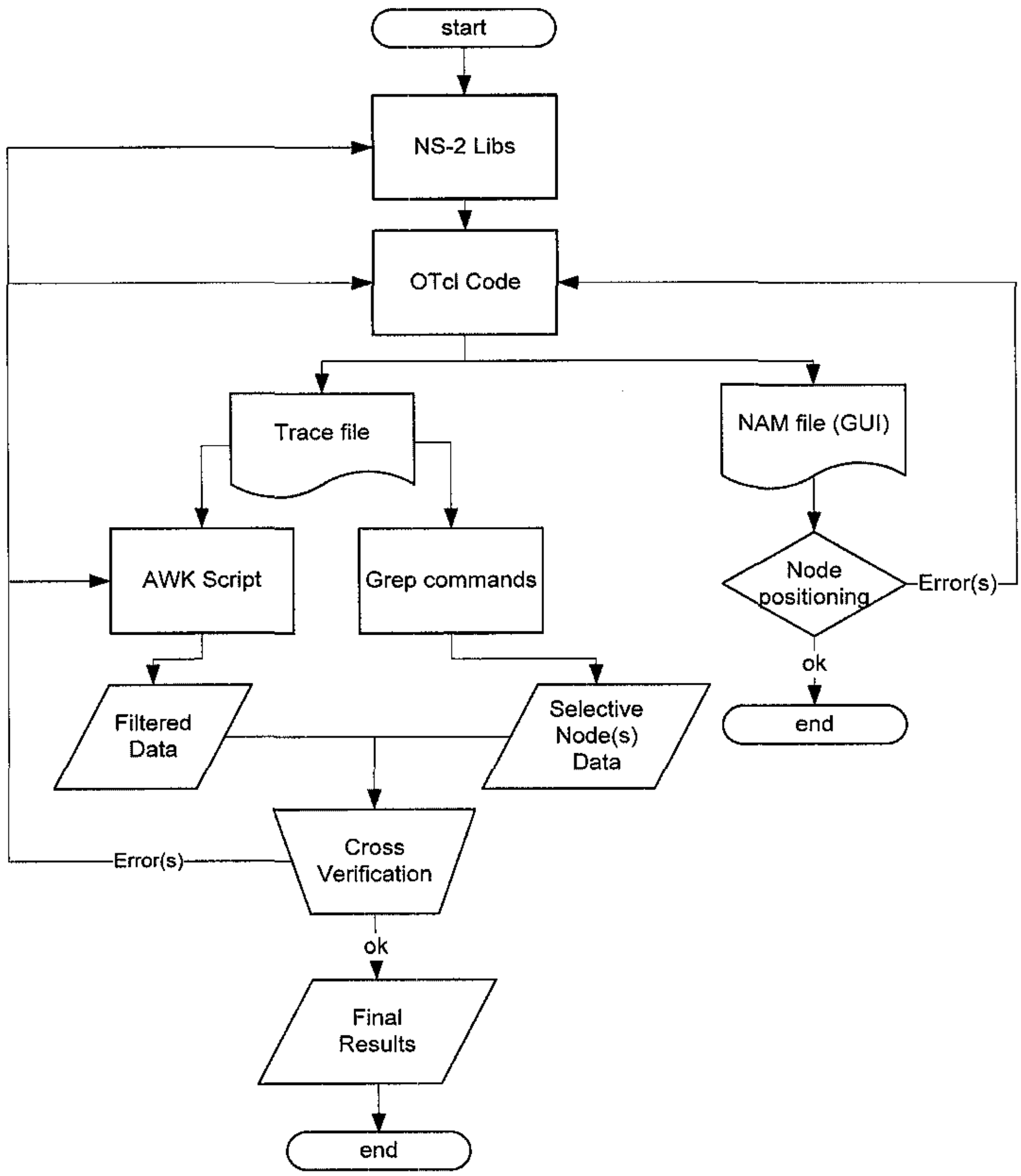


Figure 3.5: NS-2 step-by-step coding process

Direct extraction of data from huge trace files also requires some expertise in some utilities. Linux built-in grep command utility is used for this purpose. Selected node data was manually compared against the AWK script filtered data for all scenarios. Matching results mean the correct working of AWK scripts. In case of result mismatch, all possible errors are checked in library files, OTcl code or AWK scripts. The process is repeated until the correct results are obtained.

3.7 Performance Metrics

Performance evaluation metrics used in this study are per-node throughput, end-to-end delay, packet delivery ratio, and beacon loss ratio-breakup.

a) Per-node throughput

Number of packets delivered to a particular node over the period of time is known as per-node throughput of that specific node during that time. For example, if a node receives 1000 packets of 500 bytes in 20 second, its per-node throughput is (1000x500x8)/20) = 200Kbps. Overall network throughput can be obtained by cumulating per-node throughput of all the nodes in the network.

b) End-to-end delay

Average time difference between sender dispatching a packet and receiver getting it is described as end-to-end delay. It can also be described as time taken between packet sent from the specific layer at the sender and received at the specific layer at receiver. In current case, end-to-end delay represents the time spent between a frame dispatched from application layer of the sender and the same packet being received at the receiver's application layer.

c) Packet Delivery Ratio (PDR)

PDR is probably one of the most widely used QoS metrics in network communication. PDR can be measured over single and multi-hop communication. However in this study, only single hop broadcast packet delivery ratio is evaluated. Delivery of beacons to vehicles within each other's communication is of utmost importance to uphold updated information of the neighborhood. Moreover, none or limited neighborhood information can lead to ineffectiveness of safety applications.

PDR in a single-hop broadcast can generally be described in two ways, 1) number of vehicles that successfully receive a broadcast message within the communication range of the transmitter and it called PDR-recipients here; 2) percentage of beacons received by specific vehicle(s) from a specific transmitter, it named here as PDR-beacons. Majority of the previous related researches use either one of these two criterions. In this research, results are discussed with both types of PDR criterions. Furthermore, different PDR calculation methods such as average PDR, PDR at specific distances and average PDR within specific communication ranges are used to emphasize on different aspects of safety communication. For convenience, all PDR results are expressed in the form of corresponding percentage.

d) Beacon Loss Ratio - breakup

Conventionally, Beacon Loss Ratio (BLR) is the opposite of PDR. In current version of NS-2, 802.11 packet drop events are tagged with appropriate drop reasons i.e. lower reception power than carrier sensing threshold or inadequate power for a preamble to be received even without interference, packets loss when physical layer is busy in frame preamble reception, frame reception, frame transmission or channel is idle but busy in searching for a valid frame preamble [44].

There are no standard values for measuring all of the above mentioned performance evaluation metrics and in some cases we have to rely on some logical values proposed in literature.

3.8 Chapter Summary

In this chapter the research methodology approach for this study was introduced. The main components (e.g. system model, network simulator, tunable parameters, coding process and performance evaluation metrics) of the research design were discussed in detail. Simulation tests were carried out to obtain transmission power vs communication range measurements using TRG propagation model. The resulting power values for different communication ranges vary between -17.18 dBm for 50 meter and 13.96 dBm for 1000 meter. These measurements are used as reference values for intended communication ranges for all simulations. A new generic worst case highway scenario was introduced in accordance with the objectives of this study. Different highway service level and the corresponding scenarios were also discussed.

CHAPTER 4

SIMULATION SETUP

In this chapter, simulation setup for the simulations is discussed in details. Details of simulation grid and highway setup are also presented. Special emphasis is put on MAC, PHY layer setup and propagation models.

4.1 Simulation Grid and Highway Setup

To obtain realistic results, it is imperative to design a network topology that resembles the real world. Table 4.1 shows design settings for the simulation grid and highway setup.

Table 4.1: Simulation grid and highway setup

Parameter	Corresponding value(s)
Grid size	7100x1030
Grid and highway border distance	500 m
Road type	Highway
Road length	6100 m
Observed area	2000 m at center of highway
No. of lanes	6
Lane width	3.66 m
Separator distance	2 m
Total highway width	20.3 m

Here a simulation grid of 7100x1030 (m) is designed with a plain highway at its centre. The highway layout consists of a 6100 m long six lane highway-section, with three lanes in each direction. Each lane has a standard width of 3.66 m and the roads lanes in either direction are divided by two meters of separator distance. Cumulative width of the whole highway including the separator is 20.3 meters. To avoid the well known boundary effect; the observed communication area is limited to 2000 m at the centre of the highway. In addition, a distance of 500 m between highway and grid border is also kept deliberately.

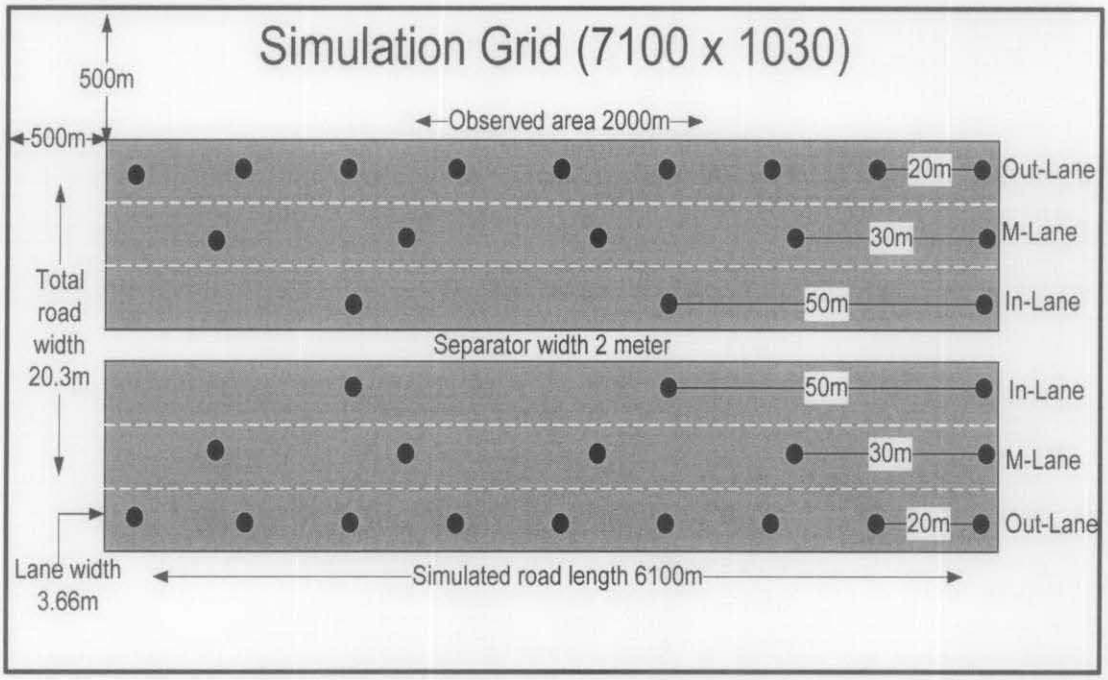


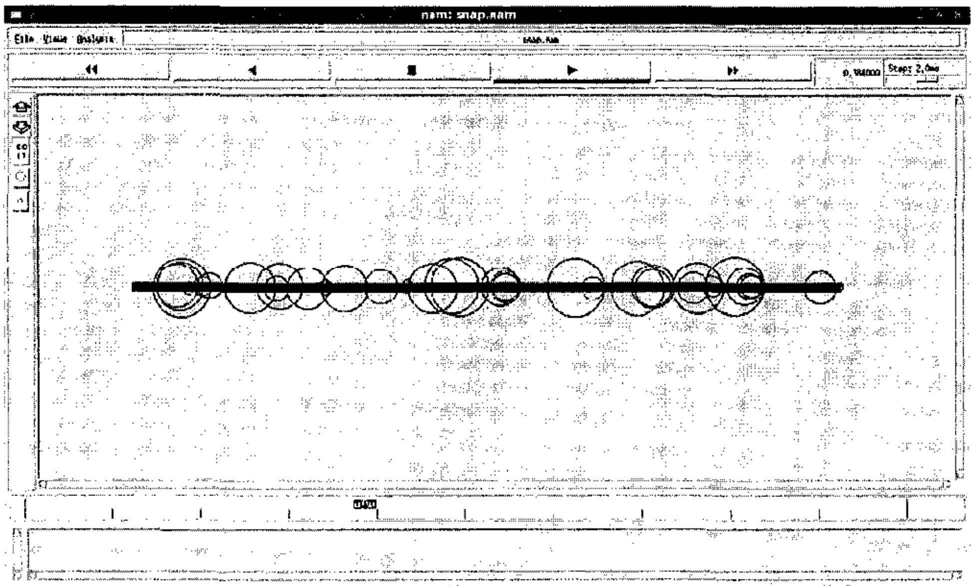
Figure 4.1: An illustration of simulation grid with worst-case scenario

A total of 1240 nodes are pseudo uniformly deployed on the highway. A total of 600 nodes (300 each) are placed on both of the outer most lanes with a distance of 20 meters in-between. Each of the two innermost lanes has 120 nodes distanced at 50 meters apart. Other two lanes contain 400 nodes (200 each) in all with intermediate distance of 30 meters. Similarly distances of 20, 30 and 50 meters depict a minimum safety distance required at the speeds of 40, 60 and 100km/h respectively.

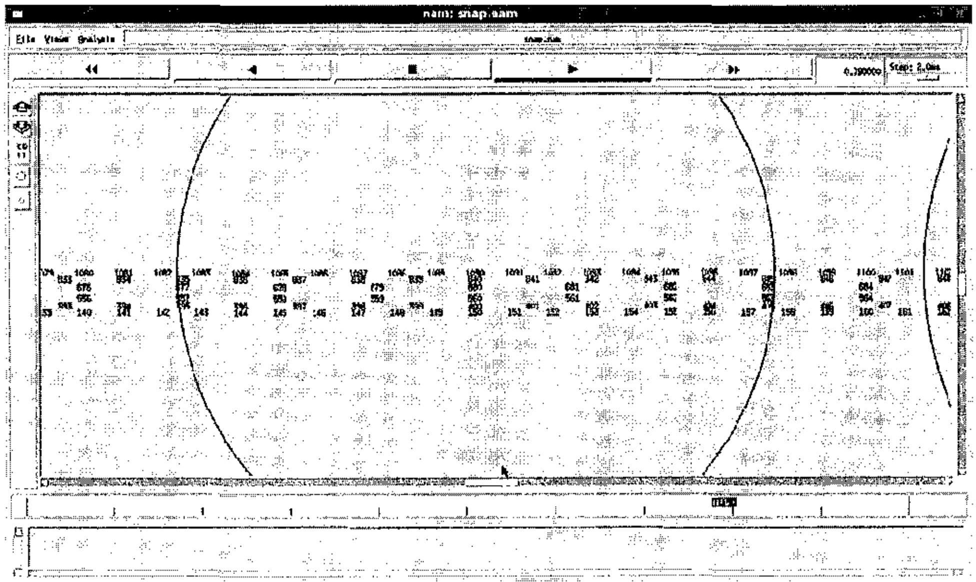
Table 4.2: Worst case scenario

Parameter	Corresponding value(s)
Avg. vehicle speed (depicted)	66.6 km/h
Avg. inter-vehicle distances	33.3 m
Maximum node density achieved	207 vehicles/km
Total number of nodes on highway	1240

Vehicle density achieved in above scenario is 207 veh/km. This scenario represents an average depicted speed of 66.6 km/h while safety distance at each lane is maintained according to the depicted speed. In most three lane highway scenarios this is the maximum achievable density with a relative causality crash risk. Figure 4.2 shows the NAM file output for actual layout of grid and highway in NS-2.



(a.) whole grid



(b.) zoom in

Figure 4.2: Simulation grid and highway layout in NS-2

For simulating different highway service levels, maximum supported density (as in Table 3.2) is maintained to create respective worst case scenarios for each service level. To maintain uniform node distribution on road minor adjustments are made. For example, the average distance between vehicles at highway service level "E" and "D" is 4 and 0.47 m less than the expected safety distance, which is not significant. For all other service levels the average inter-vehicle distance is much larger than the safety distance and is not reduced in order to meet the maximum vehicle density requirements. Furthermore, introducing actual mobility to the scenario can cause nodes to experience different level of channel stress. Consequently, we take snapshot of each worst case scenario for actual simulation implementation and node movement is disabled.

4.2 MAC Layer Setup and Configurations

For accurate results the enhanced MAC layer module (Mac802.11Ext) is used in the simulation setup. The enhanced MAC layer implementation in NS-2 is thoroughly discussed in [44]. However, a brief excerpt of MAC layer functionality from [44] in the context of VANET standard implementation is also given here.

IEEE 802.11 MAC layer implementation in NS-2 consists of six modules namely transmission (Tx), reception (Rx), channel state manager, backoff manager, transmission coordination (TxCoord) and reception coordination (RxCoord). At MAC and PHY layer in system model diagram (Figure 3.3) the solid lines represent the path for exchanging data and control frames whereas the dashed lines correspond to active signaling interfaces between the modules.

Transmission module: The transmission module acts as the outbound traffic interface to the PHY. This module receives data frames from transmission coordination module and forwards received frames to the PHY for transmissions. The module is either in *TXing* state when transmitting a frame or is simply *TX_IDLE*.

Reception module: The reception module completes the frame reception process initiated at the PHY layer. All received frames (unicast as well as broadcast) have to go through address filtering process before being forwarded to next module. Furthermore, it also updates the channel state manager regarding virtual carrier sense information. This module performs CRC check by consulting the value of error flag attached by PHY to each frame. Each incoming frame has to be verified whether its reception is successful or not.

According to the standard after each failed frame reception a node has to wait for Extended InterFrame Space (EIFS) duration instead of DCF InterFrame Space (DIFS). In this MAC implementation, the channel state manager handles the inter-frame spacing. Consequently, all CRC check errors are reported to channel state manager by reception module. From the reception module, the data and control frames are forwarded to reception coordination module. Reception module can be in either of the two distinct states i.e. *RXing* or *RX_IDLE*.

Channel state manager: The channel state manager administers the physical and virtual carrier sense status for the Carrier Sense Multiple Access (CSMA) method.

For the physical carrier sense status, the channel state manager relies on the PHY. It anticipates the PHY to indicate a busy channel when the PHY is in transmission or when the total received signal strength goes higher than the carrier sense threshold. It also anticipates a channel clear indication from PHY channel is not busy. Similarly, for virtual carrier sense status the channel state manager is dependent on reception module. However, Short InterFrame Space (SIFS) is directly managed by reception and transmission coordination modules.

Upon request from any other module, the channel state manager replies with physical and virtual carrier sense status i.e. either *CS_IDLE*/*NoCSnoNAV* or *CS_BUSY*. Backoff manager is also updated whenever channel state manager goes into or out of *NoCSnoNAV* state. Backoff manager uses this information to resume or pause its backoff process.

Backoff manager: To support Collisions Avoidance implementation, the backoff manager upholds the backoff counter. It also supports transmission coordination module to process regular backoff as well as post-transmission backoff. There are three states of backoff manager i.e. No Backoff, Backoff Running and Backoff Pause. Backoff counter handling is dependent on carrier sense state information received from channel state manager.

Transmission coordination module: The transmission coordination module handles channel access for packets received from the higher layer. When a packet is received from upper, layer transmission coordination module first checks, if there is a need to generate a RTS frame or not. In the case of safety beacon RTS/CTS mechanism is not used, consequently RTS is not generated. After making the RTS decision, if the channel state manager is in *CD_IDLE* state the data transmission attempt is initiated immediately. Otherwise, it initiates backoff process if there is none in place and goes to *Data Pending* state. In this state, transmission coordination module instructs the transmission module to quickly transmit the frame when a backoff *Done* signal is received from backoff manager. Then the broadcast frame is transmitted over the air.

After the transmission, the TXC module resets the CW parameter as well as the retry counters, and launches a post transmission backoff. Subsequently, if there is a packet already in the queue, the above process is repeated or else it goes to *TXC_IDLE* state.

Reception coordination module: The reception coordination module forwards data frames to the higher layer. This module holds three states: *RXC_IDLE, RXC SIFS Wait*, and *Wait TX Done*. In the *RXC_IDLE* state it waits for control and data frames from the reception module. The other two states are used for CTS frames. Table 4.3 shows the MAC layer parameters and their corresponding settings. Brief description of these parameters and reasoning behind the chosen subsequent values are given in the following.

Table 4.3: Fixed MAC layer parameters settings

Parameter	Corresponding value
Contention Window	Min. 15 / Max. 1023
Slot time	13μs
SIFS time	32μs
Preamble length	32μs
PLCP header length	8μs
Basic data rate	3Mbps
RTS/CTS	OFF

Contention window: In 802.11p, during backoff a random time slot value between minimum contention window (CW_{min}) and maximum contention window

(CW_{max}) size is chosen. Considering the periodic beaconing as access category index (ACI = 1) of one, subsequent values for $CW_{min} = 15$ and $CW_{max} = 1023$ are chosen.

Slot time: Each contention window value represents a slot time and each slot has a time length of 13 μs.

SIFS time: Short Interframe Spacing is set to default 32 μs and is used in unicast communication for prioritizing ACK after data reception or sending CTS in response of RTS.

Preamble length: Like many other features preamble duration has also been modified in 802.11p (32 μs) from preceding version i.e. 802.11a (16 μs).

PLCP header length: Physical Layer Convergence Procedure (PLCP) header length is set to 8 μs.

Basic data rate: For compliance to 802.11p modulation scheme of Binary Phase Shift Keying (BPSK) with $^1/_2$ coding rate was set in all simulations, which corresponds to a data rate of 3Mbps for a 10MHz channel. It is also important to note that regardless of the payload data rate; PLCP header and the preamble are to be transmitted with the lowest supported data rate i.e. 3Mbps.

RTS/CTS: Since periodic safety broadcast does not use RTC/CTS mechanism, a corresponding value of 3000 is set to effectively disable this feature in NS-2.

4.3 PHY Layer Setup and Configurations

In NS-2, we make use of extended PHY layer module (*WirelessPhyExt*) to configure physical layer setup. The complete details of the PHY extension are given in [44], however an excerpt of PHY layer functionality is also given here. *WirelessPhyExt* consists of two modules i.e. PHY state manager and power monitor. Physical Layer Convergence Procedure (PLCP) states are handled by the PHY state manager, while power monitor module keeps track of RF signals received over wireless channel.

PHY state manager handles four PHY layer operating states i.e. *Searching, PreRXing, TXing, RXing*. When neither transmitting nor receiving, the PHY is in Searching state. In this state, PHY layer calculates the signal strength of each prospective preamble notified by the wireless channel for possible reception. When a prospective frame with sufficient signal strength is detected the PHY moves from Searching to *PreRxing* state. PHY moves to *RXing* state given that, for the time duration of preamble length plus signal length of the PLCP header, no frame with sufficient signal strength to disrupt proper reception of current frame is detected (if such a frame is detected the PHY goes back to Searching state), and the SINR of this frame remains higher than the basic modulation scheme's reception threshold. During this period, if preamble capture is enabled and a frame with adequately stronger signal strength (so that its preamble can be heard above others) is detected, the preamble capture is triggered. In this case the timer for the new frame is reset while PHY remains in *PreRXing* state.

While in *RXing* state, PHY receives the body of the currently processed frame. If the SINR remains higher than the threshold required by current modulation scheme for frame body, the PHY remains in *RXing* state for frame body duration else it marks the frame with error flag. The frame is further passed on to MAC layer which uses error flag to perform CRC check. At the end of *RXing* duration, PHY reverts to searching state again. However, if the frame body capture is enabled, a later arriving frame may force PHY to go back to *PreRXing* state if the later frame has sufficiently higher signal strength than the currently processed frame.

PHY moves into *TXing* state when MAC layer issues a transmit command. With RTS/CTS mechanism absent in broadcast safety communication, the MAC layer does not initiate transmission while PHY is in *RXing* or *PreRXing* state.

At PHY layer, the power monitor module represents Physical Media Dependent (PMD) sub-layer and is responsible for processing and managing all the received signal information. PMD monitors, cumulative interference and noise for every single node separately, whenever carrier sense threshold is breached it notifies the MAC for the CS status changes. A transmission from a node itself is handled as CS busy through the same interface.

Table 4.4 shows PHY layer parameters and their corresponding values used in simulations setup. These parameters are discussed in the following:

Frequency: In USA, FCC has allocated a 75MHz Dedicated Short Range Communication (DSRC) frequency spectrum of 5.850-5.925MHz for VANETs. DSRC spectrum is divided into seven 10MHz channels and a 5MHz guard band. Furthermore only a single 10MHz Control Channel (CCH) of 5.885MHz onwards is allocated for periodic safety beacons which we have used in our simulations.

Data rate: DSRC supports various data rates between 3 to 27Mbps on single 10MHz which can be doubled by combining two channels. However, according to [50], 6Mbps is the optimal date rate for heterogeneous VANET environment. Furthermore 6Mbps is also assumed to be the default data rate for VANET communication. For compliance, modulation scheme of Quadrature Phase Shift Keying (QPSK) with $^1/_2$ coding rate is used in all simulations, which corresponds to a data rate of 6Mbps for a 10MHz channel.

Table 4.4: Fixed PHY layer parameters settings

Parameter	Corresponding value(s)
Frequency	5.885GHz
Data rate	6Mbps
Bandwidth	10MHz
Noise floor	-99 dBm
RXth	-91 dBm
CSth	-94 dBm
Preamble & Data Capture	ON
SINR_Preamblecapture	4 dB
SINR_Datacapture	10 dB
Antenna Height	1.5 m
Antenna Gain GT, GR	2.512 dB

Communication channel bandwidth: Channel bandwidth of 10MHz is analogous to the control channel bandwidth of DSRC spectrum as specified by FCC in USA.

Noise floor: For a bandwidth of 10MHz, noise floor value is set to -99 dBm, which is the most common value used in previous studies.

Reception Threshold (RxTh): is the minimum power required by a receiver to successfully decode the message. Reception threshold can be calculated using (4.1).

$$\text{RxTh} = \text{Receiver Noise floor} + \text{SNR} \quad (4.1)$$

In DSRC, to successfully receive a frame within 10MHz channel and 6Mbps data rate, a Signal to Noise ratio of 8 dB is required [50]. Thus an ultimate choice for reception threshold is 91 dBm.

Carrier Sense Threshold (CSth): Carrier sense range is the range up to which a receiver is able to sense ongoing communication but is unable to decode it successfully. The CS threshold value is set to -94 dBm which is obtained from the latest settings of NS-2 802.11p module [72].

Preamble Capture and Data Capture (Frame body capture): When captured feature is enabled, it facilitates a receiver to choose the strongest frame header signal among several. It is also well known for enhancing packet reception rate in broadcast communication. Generally in IEEE 802.11 chips, the preamble capture is an integrated feature however its usage is optional. Throughout the simulations, both preamble and data capture features are enabled. The default parameter corresponding values of *SINR_PreambleCapture* and *SINR_DataCapture* are 4 dB and 10 dB respectively.

Antenna Height: Since NS-2 only supports 2D modeling of roads, thus throughout the simulations antenna heights remain fixed to a default value of 1.5 m. Furthermore, TRG propagation model limits the same antenna height for each node.

Antenna Gains: Both the transmitter gain G_t and receiver antenna gain G_r of 2.512 is similar to that of [51].

4.4 Miscellaneous Simulation Parameter Settings

Other relevant simulation parameter and their respective settings are shown in Table 4.5.

Trace Distance: Trace distance variable represents the distance with reference to sender, up to which the communication is tracked by NS-2. In order to gain computational efficiency in terms of processing time and storage, we set the trace distance as current Communication Range (CR) + 300 m. When using TRG model in NS-2 DSRC module, an addition of 300 m to CR ensures coverage of all received/lost beacons.

Channel load: Channel load in the observed area varies depending on the tunable parameter settings and traffic scenario.

Simulation time: Each simulation is performed for 21 seconds real time. Data for the first second of all simulation is truncated due to transitory network state. So, all the results are extracted from 20 seconds of data from each simulation.

Table 4.5: 4.4 Miscellaneous simulation settings

Parameter	Corresponding Value(s)
Trace distance	CR + 300 m
Channel load	variable
Simulation time	21sec/each
Comm. Range (m)	50, 100, 200...1000
SB generation interval (ms)	50, 100, 150... 500
SB payload size (bytes)	200, 300 ... 800

Configuration details of communication range, beacon generation interval and beacon payload size have already been discussed in Section 3.4.

4.5 PBCAgent

PBCAgent functions like a *Ping_Agent* packet generator and is used to control periodic beacons. In Tool Command Language (TCL), the agent is called by setting the agent as *Agent/PBC*. To generate periodic beacons the *PeriodicBroadcast* switch of *PBCAgent* has to be set as *ON*. With the help of TCL commands, *PBCAgent* can be used to configure various parameters i.e. beacon payload size, data modulation scheme, beacon generation interval and variance. Beacon payload size is set in bytes, while beacon generation interval and variance are set in seconds. To obtain a desired data rate of 6Mbps for 10MHz DSRC Control Channel, Quadrature Phase-Shift Keying (QPSK) data modulation scheme with ½ coding rate (Reference ID 1) is used. Sample code is provided in Appendix A.

4.6 Radio Propagation Models

Actual communication range is highly dependent upon the road environment due to natural phenomenon like temperature fluctuation, reflection, refraction, scattering. In simulations, radio propagation models are used to represent different environmental conditions. Current version of NS-2 has built-in support for various radio propagation models i.e. Freespace, Shadowing, Two-Ray Ground (TRG) and Nakagami. Only the later two are used in the simulations.

4.6.1 Two-Ray Ground

Two-ray ground (TRG) propagation model is a widely used radio propagation model. However, this model does not represent realistic highway environmental phenomenon i.e. fading, multipath effect. In NS2, TRG model computes the transmission distance according to (4.2) if the transmission distance is less than the cross-over distance. For greater transmission distances, Freespace model (4.3) is used.

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \qquad \text{if } d \leq d_c \qquad (4.2)$$

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \qquad \text{if } d > d_c \qquad (4.3)$$

Where P_r , P_t are power received and power transmitted, h_t, h_r are the heights of transmitter and receiver antennas, G_t, G_r are antenna gains at transmitter and receiver,

λ is the frequency wavelength while L is system loss. By default system loss L is set to one. Crossover distance (d_c) is calculated as in (4.4).

$$d_c = \frac{4\pi h_t h_r}{\lambda} \tag{4.4}$$

TRG model is a relatively more practical than the Free-Space model when ground reflection is considered in transmission path between transmitter and receiver, adding up to the direct Line Of Sight (LOS) path. TRG is particularly helpful for predicting the received power at longer distances from the transmitter. However, TRG model does not provide good results for shorter distances due to the fluctuations caused by the constructive and destructive combination of the two rays. This model assumes received energy as the sum of the direct LOS path and the reflected path from the ground. It does not account for obstacles; in addition sender and receiver have to be on the identical elevation [82].

4.6.2 Nakagami Propagation Model

Nakagami propagation model provides more configurable parameters than TRG. Detailed description about implementation of Nakagami Propagation Model is given in NS-2 overhaul documentation (available online [72]). In this section, the general concepts of the model are briefly explained as in NS-2 overhaul documentation.

Nakagami propagation model can be described as a general mathematical modeling of a fading radio channel. In comparison of the existing NS-2 propagation models such as TRG and Freespace, Nakagami allows a closer depiction of the wireless communication channel by means of more configurable parameters. Thus it is capable of modeling various channel conditions such as free space, moderate fading channel on highway and significantly fading channel for urban environment. Nakagami distribution is expressed as the probability density function given in (4.5).

$$f(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^{m}} \exp\left[\frac{-mx^2}{\Omega}\right], \qquad x \geq 0, \qquad \Omega > 0, \qquad m \geq \frac{1}{2} \tag{4.5}$$

The corresponding probability density function of power (square of the signal amplitude) at the given distance can be acquired by a change of variables and is given by a gamma distribution in the form of (4.6)

$$P(x) = \left(\frac{m}{\Omega}\right)^m \frac{x^{m-1}}{\Gamma(m)} \exp\left[-\frac{mx}{\Omega}\right], \qquad x \geq 0 \tag{4.6}$$

where Ω is the anticipated value of the distribution and can be inferred as the average received power whereas m is the alleged shape or fading parameter. The values of the parameters m and Ω are functions of distance. Consequently, Nakagami model is defined by functions Ω (d) and m (d). Smaller values of m provide more severe fading. Complete Nakagami settings are given in Table 4.6.

Table 4.6: Nakagami settings

Parameter	Values
gamma0_, gamma1_, gamma2_	1.9, 3.8, 3.8
d0_gamma_, d1_gamma_	200, 500
m0_, m1_,m2_	1.5, 0.75, 0.75
d0_m_, d1_m1	80, 200

In [71], DSRC channel characteristics for V2V communication were empirically determined and it was shown that Nakgami fading parameter m lies between 0.5 and 1.0 for highway scenario. Nakagami settings for the simulations are set according to [43] with a mean m of 0.75 for *d1_m1*.

4.7 Chapter Summary

In this chapter the detailed reasoning behind the choice of all simulation parameters and their settings were discussed. The simulation grid design and highway setup are presented in accordance with the worst case scenario guidelines. MAC and PHY layers implementation is thoroughly discussed along with respective parameters. TRG and Nakagami propagation models are duly presented. Nakagami settings according to realistic highway environment are also given.

CHAPTER 5

RESULTS AND DISCUSSION

In this chapter, thorough results for performance evaluation of single-hop periodic safety beaconing in worst-case scenario are presented with detailed analysis. Each of the tunable parameters is evaluated exclusively in order to measure their effectiveness. Furthermore, optimal combinations of tunable parameter for different highway service levels are also presented.

5.1 Results with Two-Ray Ground Model

Initially, all simulations are carried out using two-ray ground propagation model for measuring relative effectiveness of tunable parameters. Furthermore, these results are used for comparison with Nakagami propagation model results later on.

Computing results for all simulated nodes in a broadcast communication environment is extremely difficult and requires extensive computational resources and time. Generally, results from only selected sample of nodes are computed. A large sample size is required for higher accuracy in a non-homogenous node distribution. However, in a homogenous distribution like ours, accurate results can also be acquired with a small sample size. In addition to sample size, other factors like position of the node on the grid and the distance between reference and observed nodes are also of great importance. For example, when observing packet delivery ratio for a communication range of 1000m, selecting observed nodes near the reference nodes can show exaggerated results. Similarly, selecting observed nodes far away from the reference node can also show significantly lower delivery ratio than the actual results. In the literature we find that, as a general strategy a single reference node is selected and observed nodes are chosen randomly from within the specific area.

In worst-case scenario, we select six reference nodes (one from each lane) at the centre of the highway. Centre of the highway is the ideal location to avoid border effects. Selecting random observed nodes is a useful strategy when monitoring general node behavior. However, in our case we also need to observe node behavior at various distances within the specific communication range. Thus a node near every 100 m interval within the CR is chosen as observed node. For example, for a CR of 1000 m, overall ten nodes at the distances of 100, 200, 300....1000m (with $\pm$ 10m) from reference nodes of each highway side are chosen for observation. Thus a total of 20 nodes are chosen as observed nodes in 1000m CR. Similar strategy is applied for all experimental CRs. Furthermore, all graphs presented in this section are interpolated using MATLAB®. The reference node and observed node IDs for worst-case scenario are shown in Table 5.1. Overall two sets of simulations were carried out:

- For first set, CR of all nodes was fixed at maximum (1000m) while BGI and SB size were tuned
- In second set, BGI was fixed at 100ms; on the other hand both CR and SB size were tuned

Table 5.1: The reference node and observed node IDs for worst-case scenario

Reference node IDs	Observed node IDs
150, 400, 560	403, 406, 410, 413, 416, 420, 423, 426, 430, 433
680, 840, 1090	807, 810, 814, 817, 820, 824, 827, 830, 834, 837

5.1.1 Per-node Throughput Results

Per-node throughput is calculated as the average beacon payload data received by the reference nodes and header size is not considered which is fixed at 28 bytes in NS-2. Figure 5.1 shows the impact of Beacon Generation Interval and SB size on per-node throughput with fixed CR of 1000 m. As shown, if interval is below 200 ms, varying the packet size does not bring significant change. Noticeable variations occur with BGI of 200 ms and above, as difference between throughputs of different beacon sizes increases. With SB size of 200 bytes throughput increases as the BGI is increased up to 150 ms and after BGI of 200 ms the throughput starts to decrease rapidly. For beacon sizes of 300, 400, 500, 600, 700 bytes throughput increases up to 200, 250, 350, 400, 450 ms respectively and then starts declining. Maximum throughput of 3210.51 is achieved with 800 bytes SB size and 500sec of BGI. Minimum throughput is obtained with a beacon size of 200 bytes at BGI of 500 ms. It is important to note that the maximum throughput achieved in this case is approximately half (3.21Mbps) of the used data rate (6Mbps). Furthermore, for beacon size of 500 bytes, the average throughput obtained across all simulated values of BGI is 2392.95 Kbps. While the average of the average throughput across all simulated values of beacon size and BGI is 2234.11Kbps. The most productive range of BGI is between 300 to 500 ms with beacon size range between 500 to 800 bytes, where per-node throughput remains above 2530 Kbps. Overall, larger beacon size generally contributes towards the higher average throughput.

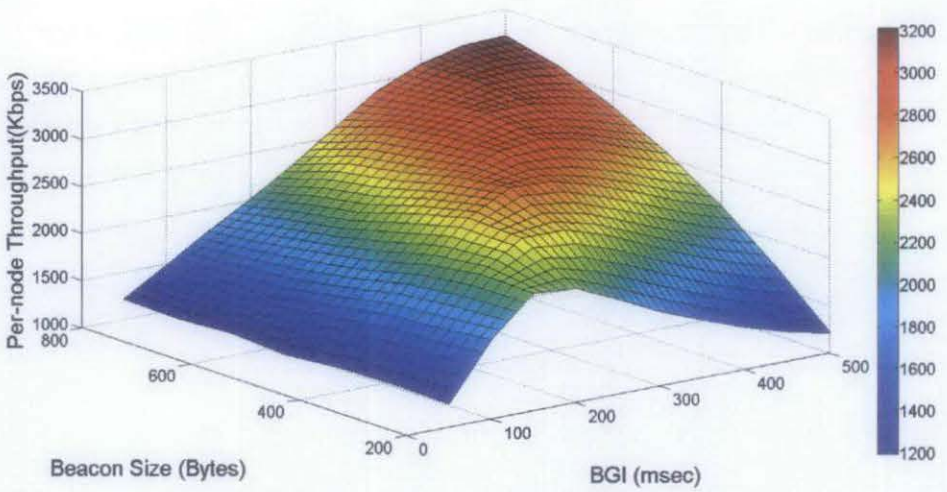


Figure 5.1: Per-node throughput results for BGI vs Beacon size, (CR=1000m)

To monitor the effect of Communication Range (CR) on per-node throughput the BGI interval is fixed at 100 ms and the CR and SB size are tuned. Obtained results are shown in Figure 5.2. The maximum per-node throughput with beacons sizes of 200, 300, 400, 500, 600, 700, 800 bytes is achieved at CR of 700, 500, 400, 300, 200, 200 and 100 m respectively. Maximum throughput of 1987.92Kbps is attained with beacon size of 500 bytes and CR of 300 m. The average throughput with the beacon size of 500 bytes across all simulated values of CR is 1658.75Kbps. While the average of the average throughput across all simulated values of beacon size and CR is 1615.33Kbps. The most productive range of CR is between 400 to 1000 m with beacon size range between 200 to 500 bytes, where per-node throughput remains above 1630 Kbps.

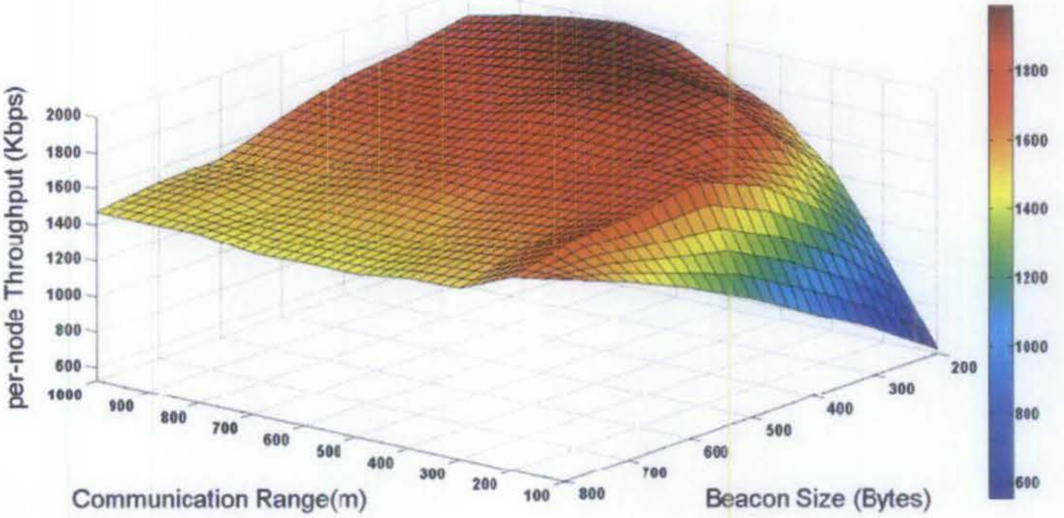


Figure 5.2: Throughput results for CR vs Beacon size, (BGI=100 ms)

In the light of above results it is evident that safety beacon size plays the most significant role in terms of per-node throughput control. Furthermore, BGI is far more effective in controlling per-node throughput than CR. Nonetheless, the most productive combination for maximum throughput in the given scenarios is 1000m CR, 800 bytes SB size and 500 ms BGI.

For maximum throughput in deterministic conditions, BGI between 300 to 500 ms is suitable for safety application with flexible delay requirements and involving larger amount of information to be exchanged over larger single-hop distance. On the other hand, safety applications with strict delay requirements should use beacon size of <= 500 bytes along with CR between 400 to 1000 m.

5.1.2 End-to-end Delay (e2e delay) Results

Most studies estimate e2e delay in non-interfering environment, however here the presented results are obtained from a fully deployed network. Although, graphs obtained are not smooth in nature, however the method applied is useful in determining overall trends of e2e delay within the boundaries of studied parameters.

It can be observed from Figure 5.3 that a combination of smaller SB size and larger BGI is more suited for minimizing e2e delay over maximum CR. Moreover, with BGI greater than 100 ms, e2e delay remains within an acceptable limit of less than 16 ms regardless of the beacon size. However, with BGI interval of 50 ms (not shown here for presentation reasons), e2e delay is 89.98 ms and 570.45 ms for beacons sizes of 700 bytes and 800 bytes respectively. The minimum recorded delay is 0.629 ms with beacon size of 200 bytes and BGI of 500 ms.

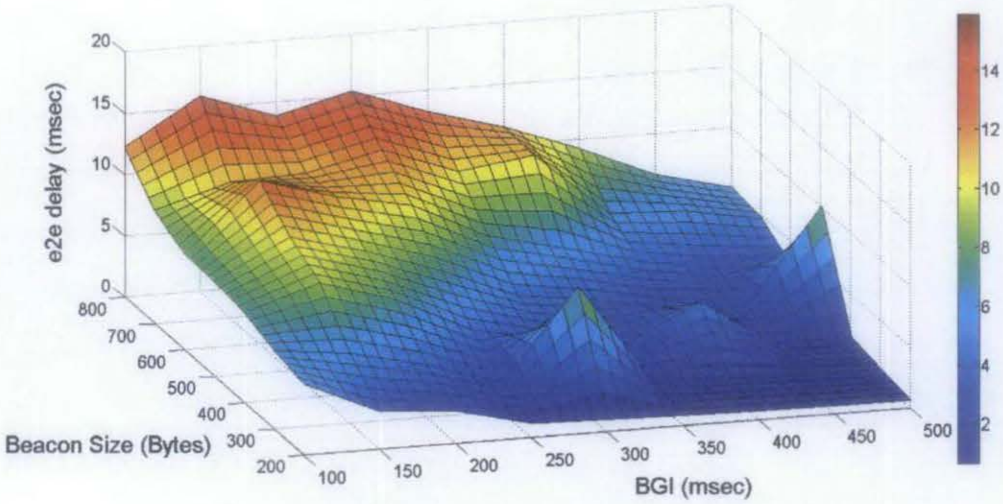


Figure 5.3: e2e delay results for BGI vs Beacon size, (CR=1000m)

Regardless of increment or decrement in CR, e2e delay remains below 19 ms (Figure 5.4). However, minimum beacon size is desirable for minimal delay.

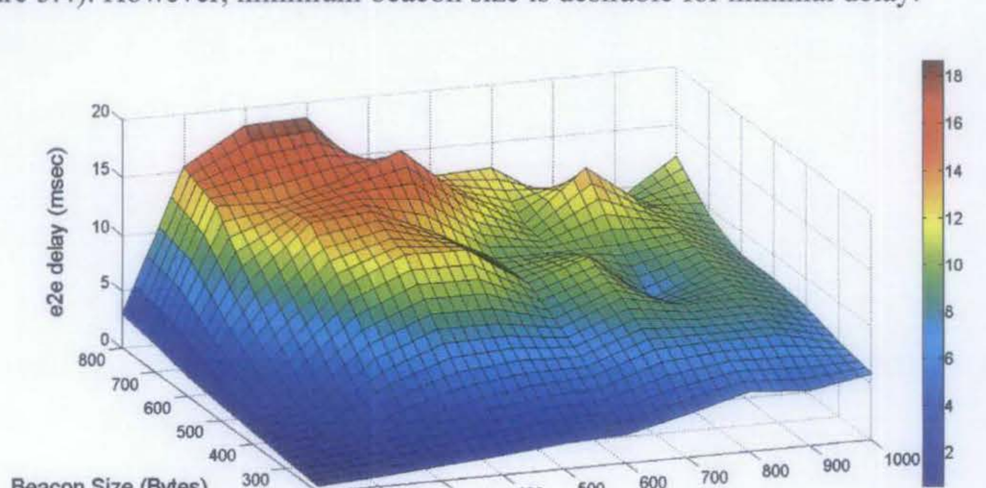


Figure 5.4: e2e delay results for CR vs Beacon size, (BGI=100 ms)

From e2e delay results presented here, it seems safe to conclude that BGI of 50 ms and below is not suitable with larger SB size for safety applications with stringent latency requirements. It is also evident from the results that, beacon size and BGI should be kept in check for timely delivery of periodic beacons. Overall, beacons sizes of less than 600 bytes and BGI of 100ms or greater appear to be safe choices.

5.1.3 Packet Delivery Ratio (PDR) Results

PDR is the most commonly used metric for evaluating network performance. In VANET life safety depends on timely and successful delivery of periodic beacons. Results from the previous section show that latency requirements for most safety applications can be met easily. The successful delivery of periodic beacons also needs to be measured appropriately. PDR can be obtained in different ways, for example by calculating percentage of recipients (PDR-recipients) that receive a broadcast packet from a specific sender or by calculating percentage of packets successfully received by a receiving node from a specific sender (PDR-beacons). In conventional networks, it is deemed sufficient to calculate average packet delivery ratio. However, due to the stringent safety application requirements in VANETs, a certain PDR should also be ensured at specific distance from the sender. In this section effectiveness of tunable parameters is measured along with usefulness of both PDR criterions. Furthermore, the effect of communication range adjustment at specific distances from the sender is also discussed.

To determine the relative effectiveness of BGI and CR control methods on PDR, it is imperative to devise a suitable way. A simple method could be to use maximum achieved PDR or average PDR for each parameter within its given boundaries. Another way is to determine overall capacity of a parameter in improving PDR within the given boundaries of that parameter. All of the above methods are used here to carry out a fair and steadfast comparison. Maximum achieved PDR is the PDR attained at any point while varying the specific parameter. Average PDR is taken as the average of the average PDR attained while varying CR/BGI with respect to different safety beacon sizes. The capacity of a tunable parameter is measured in terms of maximum gain in PDR within minimum and maximum values of the specific parameter. In this case, selecting minimum and maximum values of a parameter is important. The maximum values for BGI, CR, and beacons size are 500 ms, 1000m and 800 bytes respectively; while carefully chosen respective minimum values are 50 ms, 100 m and 200 bytes.

Figure 5.5 and Figure 5.6 show results obtained for PDR-beacons and PDR-recipients respectively. These results are acquired with fixed CR of 1000 m while values of BGI and beacons size are tuned. Overall, a maximum of 85.61% PDR-beacons and 86.84% PDR-recipients is achieved with beacon size of 200 bytes and BGI of 500 ms. With a beacon size of 500 bytes, average PDR-beacons across all BGI values is 38.85% and average PDR-recipients is 42.29%.

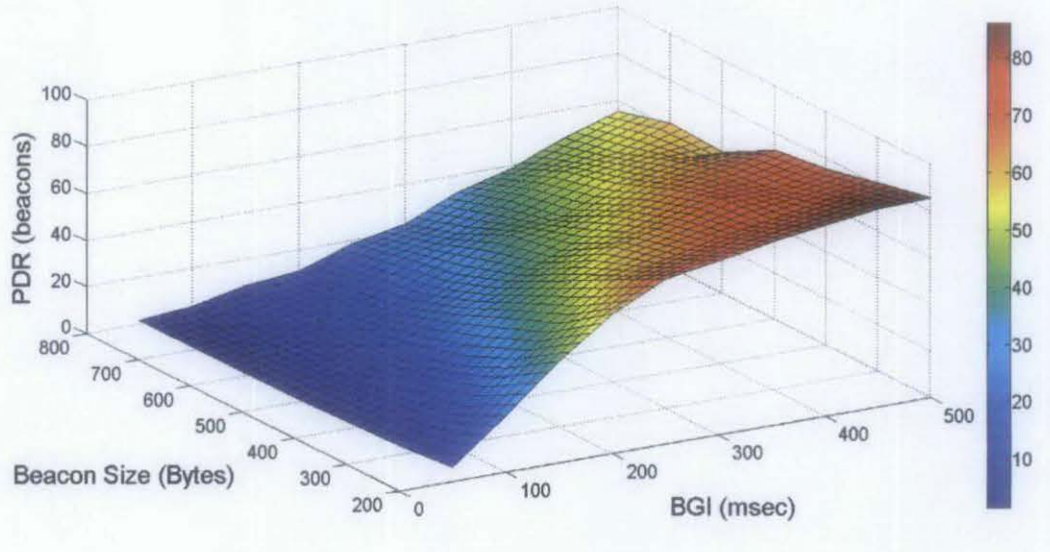


Figure 5.5: PDR-beacon results for BGI vs Beacon size, CR=1000m

Increment in BGI also causes significant gain in PDR. With beacon size of 500 bytes, PDR-beacons increases from 2.07% at 50 ms to 72.18% at 500 ms, with a maximum gain of 70.11 %. Similarly, PDR-recipients increases from 3.45 % at 50 ms to 74.59% at 500 ms with a net gain of 71.14 %. Overall, maximum average PDR gains (across all values of BGI and beacon size) for PDR-beacons and PDR recipients are 67.12% and 69.24% respectively. Maximum average PDR gain with BGI is calculated as in (5.1).

Max. Avg PDR gain with BGI =

$$\frac{1}{n}\sum_{SBsize=200}^{SBsize=800}(PDR|_{BGI=500ms} - PDR|_{BGI=50ms});\ SBsize=200{,}300\ldots800 \quad (5.1)$$

The sum at only discrete beacon size values is taken into consideration i.e. +100 bytes for each step with a total of 7 steps. At each step of beacon size, PDR at maximum BGI of 500 ms is subtracted from minimum BGI of 50 ms. Step size is represented as *n* which is 7 in this case.

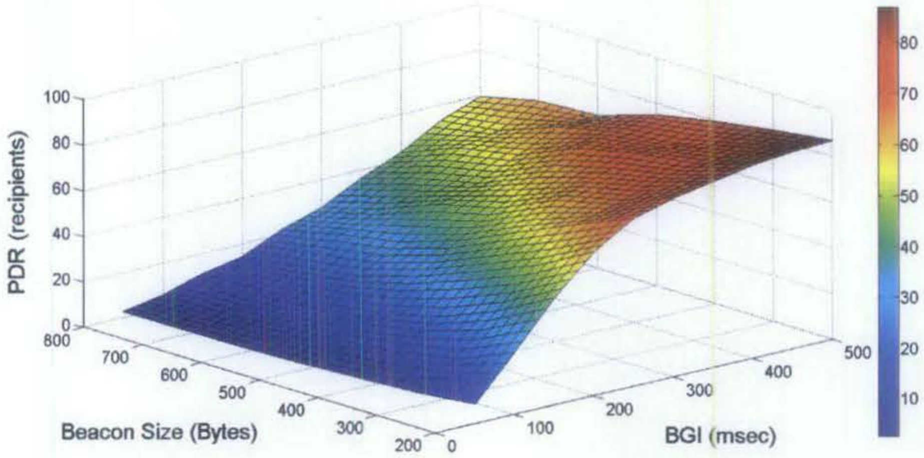


Figure 5.6: PDR-recipient results for BGI vs Beacon size, CR=1000m

A slight difference between results of PDR-beacons and PDR recipients can be observed. The difference is the direct result of different computation methods used for calculating both types of PDRs. In case of PDR-beacons, PDR averages of only selected node are considered while in the case of PDR-beacons, total numbers of recipients within the specific range are calculated. There is a difference of 1.38% at 50 ms and 4.48% at 500 ms, between the gains of both types of PDRs at all BGIs; while the overall difference is 3.44%. Furthermore, difference between the overall maximum average PDR gains for both PDR criterions is 2.12%. Regardless of the minor differences in some calculations, overall trends in increment or decrement of PDR remain similar for both criterions. Thus, it can be concluded that both PDR metrics provide reasonably accurate performance trends with PDR-beacon being the relatively pessimistic approach.

Along with increment in BGI, reducing beacons size also has a positive impact on PDR. At BGI of 50 ms, with a SB size of 200 bytes results in a PDR-beacon of 6.19% while for 500 ms BGI it is 1.66%, with a net gain of 4.53%. Similarly, at 500 ms BGI, 200 bytes SB size results in PDR-beacon of 85.61% and with 800 bytes SB it is 55.13%, with a maximum gain of 30.48%. Overall, a maximum average PDR gain with SB size, across all BGI steps is 36.86% (for PDR-beacons) and 36.29% (for PDR-recipients) with a net difference of 0.57%. Maximum average PDR gain with SB size (with reference to BGI) is calculated as in (5.2).

$$\text{Max. Avg PDR gain with SB size(with ref. to BGI)} =$$

$$\frac{1}{n}\sum_{BGI=50}^{BGI=500}(PDR|_{200B} - PDR|_{800B});\ BGI = 50{,}100 \ldots 500 \tag{5.2}$$

The sum at only discrete BGI values is taken into consideration i.e. +50 ms for each step with a total of 10 steps. At each BGI step, PDR at maximum SB size of 800 bytes is subtracted from PDR at minimum SB size of 200 bytes. Step size is represented as *n* which is 10 in this case.

Results in Figure 5.7 and Figure 5.8, show that reducing CR improves overall PDR. When beacon size is greater than 500 bytes, the improvement is significant only within shorter CR i.e. 300m or less. With a beacon size of 500 bytes, PDR-beacons increases from 6.26 % at 1000 m to 68.98% at 100 m, with a maximum gain of 62.72%. Similarly, in case of PDR-recipients, it increases from 8.82% at 1000 m to 73.93% at 100 m with a net gain of 65.11%.

The difference between both types of PDRs is 2.56% at 1000 m and 2.41% at 100 m. There is an overall difference of 1.39 % between the maximum average gains (across all values of CR and SB sizes) of PDR-beacons (60.88%) and PDR-recipients (62.27%). Since, the difference of 1.39% between the overall gains in both PDRs is not significant. It can be safely concluded that both PDR metrics provide reasonably similar performance trends with PDR-beacon being the more pessimistic approach of the two. Maximum average PDR gain with CR is calculated as in (5.3).

$$\text{Max. Avg PDR gain with CR} =$$

$$\frac{1}{n}\sum_{SBsize=200}^{SBsize=800}(PDR|_{100m} - PDR|_{1000\,m});\ SBsize = 200{,}300 \ldots 800 \tag{5.3}$$

The sum at only discrete SB size values is taken into consideration i.e. +100 bytes for each step with a total of 7 steps. At each SB size step, PDR at minimum CR of 100 m is subtracted from maximum CR of 1000 m. Step size is represented as n which is 7 in this case.

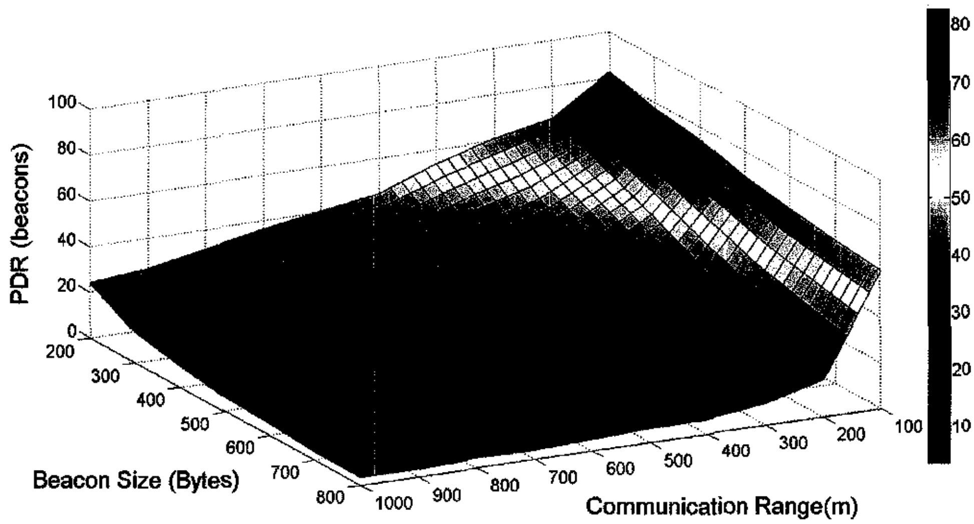


Figure 5.7: PDR-beacon results for CR vs Beacon size, (BGI=100 ms)

Along with decrement in CR, reducing beacons size also affects PDR positively. At CR of 1000 m, with a SB size of 800 bytes results in a PDR-beacon of 3.62% while for 200 bytes PDR is 24.04%, with a net gain of 20.42%. Similarly, at 100 m CR, 800 bytes SB size results in PDR-beacon of 60.32% and with 200 bytes SB size it is 82.55%, with a maximum gain of 22.23%.

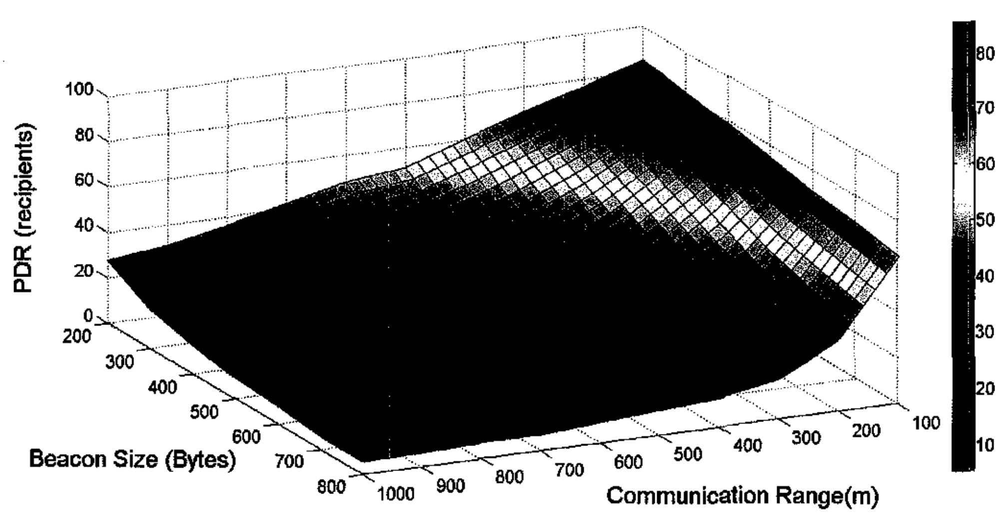


Figure 5.8: PDR-recipient results for CR vs Beacon size, BGI=100 ms

Overall, a maximum average PDR-beacon and PDR-recipient gains with SB size across all CR steps are 34.57% and 35.56% respectively. The difference of 0.99% between gains is fairly small.

Maximum average PDR gain with SB size (with reference to CR) is calculated as in (5.4). The sum at only discrete CR step values is taken into consideration i.e. +100 m for each step with a total of 10 steps. At each BGI step PDR at maximum SB size of 800 bytes is subtracted from minimum SB size of 200 bytes. Step size is represented as n which is 10 in this case. Overall, a maximum of 82.55% PDR-beacons and 85.36% PDR-recipients is achievable with SB size of 200 bytes at CR of 100 m.

$$\text{Max. Avg PDR gain with SB size (with ref, to CR)} =$$

$$\frac{1}{n}\sum_{CR=100}^{CR=1000}(PDR|_{200B} - PDR|_{800B})\,;CR = 100{,}200\ldots1000 \tag{5.4}$$

It is generally assumed that reducing CR also benefits PDR at nearby nodes of the transmitting vehicle. This phenomenon is only true when considering average PDR over the intended communication range. Furthermore, to measure the impact of transmission power adjustment on nodes nearer to the sender, PDR should be measured on nodes at specific distances from sender. PDR-beacon results for different intended CRs and their impact on nodes at specific distances is plotted in Figure 5.9.

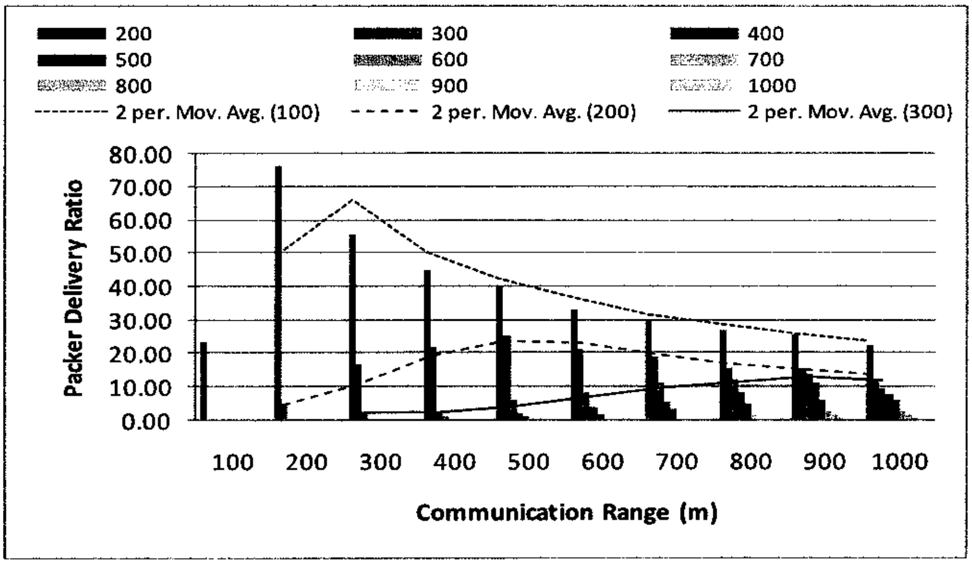


Figure 5.9: PDR-beacon results for fixed distances, (BGI=100 ms)

The x-axis represents the intended communication range and each color bar represents the observed node's distance from the transmitter. The two period moving average trend lines of nodes at 100, 200 and 300 meters show that, increment in CR results in higher PDR at closer nodes up till a specific CR before it starts to decline. For example, for the node at distance of 100 m, PDR increases up to a CR of 300; similarly for node at the distance of 300 m from the transmitter, PDR increases when increasing CR up to 900 m. The higher PDR at closer distances can be attributed to capture effect which helps a node to receive a beacon with sufficiently higher power among the beacons sensed on the channel.

5.1.4 Analysis and Discussion for TRG

Simulation results under deterministic environment validate that appropriate adjustment of tunable parameters can improve the performance of periodic vehicle-to-vehicle communication over a distance of single-hop. For maximum throughput in the given scenarios, a combination of maximum CR, maximum BGI and maximum beacon size is required. This combination is potentially fruitful for situations where large amount of information is to be exchanged over longer distances with relatively relaxed latency requirements e.g. information aggregation. It is also observed that safety beacon size plays the most significant role in terms of per-node throughput control. However, a larger beacon size has negative effect on e2e delay and PDR, which is not suitable for safety applications. Furthermore, BGI is far more effective in controlling per-node throughput than CR.

Generally, end-to-end delay remains less than 20 ms which is well within the latency requirements of most safety applications i.e. 100 ms. However, e2e delay with BGI of 50 ms and beacon size of 800 bytes, far exceeds most safety application latency limits. From these results, it is obvious that BGI of 50 ms and below is not desirable for larger beacons; however it may be feasible with smaller SB size. Reducing CR also helps to reduce e2e delay; however BGI remains relatively more important parameter in controlling e2e delay behavior. Overall, it can be concluded that the latency requirements for most safety application can be met easily.

Two types of PDR metric were evaluated i.e. PDR-recipients and PDR-beacons. Results from both types of PDRs match reasonably closely and show similar behavior for all the tested parameters. Nonetheless, PDR-beacons can be considered relatively more pessimistic metric in the given scenario. Overall, reducing SB size, CR and increasing BGI contribute towards higher PDR. Maximum average PDR-beacon gains with CR and BGI are 60.88% and 67.12% respectively. While, maximum average PDR-beacon gains with SB size in combination with CR is 34.57% and in combination with BGI is 36.86%. PDR-recipients results show the similar trends. In the light of above results, it can be concluded that BGI is potentially the most effective parameter in terms of controlling PDR behavior, with CR closely following in the second position and SB size significantly behind in the last place. It is also observed that increasing communication range does not always result in lower PDR at closer nodes. In fact, by enabling capture effect, higher PDR can be also achieved at closer distances with increment in CR.

From here onwards the main focus of the experimentation will be on CR and BGI rather than SB size for two main reasons. First, SB size is significantly effective only in terms of throughput and to some extent in e2e delay. This importance is somewhat reduced given the facts that, there are no throughput constraints directly concerning safety applications and e2e delay requirements are generally achievable for typical safety applications. Furthermore, bandwidth reservation is implicitly applied as maximum throughput achieved is almost half (3.21Mbps) the data rate (6Mbps) used. Secondly, it is not practical to artificially reduce SB size. Because, shedding SB size can be achieved in two ways that are counterproductive. One, by reducing content of the safety beacon which means loss of critical information required for safety application. Two, by eliminating the safety beacon security overhead which opens a plethora of ways to breach VANET, potentially putting lives at risk.

5.2 Results with Nakagami Model

As results obtained from TRG propagation model indicate that CR and BGI are more effective tunable parameters than beacon size. Thus, while experimenting with

Nakagami model we limit the beacon size to 200, 500 and 800 bytes for per-node throughput and e2e delay analysis, because of its noteworthy impact on these performance metrics in some cases. Although, actual results are obtained with beacon size of 200, 500 and 800 bytes, results for the rest of the beacon sizes are interpolated using MATLAB®. While a fixed SB size of 500 bytes is used for performance evaluation in terms of PDR as SB size is the least effective among tunable parameter in terms of PDR. Similar to TRG, two sets of simulation were carried out.

It is important to mention that under probabilistic Nakagami propagation model communication range is reduced due to fading and higher collision rate in dense traffic conditions. Wherever applicable, results are presented within the context of Intended Communication Range (ICR) as well as Effective Communication Range (ECR). ECR is taken as the range beyond which no beacons are received. Furthermore, under Nakagami propagation model, beacons can be received beyond the ICR with lower node density. Since the focus is on evaluating maximum safety applications requirements, the beacons delivered beyond the ICR are ignored. Furthermore, maximum ECR only equals ICR within the observed scenario.

5.2.1 Per-node Throughput Results

Figure 5.10 shows the effect of BGI and SB size on per-node throughput with fixed Intended Communication Range (ICR) of 1000 m. For beacon sizes of 200, 500 and 800 bytes, per-node throughput increases with increment in BGI up to 100, 150 and 300 ms respectively.

Maximum throughput of 3031.41Kbps is achieved with 800 bytes SB size and 250 ms of BGI while minimum throughput of 790.31Kbps is achieved with SB size of 200 bytes and BGI of 500 msec. Similarly, for SB size of 500 bytes maximum throughput of 2765.40Kbps is achieved at BGI of 150 ms and minimum throughput of 1727.23Kbps is yielded by BGI of 500 ms. On average, 800 bytes SB size provides highest per-node throughput for all BGI values. It is also important to note here that maximum per-node throughput achieved in this scenario is almost half (3.03Mbps) the data rate (6Mbps) used for simulations.

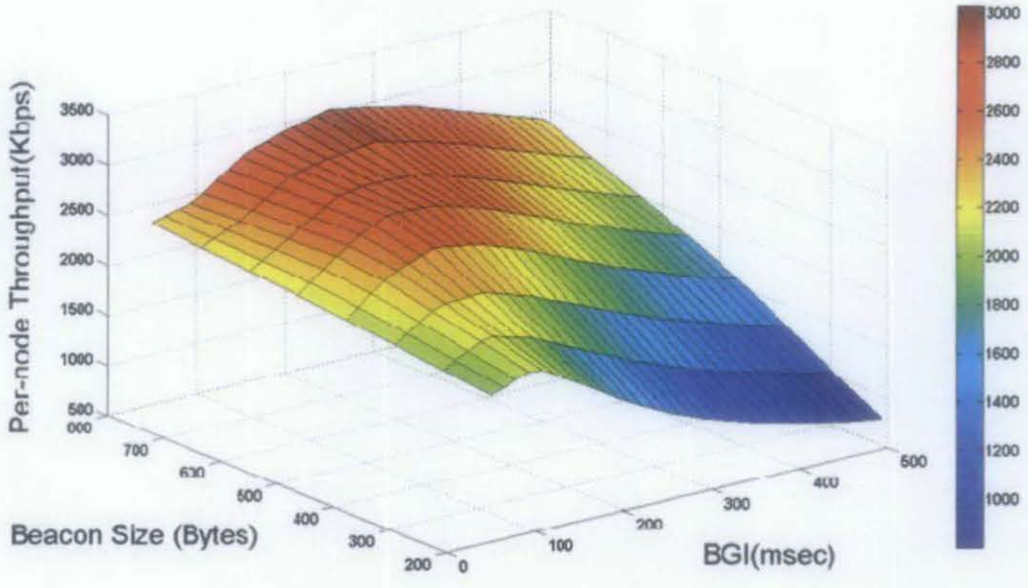


Figure 5.10: Per-node throughput results for BGI vs Beacon size, (CR=1000m)

To monitor the effect of Communication Range (CR) on per-node throughput the SB interval is fixed at 100 ms and SB size is fixed at 500 bytes while tuning the CR. Results obtained are plotted in Figure 5.11 and it can be seen that higher throughput is achievable with wider CR. Furthermore, larger SB size can also be useful for further improvement. With beacon size of 500 bytes, maximum per-node throughput of 2611.30Kbps is achieved with 700 m CR. Furthermore, for CR of more than 500 m, per-node throughput consistently remains above 2500 Kbps.

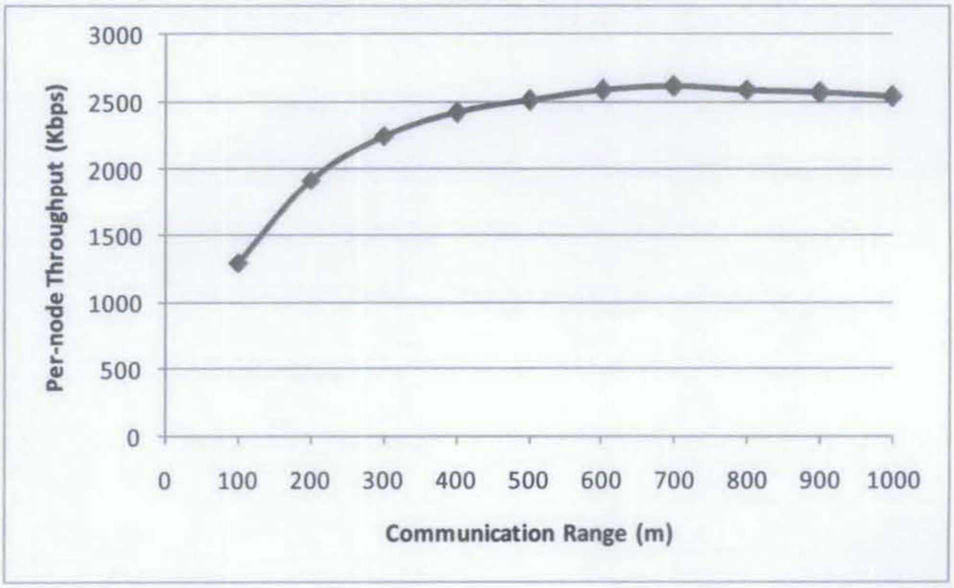


Figure 5.11: Per-node throughput results for CR (BGI=100 ms, SB size=500 bytes)

On the whole, larger beacons size is the most productive parameter for higher throughput. For optimal throughput with BGI; it should be tuned according to the beacons size. As of general trend shown in the results, with the increment in SB size increasing BGI benefits throughput up to a certain point. Furthermore, larger CR also results in higher throughput.

5.2.2 End-to-End Delay Results

Figure 5.12 and Figure 5.13, show e2e delay results with within ICR and ECR respectively. From the results, it can be observed that a smaller SB size is more suited for minimizing e2e delay with maximum ICR as well as with maximum ECR. Increasing BGI also helps to reduce e2e delay. While tuning BGI with fixed ICR of 1000 m, BGI of 50 ms (not shown for presentation reasons) with SB sizes of 500 and 800 bytes, results in respective e2e delay of 401.32 ms and 717.98 ms with ICR. The same BGI and SB sizes produce respective e2e delay of 668.87 ms and 1435.96 ms with ECR. Moreover, with BGI greater than 100 ms, e2e delay remains within an acceptable limit of less than 32 ms regardless of the beacon size.

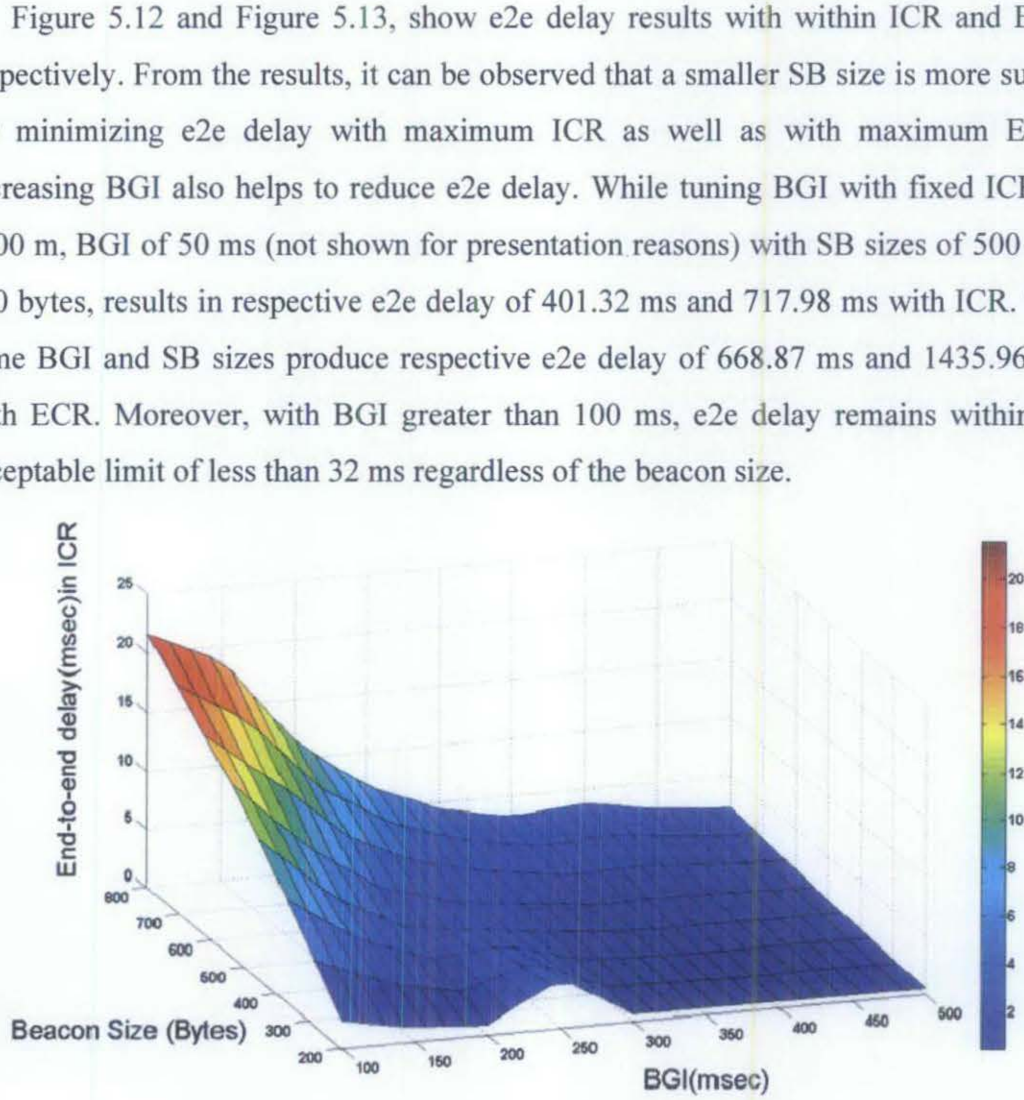


Figure 5.12: End-to-end delay within ICR, BGI vs Beacon size (CR=1000m)

The difference between ECR and ICR e2e delay results increases with increment in SB size as well as with decrement in BGI. This is the direct result of increasing gap between ICR and ECR which in turn is caused by increment in interference and collisions. Overall, ECR results for e2e delay present more realistic picture than the results obtained with ICR.

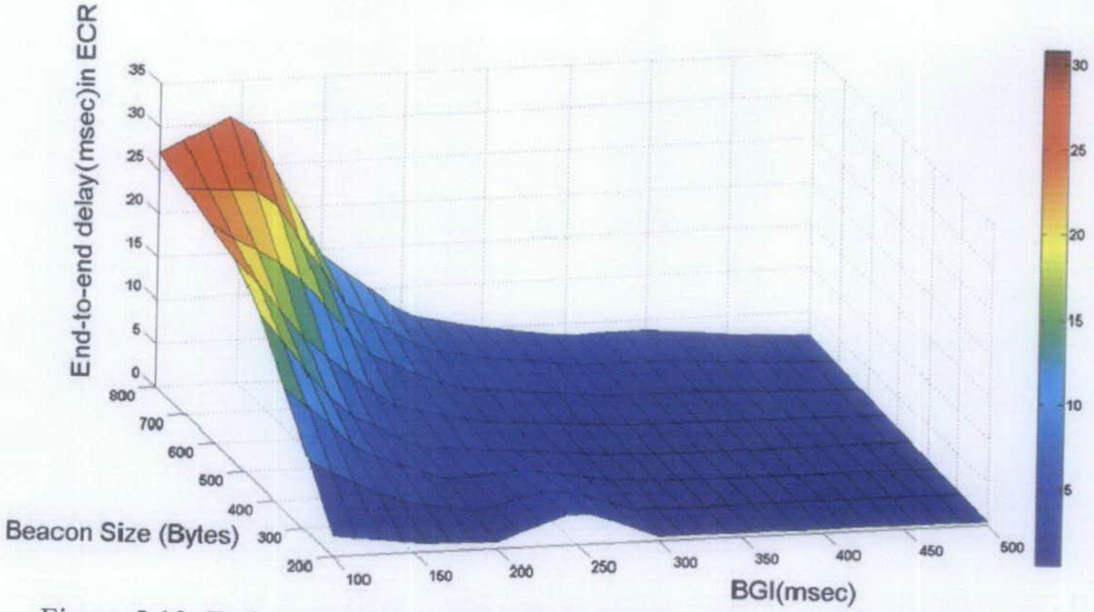


Figure 5.13: End-to-end delay within ECR, BGI vs Beacon size (CR=1000m)

A comparison of e2e delay assessment between ICR and ECR is shown in Figure 5.14 with a beacon size of 500 bytes. The e2e delay remains similar for ICR and ECR when increasing CR up to 500 m. However, the difference beyond this point begins to emerge which increases further with the increment in CR. The difference in results also shows that proper calculation of statistics is extremely important for accurate analysis.

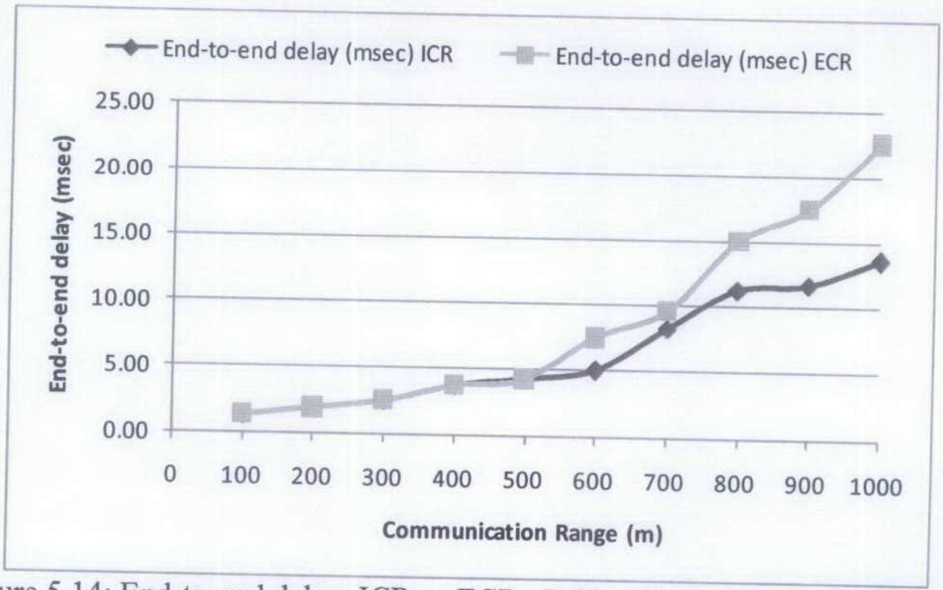


Figure 5.14: End-to-end delay, ICR vs ECR, (BGI=100 ms SB size=500 bytes)

5.2.3 Packet Delivery Ratio Results

With the help of TRG propagation model it has already been estimated that PDR-beacons and PDR-recipients yield similar trends. Thus for PDR evaluation with Nakagami model, we only use PDR-beacons as the evaluation metrics. We choose PDR-beacons over PDR-recipients because PDR-beacons not only provide the average delivery rate within a certain CR but also provide delivery rate on specific distances from the sender. Ensuring certain PDR at specific distances is important for ensuring reliability of safety applications. PDR-recipients only provide number of recipients within a specific range of the sender. In this section, terms PDR and PDR-beacons are used interchangeably unless specified otherwise.

Figure 5.15 and Figure 5.16 show PDR-beacons results within ICR and ECR respectively. The results indicate a considerable rise in PDR with increment in BGI. Highest PDR of 52.29% is achieved at BGI of 500 ms with SB size of 200 bytes. Average PDR achieved with SB size of 500 bytes across all BGI values is 30.76% within ICR and 32.34% within ECR.

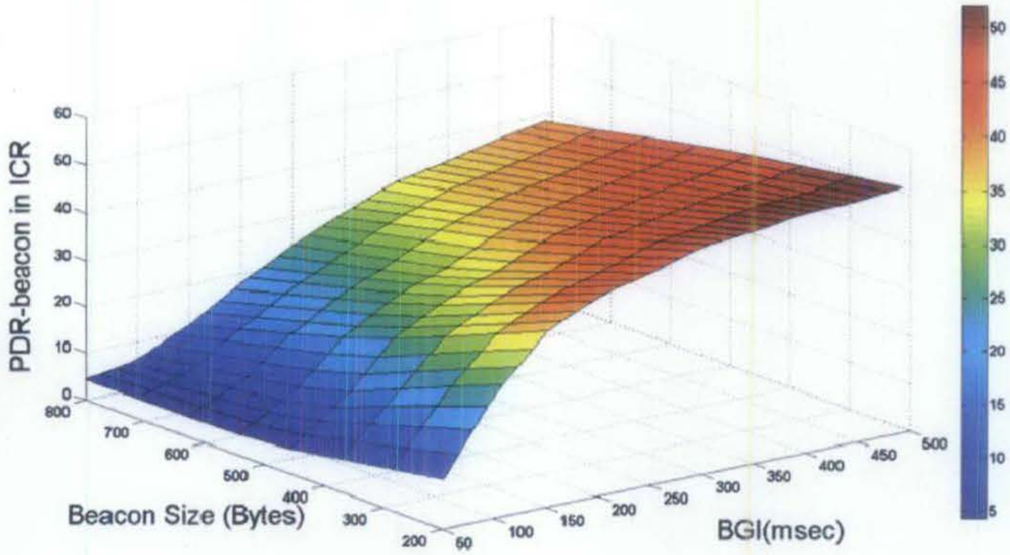


Figure 5.15:PDR-ICR results for BGI vs Beacon size, (CR=1000 m)

While estimating with ICR and beacons size of 500 bytes, PDR-beacons increase from 4.46% at 50 ms to 46.70% at 500 ms, with a maximum gain of 42.24%. Overall, a maximum average PDR-beacons gain with BGI across all beacon sizes is 39.41%

within ICR. Overall, a maximum average PDR-beacons gain with BGI across all beacon sizes is 35.44% within ECR. The gain with ICR is 3.97% higher than gain with ECR, which indicates a slight exaggeration of achieved performance when calculating within ICR. Maximum average PDR gain with BGI is calculated using (5.1) with $n = 3$ and SBsize=200,500,800.

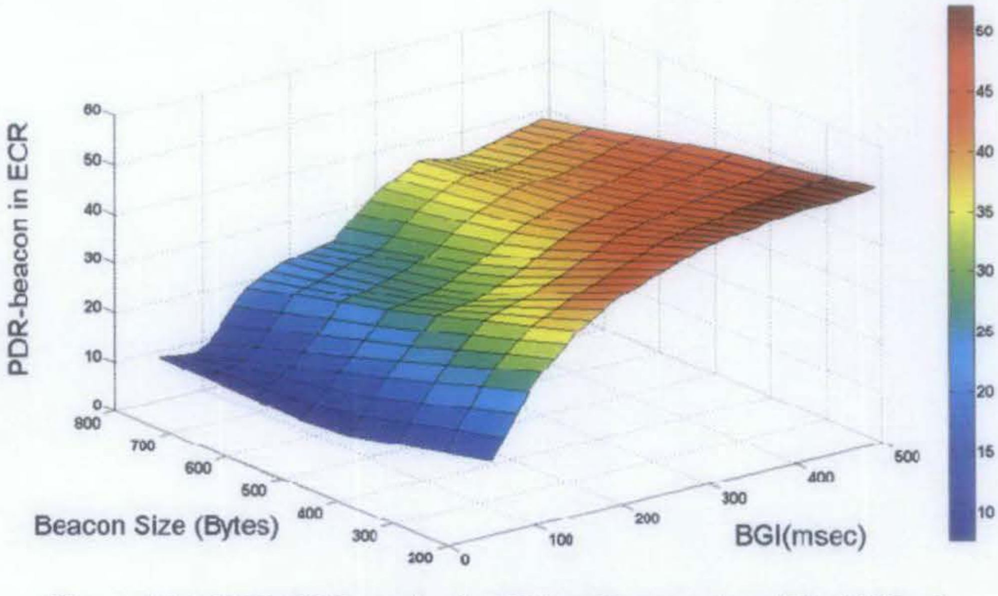


Figure 5.16: PDR-ECR results for BGI vs Beacon size, (CR=1000 m)

Smaller SB size also contributes towards higher PDR. Maximum average PDR-beacon gain with SB size across all BGI steps is 18.09% within ICR and 16.38% within ECR. A 1.71% higher gain with ICR also indicates slight performance exaggeration. Maximum average PDR-beacons gain with SB size across all BGI steps is calculated using (5.2) with $n = 10$ and $BGI = 50,100\ldots500$.

The results for varying CR, with a fixed BGI of 100 ms and fixed SB size of 500 bytes are shown in Figure 5.17. Results indicate that reducing CR improves overall PDR. In the given scenario, maximum PDR of 35.14% is achieved at CR of 200 m. Average delivery ratio within ICR is 21.80% and 24.86% within ECR. Beyond 500 m, PDR lines for ICR and ECR drift apart, causing exaggerated PDR gain results with ICR. The maximum PDR gain in the given scenario is 19.80% for ICR and 12.40% with ECR.

Highest PDR achieved with SB size of 500 bytes while tuning BGI is 46.70% and for the same scenario tuning CR results in a maximum PDR of 35.14%. Within ECR, varying BGI yields a gain of 39.26% while varying CR results in a gain of 12.40% for SB size of 500 bytes. Similarly for the same scenario, average PDR achieved with varying BGI is 32.34% and with CR it is 24.86%. A difference of 11.56% in maximum achieved PDR, 26.86% in gain and 7.48% in average achieved PDR clearly show that tuning BGI is more effective method in terms of controlling PDR.

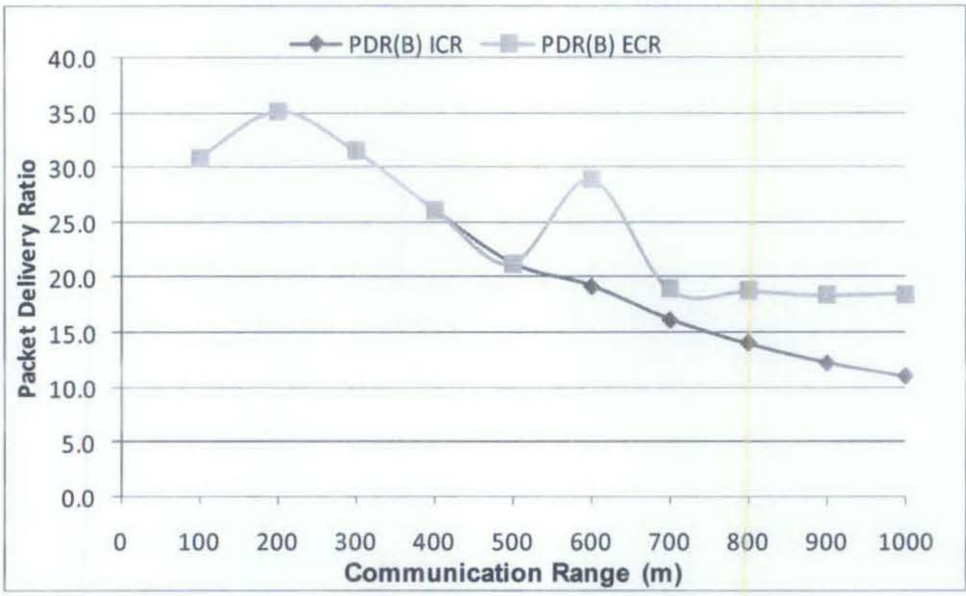


Figure 5.17: PDR-beacons results for ICR vs ECR, (BGI=100 msec)

To measure the impact of increasing transmission power on nodes nearer to the sender with more realistic probabilistic communication, PDR-beacon results for different intended CRs and their impact on nodes at specific distances is plotted in Figure 5.18.

The x-axis represents the intended communication range and each color bar represents the node distance from the transmitting vehicle. The two period moving average trend lines of nodes at 100, 200 and 300 meters show that, increment in CR results in higher PDR at closer nodes up till a specific CR and then starts to decline. A CR of 100 m is the minimum among safety applications requirements in Table 2.2. Considering this, PDR increases for all distances for up to 600 m CR. For fixed distances of 300 m and above, PDR generally benefits from increment in CR. The higher PDR at closer distances can be attributed to capture effect which enables a node to receive a frame with adequately higher power among the frames sensed on the channel.

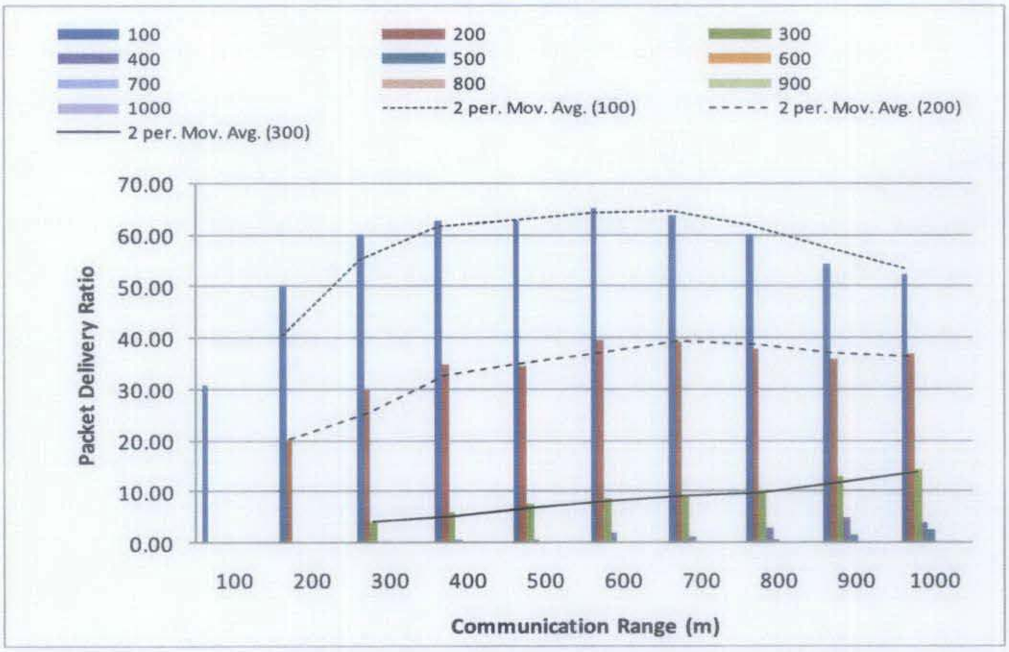


Figure 5.18: PDR-beacon results for fixed distances, (BGI=100 ms)

5.2.4 Analysis and Discussion for Nakagami

Results from simulation in probabilistic environment also validate that appropriate adjustment of tunable parameters can improve the performance of periodic single-hop vehicle-to-vehicle beaconing.

After initial increase, throughput is gradually reduced with the increment in BGI because of the shortened communication range. For beacon sizes of 200, 500 and 800 bytes, per-node throughput increases with increment in BGI up to 100, 150 and 300 ms respectively. Wider CR benefits throughput along with larger SB size. Maximum throughput is achieved with 800 bytes SB size and 250 ms of BGI at 1000 m CR. This optimal combination is particularly useful for scenarios where large amount of aggregated information is to be forwarded over longer distances with reasonably relaxed latency requirements. Amongst tunable parameters, SB size plays the most important role for optimal throughout. However, larger beacon size can have negative effect on e2e delay and PDR, which is not desirable for safety applications.

Within ICR, BGI of 50 ms and below results in e2e delay of 401.32 ms for SB size of 500 bytes and 717.98 ms for SB size of 800 bytes. Situation is worst for ECR, same BGI results in e2e delay of 668.87 ms and 1435.96 ms for SB sizes of 500 bytes and 800 bytes respectively. With BGI >= 100ms and SB size of 500 bytes, e2e-delay remains below 32 ms regardless of the communication range. This is well within the acceptable latency requirement (i.e. 100 ms) of most safety applications. Overall, reducing BGI below 100 ms is not desirable for larger beacon sizes, even though it is feasible in some cases for smaller SB size. Reducing CR also helps to reduce e2e delay; however BGI remains relatively more effective parameter. Overall, it can be concluded that generally the latency requirements for typical safety application can be met even under realistic conditions.

On the whole, reducing SB size, CR and increasing BGI contribute towards higher PDR. At fixed SB size of 500 bytes, maximum PDR-beacon gain with BGI is 42.23% within ICR and 39.26% within ECR. Furthermore, highest PDR of 46.70% is achieved with maximum BGI of 500 ms. With the same SB size, maximum PDR-beacon gain with CR is 19.80 % within ICR and 12.40 % within ECR. Moreover, highest PDR of 30.90% is achieved with maximum CR of 100 m. Within the given boundaries of tunable parameters, it can be concluded that BGI is the most effective parameter in terms of maximum achievable PDR, as well as maximum gain capacity.

Overall, average PDR increases with the increment in BGI and/or with decrement in communication range. Furthermore, it is observed that increasing communication range does not always result in lower PDR at closer nodes. In fact by enabling capture effect, higher PDR can be achieved at closer distances by increasing transmission power (alternately CR).

The results obtained from deterministic as well as probabilistic propagation models clearly show that achieving higher PDR is very difficult in v2v safety communication. Furthermore, PDR level achieved under realistic conditions (Nakagami) is far from satisfactory when considering safety application constraints. To explore alternate ways for increasing PDR, it is important to further investigate the causes of beacon loss.

5.3 Performance Comparison (TRG vs Nakagami)

Generally, deterministic propagation models are deemed sufficient to investigate generic behavior of different parameters. In this section, performance of safety communication parameters is compared in the light of deterministic (TRG) and probabilistic (Nakagami) propagation models. All the results in this section are presented with fixed SB size of 500 bytes only.

5.3.1 Per-node Throughput Comparison

As discussed earlier, per-node throughput is largely dependent on beacons size. However, BGI and CR also have practical effect on per-node throughput. Figure 5.19, shows the result varying BGI with TRG and Nakagami. Per-node throughput increases up to 100 ms and 350 ms for TRG and Nakagami respectively before it starts to decline again. When only observing results for BGI between 100 ms to 350 ms, both propagation models show contrasting trends as per-node throughput is increasing with Nakagami while it is decreasing with TRG. This indicates that in complex systems like VANET, using a deterministic propagation model like TRG may yield unrealistic trends as in this case. This also shows that, studies that only observe partial range of tunable parameters do not necessarily exhibit accurate performance trends.

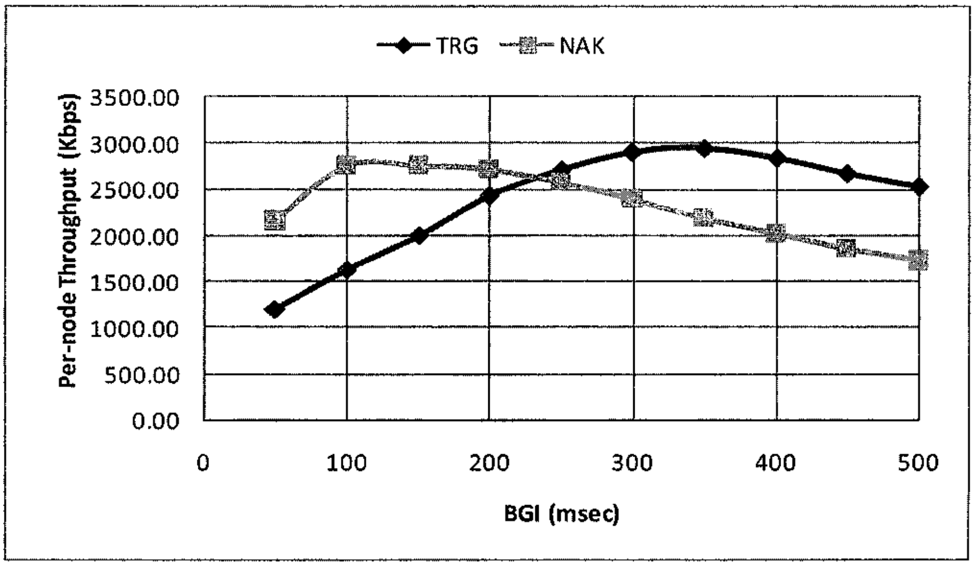


Figure 5.19: Per-node throughput results for BGI (CR =1000 m & SB size=500 bytes)

While adjusting communication range (Figure 5.20), results from both propagation models also show different trends for a large portion of the CR. Between, CR of 200 m to 700 m, throughput increases for Nakagami propagation model and decrease for TRG propagation model.

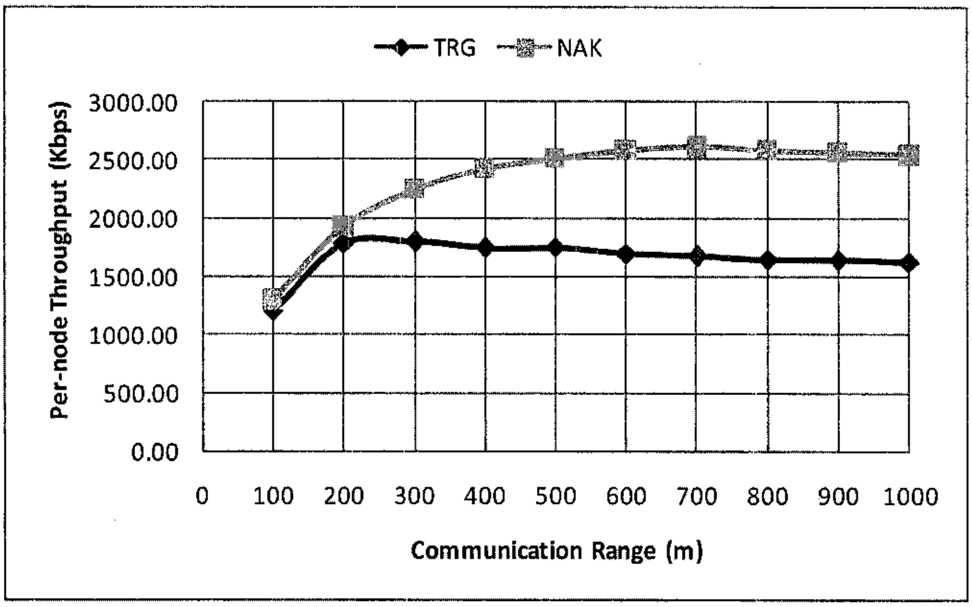


Figure 5.20: Per-node throughput results for CR (BGI=100 msec & size=500 bytes)

The contrasting trends with both propagation models suggest that predicting per-node throughput behavior is not reliable with TRG. Thus, for accurate trends and measurements more realistic propagation models like Nakagami should be used.

5.3.2 End-to-end Delay Comparison

As shown in Figure 5.21, e2e delay results with TRG and Nakagami show similar trends the most part. However, results obtained with TRG show inconsistent behavior. With TRG, e2e delay between 100 to 150 ms and 450 to 500 ms increases in contrast with the Nakagami results. For all other beacon sizes, TRG model result show a decrement in e2e delay as the BGI increases which is in accordance with Nakagami results.

Results with Nakagami model show that average e2e delay increases with the increment in communication range (Figure 5.22). This is logical because the distance between sender and receiver is increasing. However, e2e delay results with TRG are inconsistent for CR of 500 m and beyond.

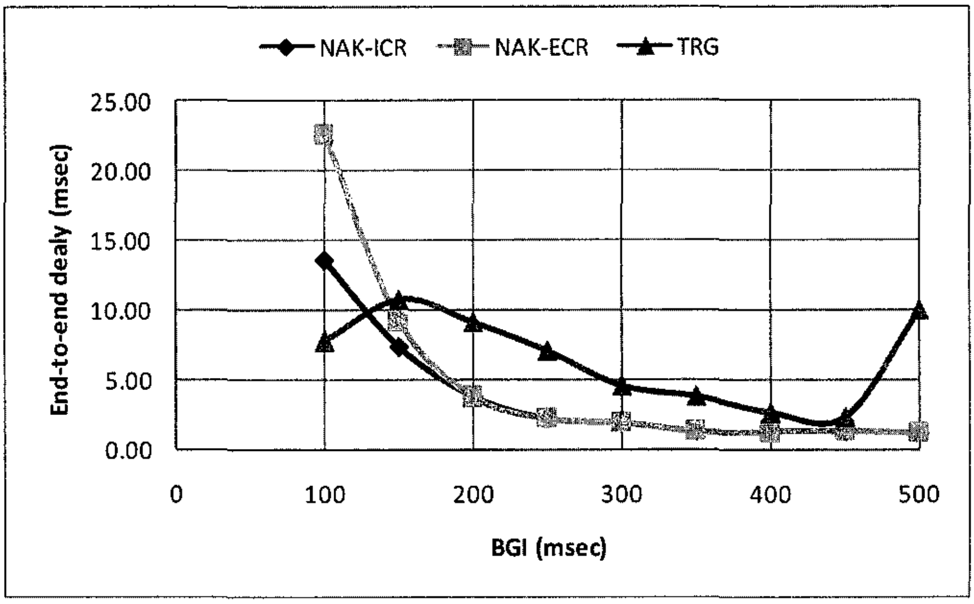


Figure 5.21: e2e delay results for BGI (CR =1000 m & size=500 bytes)

Overall, it can be concluded that TRG may be a suitable option for e2e delay measurements only with smaller beacon sizes. However, it is strongly recommended that more realistic propagation model like Nakagami be used for accurate analysis.

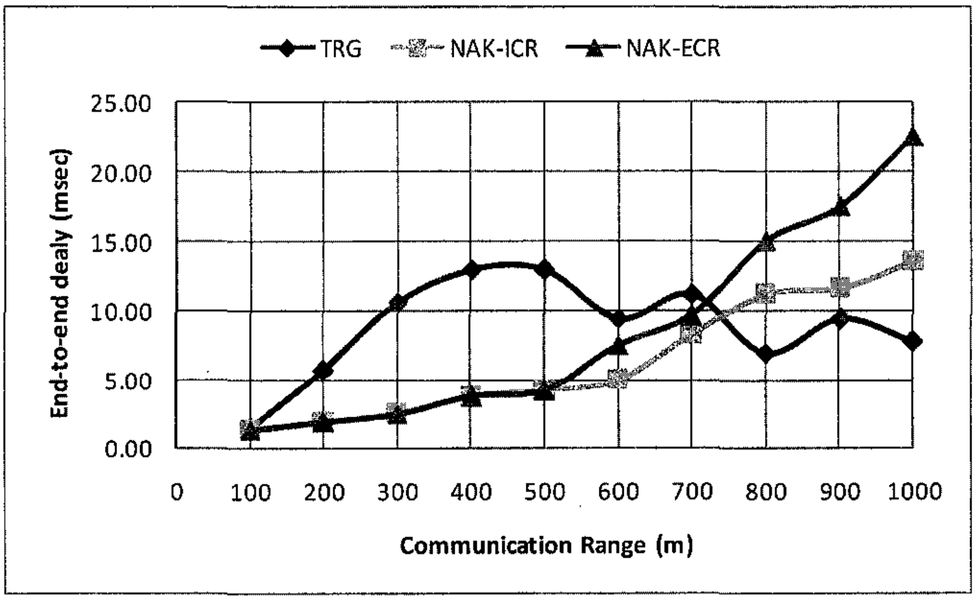


Figure 5.22: e2e delay results for CR (BGI=100 msec & size=500 bytes)

5.3.3 Packet Delivery Ratio Comparison

BGI results with both TRG and Nakagami model, show similar trends for PDR-beacons (Figure 5.23). However, it can also be observed that with TRG model PDR-beacons is somewhat underestimated for smaller BGI (e.g. < 200 ms) and over estimated for larger BGIs (>200 ms).

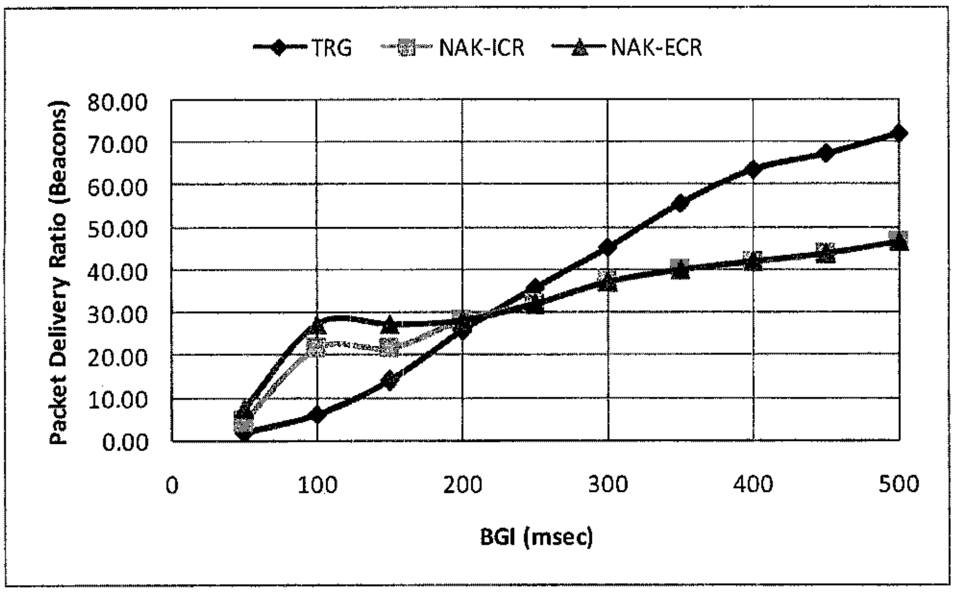


Figure 5.23: PDR-beacons results for BGI (CR =1000 m & size=500 bytes)

Furthermore, the gap between TRG and Nakagami widens with increment in BGI beyond 200 ms. PDR-recipients results for TRG and Nakagami also show similar trends (Figure 5.24).

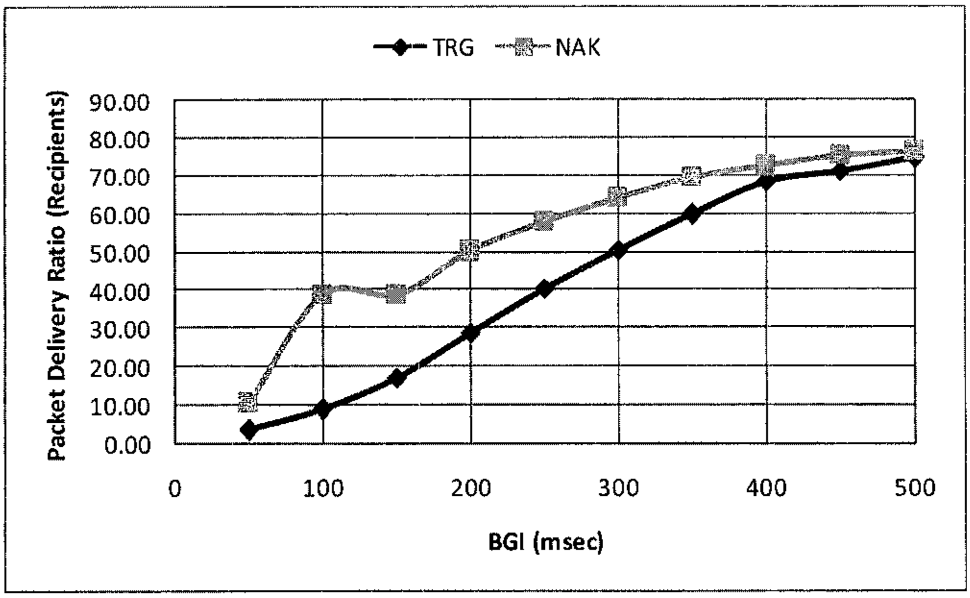


Figure 5.24: PDR-recipients results for BGI (CR =1000 m & size=500 bytes)

When varying communication range, results with both TRG and Nakagami model generally show similar trends for PDR-beacons (Figure 5.25) as well as PDR-recipients (Figure 5.26). It can also be seen from these figures that, TRG mostly underestimates the average packet delivery ratio. However, it can be safely concluded that using TRG model is useful to predict PDR trend for the evaluated parameters.

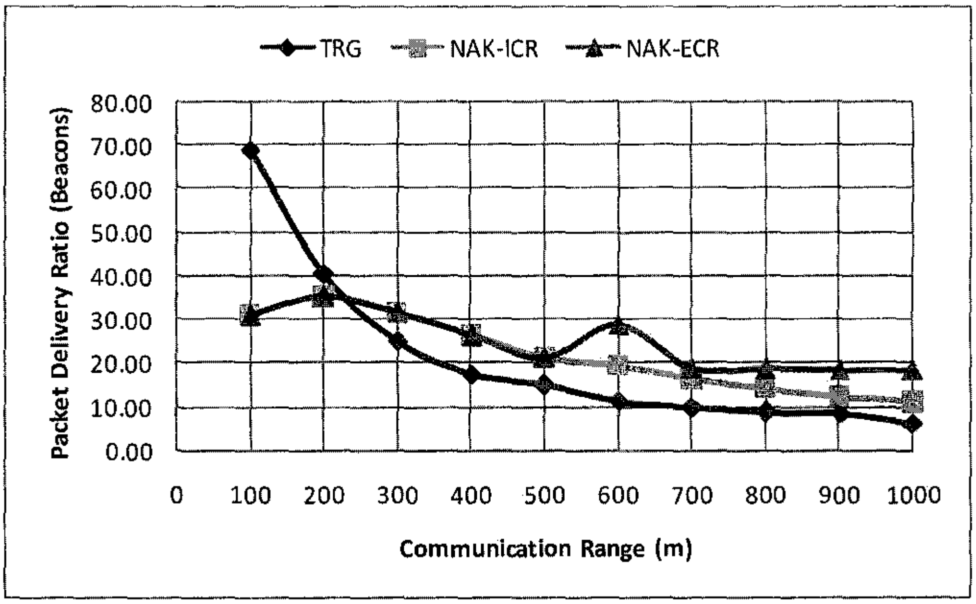


Figure 5.25: PDR-beacons results for CR (BGI=100 msec & size=500 bytes)

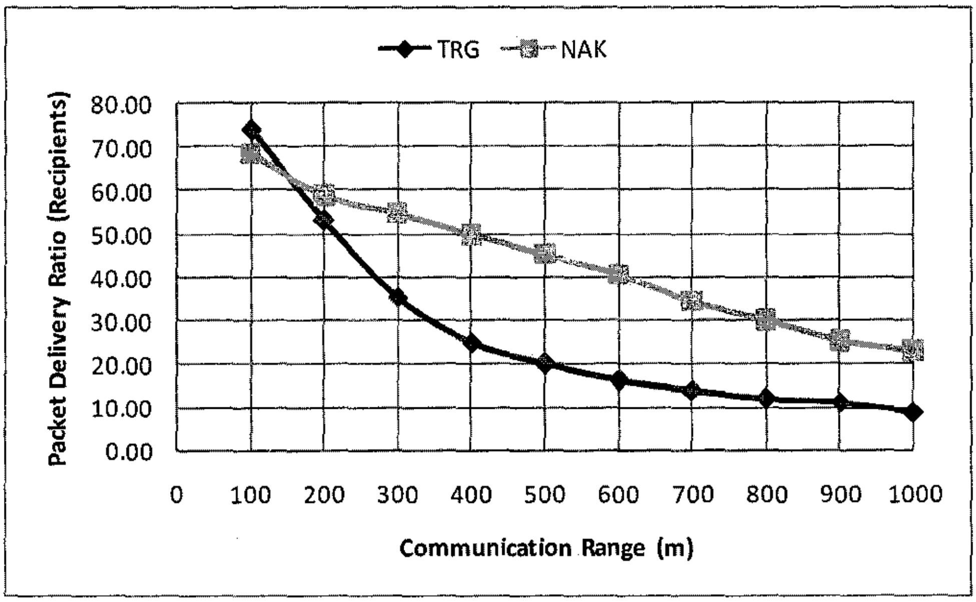


Figure 5.26: PDR- recipients results for CR (BGI=100 msec & size=500 bytes)

5.4 Beacon Loss and Its Reasons

Conventionally, Beacon Loss Ratio (BLR) is the opposite of PDR. In this section, results for beacon loss as well as some of the reasons behind it are presented. These results are acquired from same sets of simulations as above. In current version of NS-2 802.11, packet drop events are tagged with appropriate drop reasons. According to [72], following are the drop-event tags available in NS-2.

PND: Reception power is either lower than the carrier sensing threshold or not enough for its preamble being received even without any interference

DND: Reception power is higher than the CS threshold but not enough to decode the data even without any interference

INT: A message is dropped because of the interruption from the MAC, (MAC forces the abortion of the current reception, usually for transmitting a control frame of its own, like an ACK or CTS frame)

RXB: a message is dropped when the PHY interface is busy in receiving a frame

PXB: a message is dropped when the PHY interface is in the progress of receiving a frame preamble

SXB: a message is dropped when the PHY interface is IDLE, but busy searching for a valid preamble

TXB: a message is dropped when the PHY interface is busy in transmitting a frame

While calculating BLR, PND and INT drop tags are not considered. Beacons with PND tag are not considered as they are simply ignored by the system due to lack of power required for proper reception. There were no beacons tagged with INT within the given scenario, as ACK and CTS frames are not used in periodic safety communication. Thus, total lost beacons with respect to all reference nodes can be calculated as the sum of all events except PND (Total lost beacons = DND + RXB + PXB + SXB + TXB).

5.4.1 Beacon Loss with TRG

Figure 5.27 and Figure 5.28 show overall BLR with the fixed range of 1000m and BGI of 100 ms respectively. It can be seen that minimum BLR is achievable with smallest beacon size. With default BGI of 100ms, BLR is very high. However, with the increment in BGI, BLR decreases rapidly and reaches minimum at 500ms.

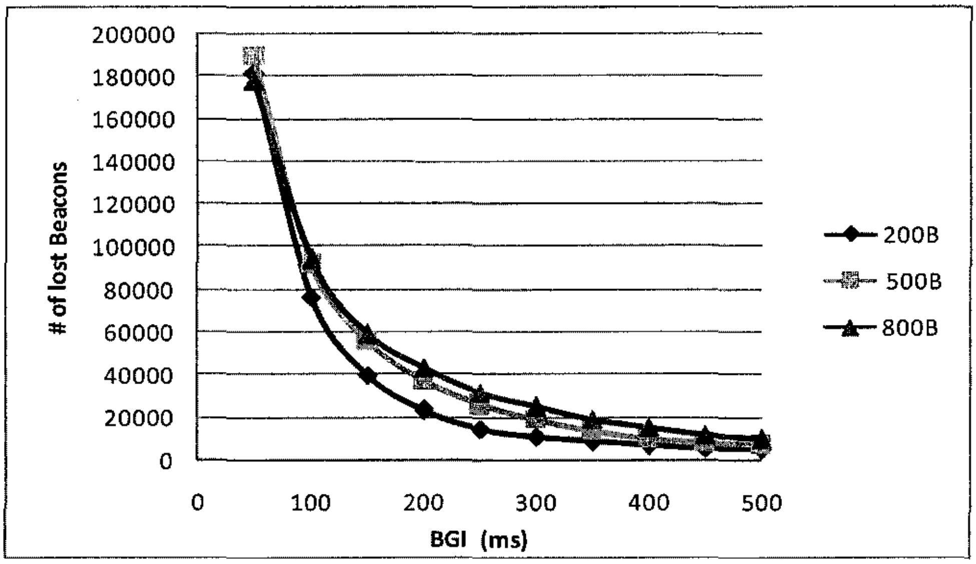


Figure 5.27: Number of lost beacons for BGI, (CR=1000 m)

Figure 5.28 shows that BLR increases almost in a linear fashion with increment in CR. Overall fewer beacons are lost with increase in BGI and decrease in CR.

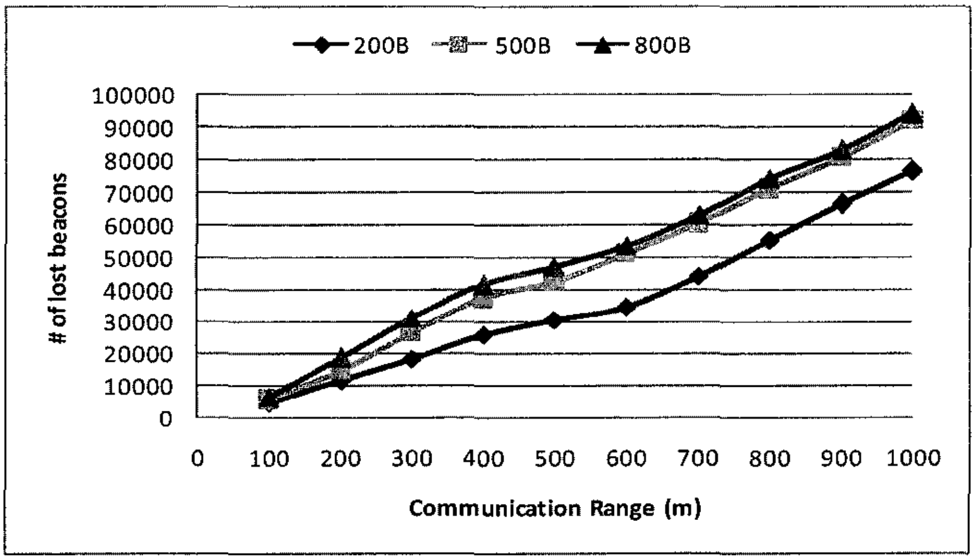
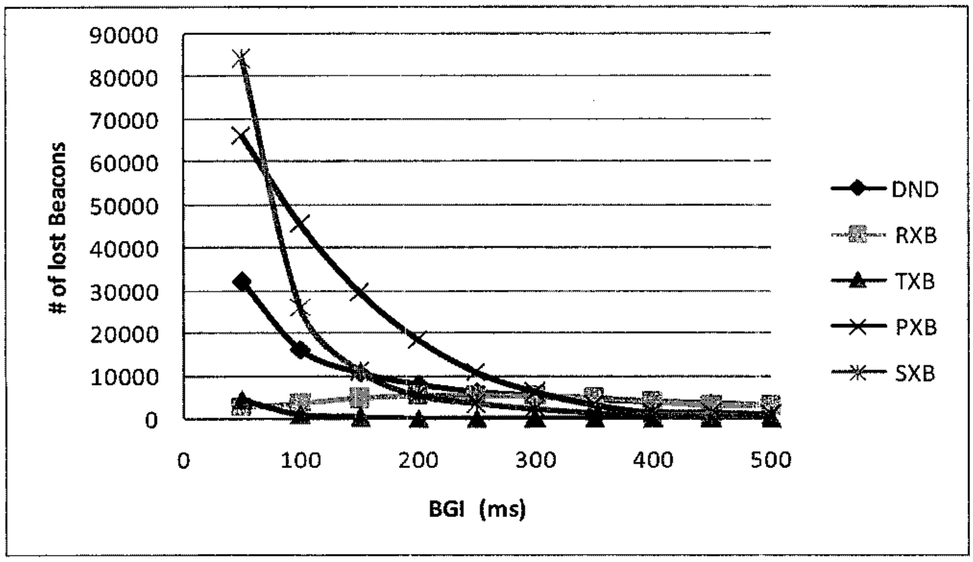


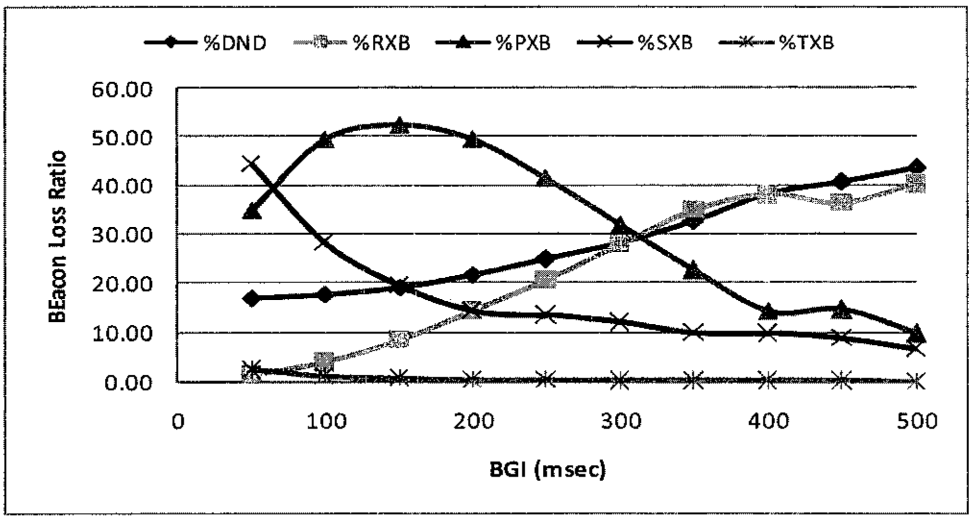
Figure 5.28: BLR-breakup results for CR, (BGI=100 msec)

Figures 5.29(a) and 5.29(b) show beacon loss ratio breakup with SB size of 500 bytes. The different trends within the dropped tags show relative effectiveness of BGI increment on different tags. All loss tags decrease with increment in BGI except

RXB. Initially RXB increases up to a BGI of 200 ms and then starts to decrease up till 500 ms. The initial rapid increase in RXB is due to abrupt higher packet reception, as channel detects more receivable preambles. After a BGI of 200 ms total number of receivable events decrease as total number of beacons generated by the system also decrease significantly. Increment in BGI effectively reduces BLR in terms of SXB, TXB and PXB. However, DND and RXB are the least effected loss-tags and cumulatively comprise of more that 83% of the lost beacons at BGI of 500 ms (Figure 5.21b). Percentage of each tag shown in the figures is calculated from within the lost beacons only "Beacon loss ratio (loss tag) = (number of beacons lost (loss tag)/total lost beacons) x100".



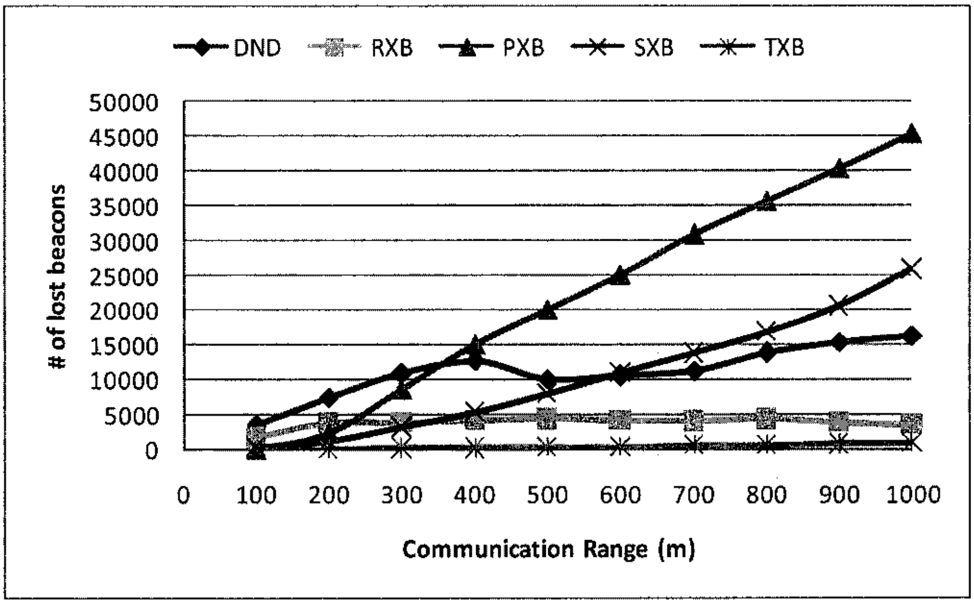
(a.) Total lost beacons for each tag



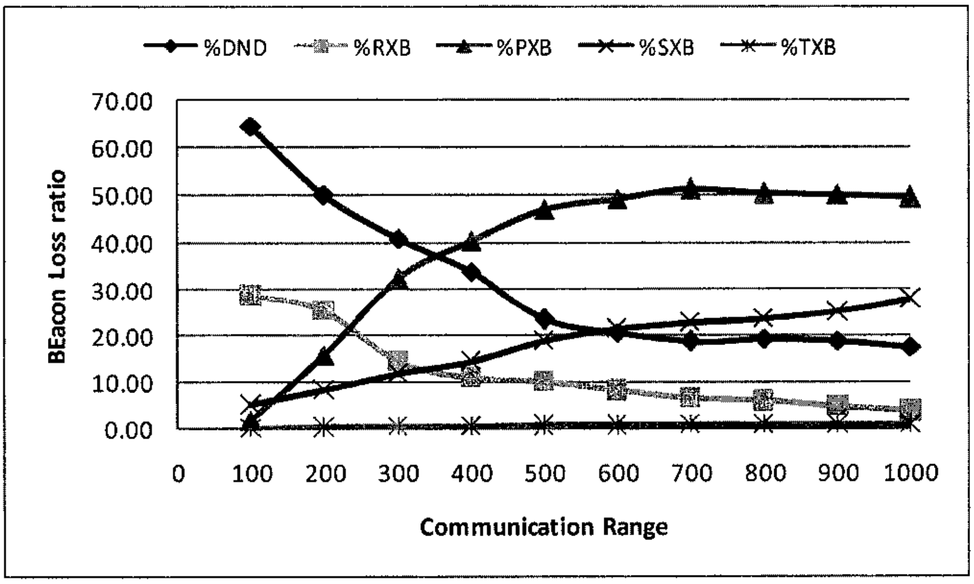
(b.) BLR-breakup within the lost beacons

Figure 5.29: BLR-breakup results for BGI (CR=1000 m & SB size=500 bytes)

Reducing beacon size significantly helps to reduce TXB and SXB. BLR caused by PXB decreases with the increment in beacon sized due to lesser number of preambles handled by the channel. In case of RXB, increasing beacon size reduces the usefulness of increment in BGI. Moreover, beacon size has little effect on BLR caused by DND. Furthermore, beacon loss caused by TXB is almost negligible for BGI of 100ms and above. Figure 5.30(a) and 5.30(b) show beacon loss results with communication range adjustments.



(a.) Total lost beacons for each tag



(b.) BLR-breakup within the lost beacons

Figure 5.30: BLR-breakup results for CR, (BGI=100 ms & size=500 bytes)

Reducing CR also helps reduce beacon loss caused by DND, TXB, PXB and SXB with all the beacon sizes. However, RXB tends to increase from CR of 1000 m to 500 m and then decreases for smaller CR. The amount of change in RXB is also dependent on beacon size as the smaller the beacons size more the change and larger the beacons size smaller the change. Beacons lost due to DND decreases overall with the reduction of CR, however, beacon size has virtually no effect on DND.

A node's ability to transmit a beacon is not a problem for BGI greater than 100ms, as beacon loss due to TXB is almost negligible. Thus, it can be said that safety application latency requirements are dependent on number of beacons transmitted per second (BGI) rather than communication range. Furthermore, to satisfy safety application requirements for BGI of less than 100 ms, safety message queuing mechanism should be carefully implemented to avoid higher TXB.

5.4.2 Beacon Loss with Nakagami

Similar set of simulations were performed with Nakagami propagation model to obtain insight into beacon loss causes under more realistic conditions. Figure 5.31, shows total number of lost beacons at specific beacon generation intervals with different beacons sizes at CR of 1000 m.

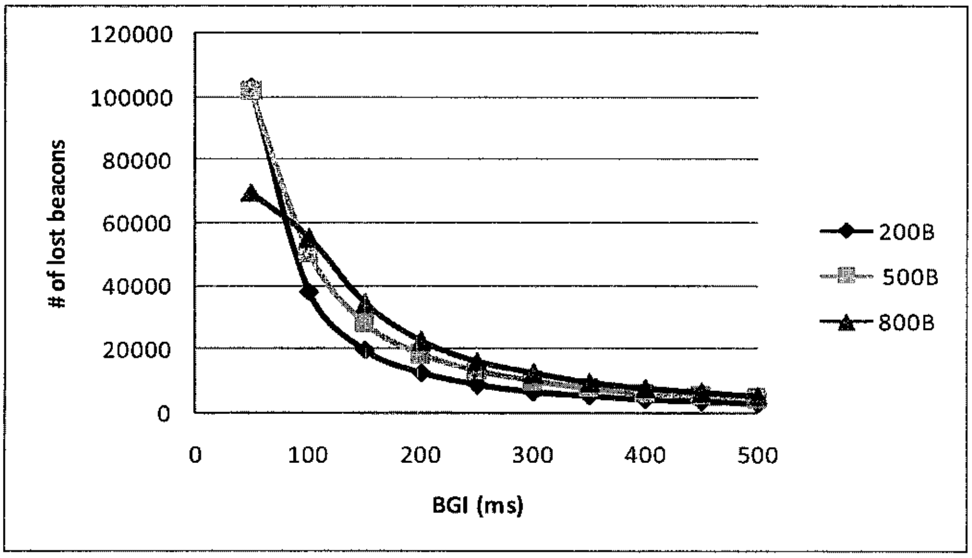


Figure 5.31: BLR results for BGI, (CR=1000 m)

It is clearly observed that increasing BGI is very effective in reducing lost beacons even under realistic highway conditions. Similarly, smaller beacon size also results in lesser beacon loss.

Shorter communication range also considerably reduces beacon loss rate as shown in Figure 5.32. Although, altering BGI and CR have similar effects as with TRG mode, overall number of lost beacons is considerably lower with Nakagami. This is due to the reduced CR caused by severe fading conditions. Safety beacons size also plays important role in beacon loss reduction however it is relatively less effective than BGI and CR. Overall, BGI remains the most effective parameter among all tunable parameters.

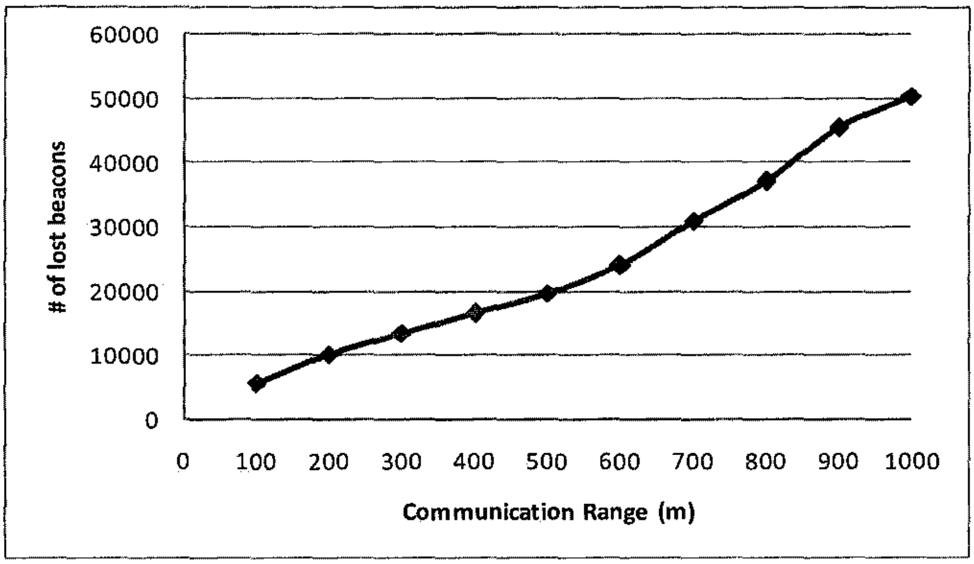
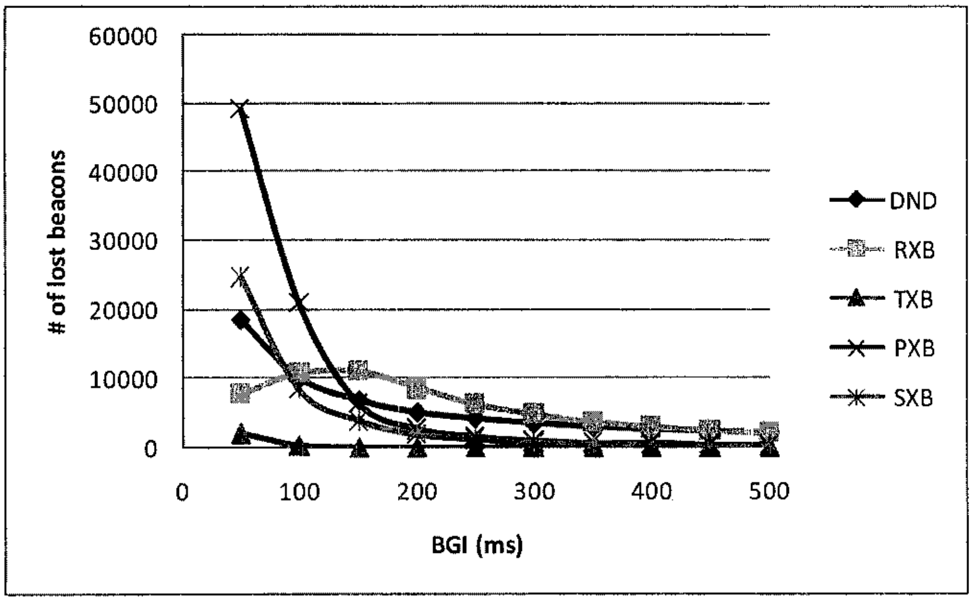
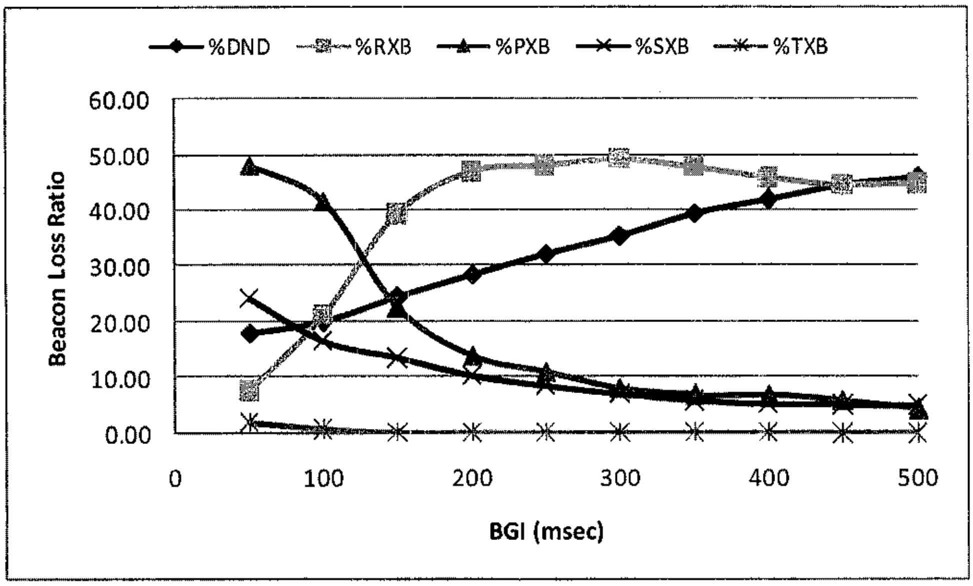


Figure 5.32: BLR results for CR, (BGI=100 ms & size=500 bytes)

Figure 5.33(a) and 5.33(b) show the breakup beacon loss causes with BGI adjustment. Overall, all beacon loss tags decrease with increment in BGI. However, DND and RXB are relatively less affected as even at 500 ms BGI, they collectively comprise of more than 90% of the all lost beacons.



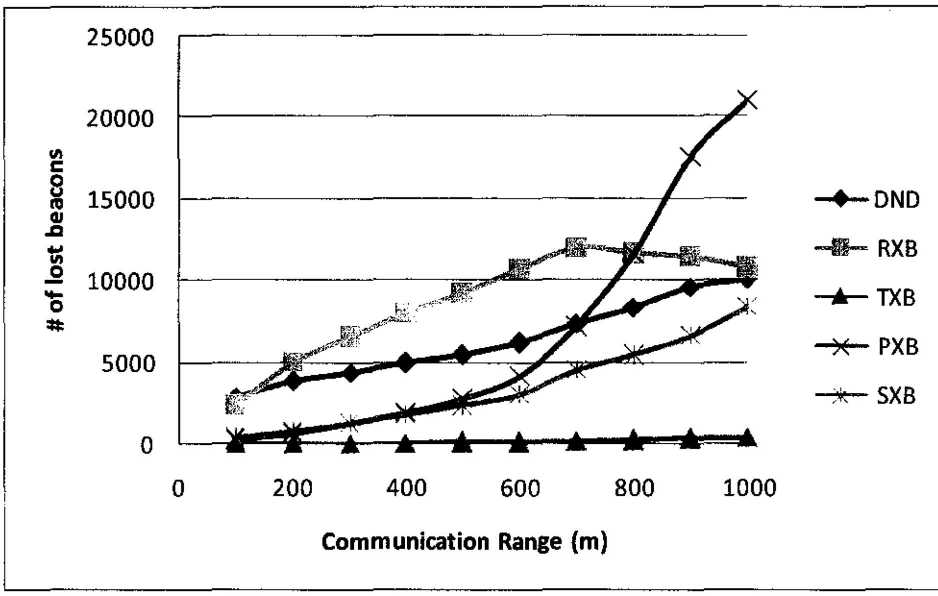
(a.) number of lost beacons



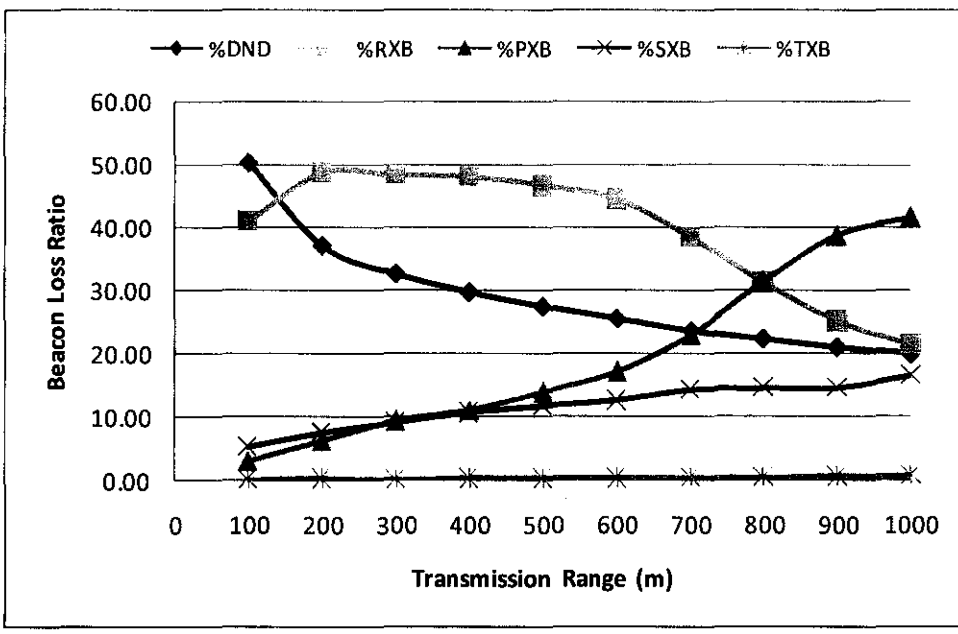
(b.) Loss ratio

Figure 5.33: BLR-breakup results for BGI, (CR=1000 m & SB size=500 bytes)

Shorter communication range also reduces beacon loss as shown in Figure 5.34(a). However, similar to the BGI, DND and RXB collectively make more than 90% of the lost beacons even at CR of 100 m see Figure 5.34(b).



(a.) number of lost beacons



(b.) Loss ratio

Figure 5.34: BLR-breakup results for CR (BGI=100 msec & size=500 bytes)

5.4.3 Beacon Loss Breakup Comparison (TRG vs Nakagami)

BLR caused by RXB using Nakagami is much higher than TRG under similar settings with BGI (Figure 5.35) as well as CR adjustment (Figure 5.36).

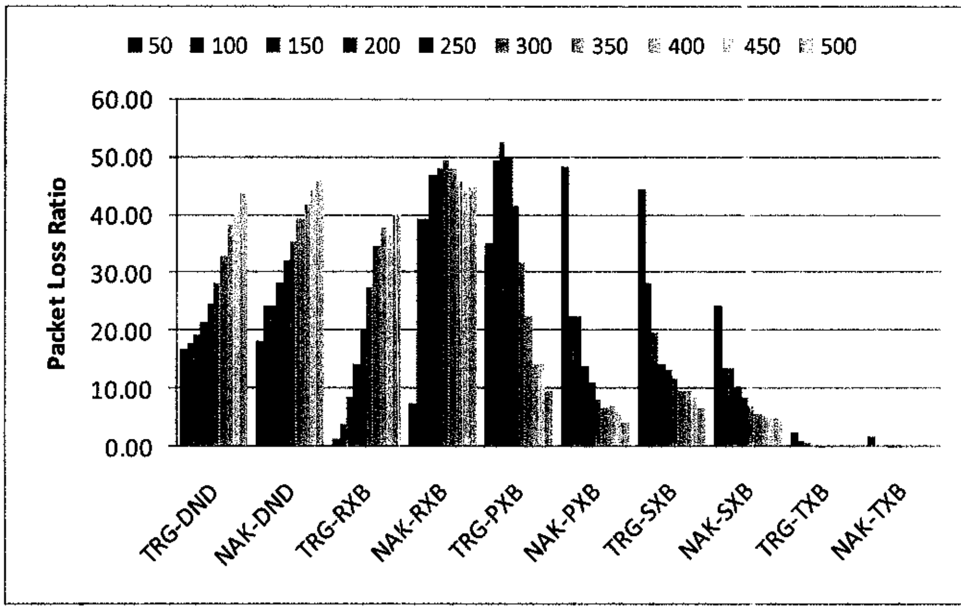


Figure 5.35: BLR-breakup results for BGI, (CR=1000 m & SB size=500 bytes)

However, the beacon loss caused by other tags is higher with TRG. Nakagami settings with severe fading result in shortened CR and higher number beacons lost due to lower signal power. Since total number of dropped beacons lost due to reception power below carrier sense threshold are not considered here. Consequently, total number of lost beacons with TRG is higher than that of Nakagami. It can also be observed that TXB is very low with TRG and is almost negligible with Nakagami. This comparison indicates that all tags except RXB are somewhat overestimated with TRG simulations.

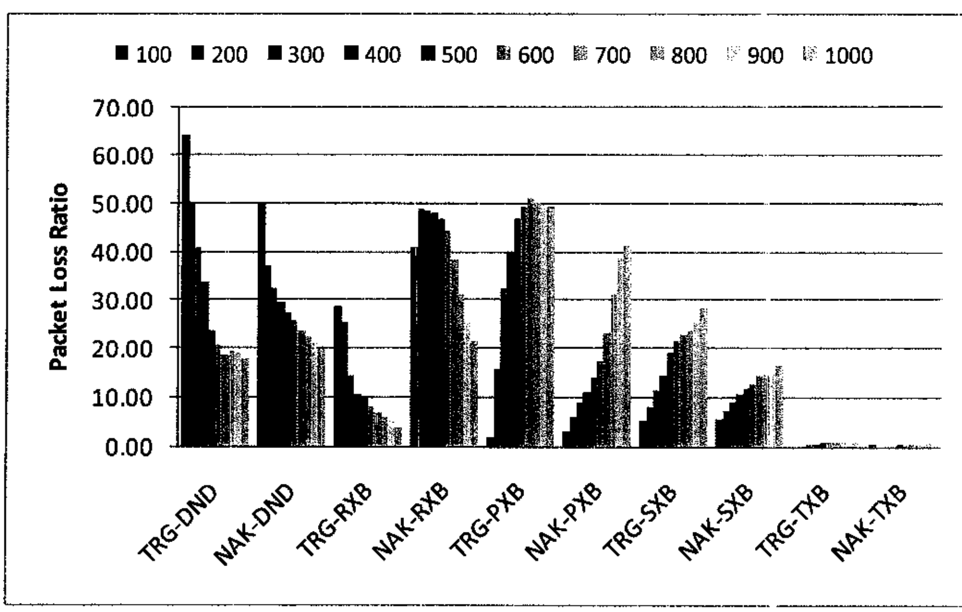


Figure 5.36: BLR-breakup results for CR, (BGI=100 ms & size=500 bytes)

5.4.4 Beacon Loss Analysis

Obtained results show that parameters i.e. CR, BGI are more effective in reducing, BLR caused by PXB, TXB, SXB. However, these parameters are relatively less effective in case of RXB especially with larger beacon size and longer communication range. With the beacon size of 500 bytes, RXB and DND collectively make more than 90% of the lost beacons even at BGI of 500 ms and CR of 100 m. Thus, to further reduce BLR beyond these points, methods other than tunable parameter adjustment should be explored. Overall smaller beacon size contributes to lower BLR; however it does not affect beacon loss caused by DND.

A BLR comparison between TRG and Nakagami propagation models shows that under realistic conditions (Nakagami) it is difficult to reduce BLR caused by RXB. Furthermore, it is also observed that beacon size is the least effective tunable parameter among all evaluated parameters. In the light of obtained results it is concluded that situation-aware dynamic adaption of CR and BGI is essential for beaconing optimization in VANETs.

5.5 Optimal Combinations of Tunable Parameters

All of the results presented in previous sections show that dynamic adaption of communication range and BGI can be useful to control the impact of periodic beaconing on vehicle-to-vehicle communication. Although varying beacon size can positively contribute towards performance enhancement in safety communication but considering the security constraints and dynamic environment in VANET it is not desired to artificially tune beacon size.

The results in previous section show that safety applications latency requirements can be generally met for all parameter configurations above BGI of 100 ms. It is also observed that achieving acceptable level of PDR is extremely difficult in safety communication. The maximum PDR achieved with TRG propagation model is approximately 87%, which of course is greatly exaggerated when compared to more realistic Nakagami propagation model. In realistic conditions highest PDR achieved is approximately 52%, with beacons size of 200 bytes and BGI of 500 ms at maximum CR. Thus, it is can be concluded that techniques solely relying on either dynamic adjustment of BGI or CR will not be able to achieve satisfactory PDR level under adverse conditions. However, combined adjustment of BGI and CR seems a more suitable solution to optimize PDR.

Extensive simulations were carried out on different service level highways to find optimal combination of BGI and CR for various safely application communication range requirements. Safety beacons size was fixed to 500 bytes throughout these simulations. Maximum range requirements for some safety applications described in Table 2.2 are between 100 to 500 m. We divide this required range into five distinct sets of 1-100, 101-200, 201-300, 301-400 and 401-500 meters to accommodate all possible safety applications requiring the similar range. Furthermore, there are no standard values for PDR measurement in VANET. We assume PDR values of 90%, 95% and 99% as acceptable; these values are taken from [35], [30] and [34] respectively. Furthermore, optimal combination of communication range and BGI are prioritized in the following order:

- First priority is given to the smallest beacon generation interval,
- Secondly, smaller CR is preferred over longer communication range,
- Lastly, the priority is given to the combination with lowest end-to-end delay.

For simulations, all highways are populated with maximum vehicle density as given in Table 3.2. Minimum safety distance is ensured on highways with service level D and E. Due to lower vehicle density, minimum safety distance is not an issue on highways with service level A, B and C.

Checking all possible combinations of BGI and CR through simulations is a daunting task. Instead we use a simple binary search like approach based on above mentioned priorities, to find the optimal combinations. Initially different communication ranges are simulated against BGI of 100, 250 and 500 ms only. Then depending on the outcome, the BGI range near to the target PDR is simulated with highest CR to lowest CR, this process is repeated till the target PDR or the maximal PDR is achieved. The same process is used for all highway service levels.

Figure 5.37, shows results obtained for up to 500 m range with CR between 600m to 1000 m for a target PDR of 90%. Figure 5.38 and Figure 5.39 show results for BGI to 250 and 500 ms respectively, with CR range between 300 to 500m. Figure 5.37 shows that achieving 90% PDR, is possible with BGI of 100 ms at ranges of 100, 200 and 300 m. However, to achieve the same PDR at 400 m, a minimum of 250 ms BGI and 1000 m CR is required. Maximum achieved PDR at 500 m distance is 89.29% with BGI of 500 ms and CR of 1000 m.

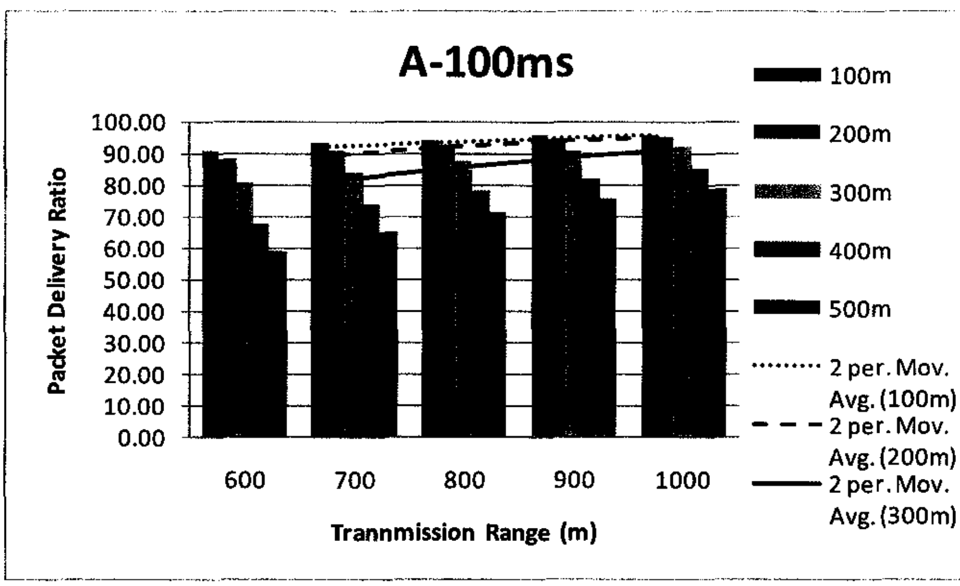


Figure 5.37: CR-BGI combination values for service level "A" highway (BGI 100ms)

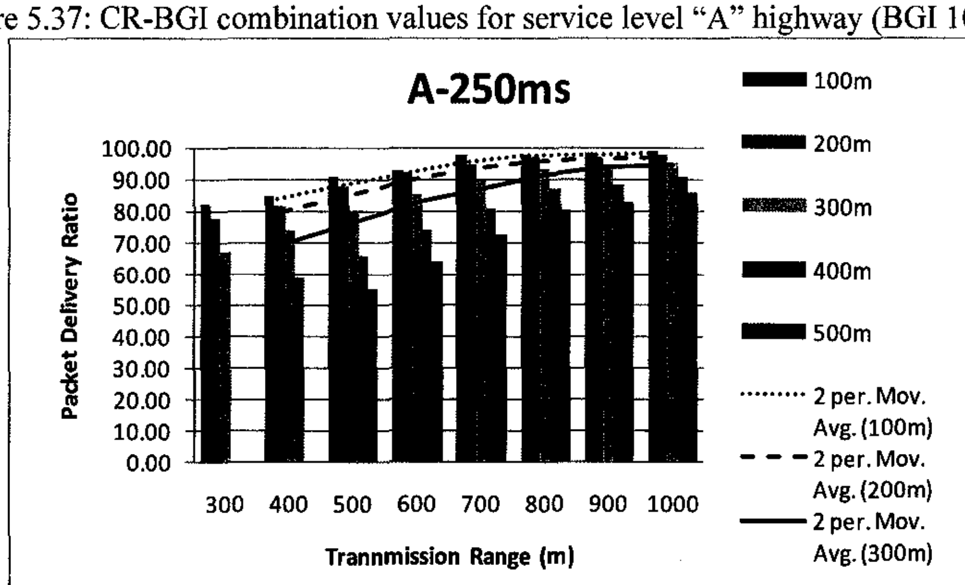


Figure 5.38: CR-BGI combination values for service level "A" highway (BGI 250ms)

The trend lines plotted in Figures (5.37, 5.38, and 5.39) also show that PDR increases at nodes nearer to the transmitter when transmission power is increased. The same trends are observed in all highway service level results. Thus, it can be concluded that enabling capture feature, overall improves the PDR at nearer nodes regardless of the vehicle density on the highway.

To find an optimal combination for different PDR targets, numerous combinations of BGI and CR were tested on all highway service levels. All tested combinations results for only service level "A" highway are shown here. However, optimal combinations are presented in tabular form.

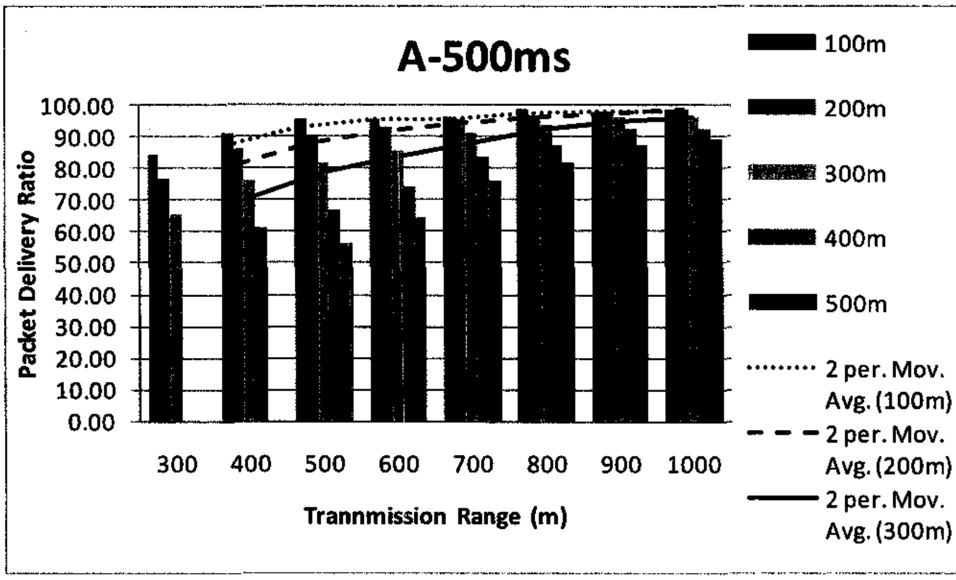


Figure 5.39: CR-BGI combination values for service level "A" highway (BGI 500ms)

Optimal combinations (BGI and CR) that achieved a minimum of 90% PDR at different service level highways as well as in worst case scenario are presented in Table 5.2. It is observed that target PDR was never achieved at target range of 500 m (highlighted in dark grey) regardless of the highway service level. Similarly, at service level "E" and the WC scenario, 90% PDR was also not achievable at target range of 400 m (also highlighted in dark grey). However, to optimize PDR for all such ranges a combination of 500 ms BGI and 1000 m CR is suitable.

Table 5.2: Optimal combination of BGI and CR (target PDR = 90%)

Highway Service Level	Application target range (m)	Optimal Transmission Range (m)	Optimal BGI (msec)
A	1-100	600	100
	101-200	700	100
	201-300	900	100
	301-400	1000	250
	401-500	1000	500
B	1-100	400	100
	101-200	800	100
	201-300	900	150
	301-400	1000	300
	401-500	1000	500
C	1-100	500	100
	101-200	800	100
	201-300	900	250
	301-400	1000	500
	401-500	1000	500
D	1-100	700	150
	101-200	900	150
	201-300	900	500
	301-400	1000	500
	401-500	1000	500
E	1-100	700	150
	101-200	900	250
	201-300	800	500
	301-400	1000	500
	401-500	1000	500
WC	0-100	600	250
	101-200	600	500
	201-300	1000	500
	301-400	1000	500
	401-500	1000	500

For a target PDR of 95%, optimal combinations of BGI and CR are shown in Table 5.3. At maximum vehicle density, target PDR was not achieved for target range of 400 m and beyond for all highway service levels. For service level D and E, the target PDR was not achieved for target range of 300 m and beyond. While for WC scenario, target PDR was not achieved at target range 200 m and above.

Table 5.3: Optimal combination of BGI and CR (target PDR = 95%)

Highway Service Level	Application target range (m)	Optimal Transmission Range (m)	Optimal BGI (msec)
A	1-100	900	100
	101-200	1000	100
	201-300	1000	250
	301-400	1000	500
	401-500	1000	500
B	1-100	700	100
	101-200	900	150
	201-300	900	400
	301-400	1000	500
	401-500	1000	500
C	1-100	800	100
	101-200	1000	200
	201-300	1000	400
	301-400	1000	500
	401-500	1000	500
D	1-100	1000	150
	101-200	700	400
	201-300	1000	500
	301-400	1000	500
	401-500	1000	500
E	1-100	800	200
	101-200	800	500
	201-300	1000	500
	301-400	1000	500
	401-500	1000	500
WC	1-100	900	500
	101-200	1000	500
	201-300	1000	500
	301-400	1000	500
	401-500	1000	500

The situation is even worst for target PDR of 99%, as it was never achieved at highway service level D, E and WC scenario. At service level A, B, and C, it is also not achievable at target range of 200 m and above. A combination of 500 ms BGI and 1000 m CR is required for maximum PDR, regardless of the highway level.

The optimal combination values are useful for testing safety applications, routing protocols and congestion control schemes. Table 5.2, table 5.3 and table 5.4 can also be used as lookup tables for performance enhancement schemes when highway service levels are known beforehand.

5.6 Chapter Summary

In this chapter simulation results from extensive simulations were presented and discussed in detail. The results show that, among tunable parameters, safety beacon payload size plays the most important role in terms of optimal throughout. This could be particularly useful for non-safety applications that require larger payload (e.g. multimedia advertisements) to be exchanged. The results from TRG as well as Nakagami propagation model show that end-to-end-delay requirements for typical safety applications can be easily met. However, with BGI below 100ms e2e delay increases rapidly particularly with larger beacon payload. Furthermore, in sole comparison between tunable parameters, BGI is more useful in controlling e2e delay.

For performance evaluation, two types of PDR metric were used i.e. PDR-recipients and PDR-beacons. Results from both types of PDRs match reasonably closely and show similar behavior for all the tested parameters. Furthermore, different PDR calculation methods (average PDR within ICR/ECR, PDR at fixed distance, average PDR at nearby vehicles) were used to thoroughly analyze impact of tunable parameter on periodic safety beaconing. An exclusive comparison between tunable parameters shows that BGI has more productive capacity in terms of overall PDR gain than other parameters. Furthermore, maximum PDR-beacon achieved as a result of BGI adjustment is 46.70% (at 500 ms), while with the same SB size, CR adjustment results in a maximum PDR-beacon of 30.90% (at 100 m). Furthermore, by enabling capture feature, higher PDR can be achieved at closer distances with increment in CR (transmission power). Beacon Loss Ratio – breakup results under realistic conditions (Nakagami) show that proper adjustment in tunable parameters is useful in reducing overall beacon loss. However, it is relatively more difficult to reduce beacon loss incurred as a result of RXB (when node is already busy in frame reception). For controlling BLR, beacon size is the least effective among evaluated tunable parameters.

A comparison of results obtained with TRG and Nakagami propagation model was also presented in this chapter. Varying BGI can result in contrasting behavioral trends of per-node throughput with both propagation models (e.g. between BGI 100-350 ms). Some inconsistencies were also found with e2e delay, with larger beacon size while varying CR. TRG largely underestimates the overall packet delivery ratio. However, PDR trends with TRG were consistent with Nakagami results.

For achieving maximum PDR, the optimal combination values of BGI and CR for different highway service levels are also given. The optimal combination values can be used as a lookup table for testing different protocols and schemes under less stressed conditions for various scenarios. Overall, the results demonstrate the maximal performance enhancement capability of each tunable parameter separately as well as combined. It is concluded that dynamic adjustment of tunable parameters to their optimal values, does not fully satisfy the performance level required for safety communication.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

This chapter discusses the research findings, recommendations, and contributions of the present research. Future direction of the research is also discussed in the light of research outcomes.

6.1 Research Findings

a. SB size is the most effective among tunable parameters in terms of per-node throughout. Results show that per-node throughput rarely exceeds half the data rate used regardless of the tuned parameter combinations (maximum achieved throughput is 3.21Mbps out of 6Mbps regardless of the scenario).

b. While solely adjusting CR or BGI, e2e-delay remains below an acceptable limit of 30 ms with realistic highway conditions for BGI of 100ms and above. However, reducing BGI below 100 ms with larger beacon sizes results in rapid increase in e2e delay. Furthermore, for optimal BGI and CR combinations, e2e delay remains less than 5 ms with beacon size of 500 bytes, regardless of the highway service level. Overall, SB size and BGI are the most effective parameters in terms of e2e delay.

c. Overall, average PDR increases with the increment in BGI and/or with decrement in communication range. It is also observed that increasing communication range does not always result in lower PDR at closer nodes. In fact by enabling capture effect, higher PDR can be achieved at closer distances by increasing CR (transmission power). BGI is the most effective among evaluated parameters in terms of PDR followed by CR and safety beacon size.

d. It is also observed that achieving high level of average PDR is extremely difficult while solely adjusting any of the tunable parameters. By solely adjusting any of the tunable parameters, the highest achieved average PDR with TRG and Nakagami propagation models is ≈87% and ≈52% respectively.

e. CR and BGI are more effective in reducing BLR caused by PXB, TXB, SXB. However, these parameters are relatively less effective in case of DND and RXB especially with larger SB size and longer CR. DND and RXB loss tags cumulatively comprise of more than 83% of the lost beacons at minimum BLR achieved with BGI of 500 ms using Nakagami. Furthermore, beacon size has negligible effect on BLR caused by DND.

f. A node's ability to transmit a beacon is not a problem for BGI of 100ms and above, as beacon loss due to TXB is almost negligible. Thus, it can be concluded that for BGI of 100 ms and above, adequate room is available to launch a few event-driven messages in-between periodic beacons.

g. A comparison of TRG and Nakagami propagation results model, exhibits contrasting trends in some scenarios, which raises many question marks on reliability of TRG model. Some of the related findings while solely adjusting CR or BGI are:

    i. The per-node throughput results obtained with TRG and Nakagami propagation models show contrasting trends for large portion of the respective parameter's range i.e. for BGI of 150 to 350 ms, and CR of 200 to 700 m.

    ii. The e2e delay measurements results obtained with TRG model are not consistent especially for larger SB sizes and longer CR.

    iii. For PDR measurements, both propagation models show similar trends. However, TRG underestimates the average packet delivery ratio in general. Similarly, when considering average BLR, all loss tags except RXB are somewhat overestimated with TRG model.

h. For a combined adjustment of BGI and CR, the target PDR of 90% was never achieved at desired range of 500 m and beyond, regardless of the highway service level. Furthermore, on highway service level "E" and the WC scenario, target PDR of 90% was also not achievable at target range of 400 m and beyond.

i. At maximum vehicle density, target PDR of 95% was not achieved for desired range of 400 m and beyond for all highway service levels. For service level D and E, the target PDR was not achieved for desired range of 300 m and beyond. While for WC scenario, target PDR was not achieved at target range of 200 m and above.

j. The situation is even worst for target PDR of 99%, as it was never achieved at highway service level D, E and WC scenario. At service level A, B, and C, it is also not achievable at target range of 200 m and above. A combination of 500 ms BGI and 1000 m CR is required for maximum PDR, regardless of the highway service level.

6.2 Recommendations

a. Safety communication schemes and protocols should always be analyzed under worst-case scenarios. The proposed guidelines for the worst case scenario here are useful for calculating appropriate safety distance between nodes, node density and speed, while justifying the use of safety applications.

b. Simulation results show that transmitting event-driven message should not be an issue even under stressed channel conditions. In fact per-node throughput rarely exceeds half the used data rate and ample space is available for event-driven messages. Thus, bandwidth reservation schemes designed to facilitate event-driven message transmission are not recommended.

c. For optimal packet delivery ratio of safety beacons, it is highly recommended that dynamic adjustment of beacon generation interval and communication range be implemented in tandem. Ideally a scheme allowing both parameters to reach closer to their optimal combination points can be more beneficial under worst-case scenarios.

d. Dynamic adjustment of SB size is not recommended for safety and security reasons. In addition, adjusting SB size is far less effective in improving overall periodic beaconing performance in comparison to BGI or CR. However, SB size should be kept to a minimum e.g. < 200/300bytes, possibly by implementing compression techniques. Further studies need to be conducted for selecting prompt compression/decompression techniques suitable for safety communication.

e. It is also recommended that beacon generation interval of less than 100 ms should be avoided especially with larger SB sizes. However, delay tolerant safety information can be sent via large beacons periodically but less frequently than regular safety beacons.

f. It is strongly recommended that capture feature be made a compulsion rather than an option in VANET transceivers. This can greatly enhance PDR at nearby vehicles and also permits use of higher transmission power which enables VANET nodes to transmit safety information over longer distances.

g. To further reduce beacon loss caused by RXB, methods other than tunable parameter adjustment should be explored. For example, an efficient queuing mechanism is required to reduce queue load that should be able to discard beacons older than certain time periods, e.g. message update frequency.

h. In order to obtain uniform results with simulations, mapping values of transmission power vs. communication range should be empirically determined for VANET.

i. For VANET simulations, deterministic propagation model like TRG should not be used as they are likely to demonstrate erroneous trends. Thus, for accurate trends and measurements only realistic propagation models like Nakagami should be used. Nonetheless, there is ample space for improvements in available simulation architecture for a fully functional VANET.

6.3 Research Contributions

The following are the contributions of this research:

a. All the results were presented with high level of accuracy through appropriate implementation of PHY and MAC layer for VANET trial standards using latest NS-2 simulator. Furthermore, various result calculation methods were used for broader evaluation of the parameters involved.

b. It is validated that conventional dynamic power control and beacon generation interval schemes do not fully satisfy V2V safety application requirements. This leads to the conclusion that dynamic adjustment of both parameters is necessary for efficient V2V single-hop periodic beaconing.

c. To evaluate the performance of V2V single-hop periodic safety beaconing extensive simulations were carried out using a realistic system model and several findings are presented along with perceptive recommendations.

d. A new realistic worst case traffic scenario for highway is introduced. The scenario depicts challenging environment in which VANET has to operate and also considers life threatening situation, justifying the use of safety applications. Several worst case scenarios for different highway service levels are also presented.

e. Optimal range of each tunable parameter in worst case scenario and optimal combinations of BGI & CR for different highway service levels are presented. These optimal combination values can be used as lookup tables for efficient safety communication and can also facilitate development of new safety applications.

f. Micro level details of the simulation configurations for VANET implementation are provided along with sample codes for seamless reproduction of results. These settings can also be used by other researchers without going into preliminaries. More than 800+ GB of available trace data can be used for further analysis of different V2V communication aspects.

6.4 Conclusions

In VANET, single-hop periodic safety beaconing among nearby vehicles will work as the heartbeat of system. It is also the fundamental method for collecting information that can be used by geographic routing and/or message dissemination. Thus, all safety applications and messaging schemes are directly or indirectly dependent upon information collected by them. Accordingly, it becomes essential that their effects on overall VANET performance be known beforehand. Furthermore, it is also important to measure the effectiveness of the parameters that govern the behavior of periodic safety beacons, i.e. Beacon Generation Interval, Safety Beacon Payload size, and Communication Range (alternately transmission power). This research comprehensively explores V2V single-hop periodic safety beaconing with the help of realistic simulations.

Overall, the results show the maximal performance enhancement capability of each tunable parameter separately as well as combined. It is concluded that dynamic adjustment of tunable parameters to their optimal points, cannot fully satisfy the performance level required for safety communication. Thus, instead of focusing on optimal transmission power or transmission rate control schemes, there is a strong need to think out of the box. Some of the possible solutions may require considerable alterations in proposed standards or may require sophisticated hardware. However, this can raise compatibility and cost issues, which are not desired in order to make swift VANET adoption possible. Failing to do so may make VANET an optional technology, while its true success remains in its large-scale implementation.

6.5 Future Work

We believe that, with assistance from built-in maps and sender information (e.g. sending time of the beacon, speed/acceleration and intended destination) available in safety beacon itself, it is possible for receiving nodes to predict the current position of the sending node even between the reception of two concurrent periodic safety beacons. Given the same information along with efficient use of artificial intelligence, other vehicles may also be able to estimate the current state of the reference vehicle and vice versa. An accurate prediction, even for a small duration can potentially reduce periodic broadcast of beacons in the context of vehicular communication. The future work will be focused on

- Reducing periodic broadcast using artificial intelligence.
- Developing protocols to facilitate vehicle state prediction for an appropriate period of time.
- Investigating suitable beacon generation interval beyond human reaction time that is required to obtain maximum PDR.

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3) B. M. Mughal, A. A. Wagan, and H. Hasbullah, "Impact of Safety Beacons on the Performance of Vehicular Ad Hoc Networks," in Software Engineering and Computer Systems, vol. 181, J. M. Zain, W. M. bt Wan Mohd, and E. El-Qawasmeh, Eds. Springer Berlin Heidelberg, 2011, pp. 368-383.
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APPENDIX A

SAMPLE OTCL CODE

```
#PHY layer configurations
Phy/WirelessPhyExt set RXThresh_          7.943282347242822e-13    ;
# -91dBm
Phy/WirelessPhyExt set CSThresh_          3.9810717055349697e-13   ;
# -94 dBm
Phy/WirelessPhyExt set Pt_                0.0101848735550545000O   ;
Phy/WirelessPhyExt set freq_                    5.885e+9           ;
#DSRC CCH
Phy/WirelessPhyExt set noise_floor_        1.2589254117941663e-13  ;
#-99 dBm
Phy/WirelessPhyExt set L_                       1.0    ;
#default radio circuit gain/loss
Phy/WirelessPhyExt set PowerMonitorThresh_      6.310e-14          ;
#-102dBm
Phy/WirelessPhyExt set HeaderDuration_          0.000040           ;
#40 us
Phy/WirelessPhyExt set BasicModulationScheme_   0
Phy/WirelessPhyExt set PreambleCaptureSwitch_   1
Phy/WirelessPhyExt set DataCaptureSwitch_       1          ;
#1 for CP enabled
Phy/WirelessPhyExt set SINR_PreambleCapture_    2.5118          ;
# 2.5118 = 4 dB
Phy/WirelessPhyExt set SINR_DataCapture_        10.0;       ;
# 10 dB
Phy/WirelessPhyExt set trace_dist_              1100        ;
Phy/WirelessPhyExt set PHY_DBG_                 0
Phy/WirelessPhyExt set bandwidth_         10e6
Phy/WirelessPhyExt set CPThresh_          7

#MAC layer configurations
Mac/802_11Ext set CWMin_                        15
Mac/802_11Ext set CWMax_                        1023
Mac/802_11Ext set SlotTime_                     0.000013
```

```
Mac/802_11Ext set SIFS_                      0.000032
Mac/802_11Ext set ShortRetryLimit_           7
Mac/802_11Ext set LongRetryLimit_            4
Mac/802_11Ext set HeaderDuration_            0.000040
Mac/802_11Ext set SymbolDuration_            0.000008
Mac/802_11Ext set BasicModulationScheme_     0
Mac/802_11Ext set use_802_11a_flag_          true
Mac/802_11Ext set RTSThreshold_              3000  ;
#3000 to disable RTS/CTS in 802.11
Mac/802_11Ext set MAC_DBG                    0

#Radio antenna settings
Antenna/OmniAntenna set Gt_ 2.512
Antenna/OmniAntenna set Gr_ 2.512
Antenna/OmniAntenna set Z_ 1.5

#Nakagami propagation model settings
    Propagation/Nakagami set use_nakagami_dist_ true
    Propagation/Nakagami set gamma0_ 1.9
    Propagation/Nakagami set gamma1_ 3.8
    Propagation/Nakagami set gamma2_ 3.8

    Propagation/Nakagami set d0_gamma_ 200
    Propagation/Nakagami set d1_gamma_ 500

    Propagation/Nakagami set m0_  1.5
    Propagation/Nakagami set m1_  0.75
    Propagation/Nakagami set m2_  0.75

    Propagation/Nakagami set d0_m_ 80
    Propagation/Nakagami set d1_m_ 200

#=====================================================================

set val(chan)       Channel/WirelessChannel
set val(prop)       Propagation/Nakagami
set val(netif)      Phy/WirelessPhyExt
set val(mac)        Mac/802_11Ext
set val(ifq)        Queue/DropTail/PriQueue
```

```
set val(ll)          LL
set val(ant)         Antenna/OmniAntenna
set val(x)           7100        ;# X dimension of the topography
set val(y)           1030        ;# Y dimension of the topography
set val(ifqlen)      20          ;# max packet queue length
set val(nn)          1240        ;# Total number of simulated nodes
set val(rtg)         DumbAgent
set val(stop)        21          ;# Total simulation time

# ===================================================================
# Main Program
# ===================================================================

# Initialization of global variables

global defaultRNG
$defaultRNG seed $val(seed)

set ns_            [new Simulator]
set topo     [new Topography]
set tracefd   [open file_name.tr w]
#$ns_ use-newtrace
$ns_ trace-all $tracefd

#NAM trace configurations "remove respective comments for nam output"
#set namtrace [open file_name.nam w]            ;# nam trace file name
#$ns_ namtrace-all-wireless $namtrace $val(x) $val(y)

#Simulation grid initialization
$topo load_flatgrid $val(x) $val(y)
set god_ [create-god $val(nn)]
$god_ off

#Channel parameters
set chan [new $val(chan)]
$ns_ node-config -adhocRouting $val(rtg) \
                 -llType $val(ll) \
                 -macType $val(mac) \
                 -ifqType $val(ifq) \
```

```
                -ifqLen $val(ifqlen) \
                -antType $val(ant) \
                -propType $val(prop) \
                -phyType $val(netif) \
                -channel $chan \
                    -topoInstance $topo \
                    -agentTrace ON \
                -routerTrace OFF \
                -macTrace OFF \
                -phyTrace ON

#===================================================================
#Start - Node placement starting from bottom lane

for {set i 0} {$i < 300 } {incr i} {
    set ID_($i) $i
    set vehicle_($i) [$ns_ node]
    $vehicle_($i) set id_  $ID_($i)
    $vehicle_($i) set address_ $ID_($i)
    $vehicle_($i) set X_ [expr $i * 20 + 500]
    $vehicle_($i) set Y_ 501
    $vehicle_($i) set Z_ 0
    $vehicle_($i) nodeid $ID_($i)
#        $ns_ initial_node_pos $vehicle_($i) X_

}

for {set i 300} {$i < 500 } {incr i} {
    set ID_($i) $i
    set vehicle_($i) [$ns_ node]
    $vehicle_($i) set id_  $ID_($i)
    $vehicle_($i) set address_ $ID_($i)

      $vehicle_($i) set X_ [expr $i * 30 - 9000 + 500]
      $vehicle_($i) set Y_ 504.66
      $vehicle_($i) set Z_ 0
    $vehicle_($i) nodeid $ID_($i)
#             $ns_ initial_node_pos $vehicle_($i) X_
}
```

```
for {set i 500} {$i < 620 } {incr i} {
    set ID_($i) $i
    set vehicle_($i) [$ns_ node]
    $vehicle_($i) set id_  $ID_($i)
    $vehicle_($i) set address_ $ID_($i)

      $vehicle_($i) set X_ [expr $i * 50 - 25000 + 500]
      $vehicle_($i) set Y_ 508.32
      $vehicle_($i) set Z_ 0
    $vehicle_($i) nodeid $ID_($i)
#              $ns_ initial_node_pos $vehicle_($i) X_
}

for {set i 620} {$i < 740 } {incr i} {
    set ID_($i) $i
    set vehicle_($i) [$ns_ node]
    $vehicle_($i) set id_  $ID_($i)
    $vehicle_($i) set address_ $ID_($i)

      $vehicle_($i) set X_ [expr $i * 50 - 31000 + 500]
      $vehicle_($i) set Y_ 513.98
      $vehicle_($i) set Z_ 0
    $vehicle_($i) nodeid $ID_($i)
#              $ns_ initial_node_pos $vehicle_($i) X_
}

for {set i 740} {$i < 940 } {incr i} {
    set ID_($i) $i
    set vehicle_($i) [$ns_ node]
    $vehicle_($i) set id_  $ID_($i)
    $vehicle_($i) set address_ $ID_($i)

      $vehicle_($i) set X_ [expr $i * 30 - 22200 + 500]
      $vehicle_($i) set Y_ 517.64
      $vehicle_($i) set Z_ 0
    $vehicle_($i) nodeid $ID_($i)
#              $ns_ initial_node_pos $vehicle_($i) X_
}
```

```
for {set i 940} {$i < 1240 } {incr i} {
    set ID_($i) $i
    set vehicle_($i) [$ns_ node]
    $vehicle_($i) set id_  $ID_($i)
    $vehicle_($i) set address_ $ID_($i)

      $vehicle_($i) set X_ [expr $i * 20 - 18800 + 500]
      $vehicle_($i) set Y_ 521.3
      $vehicle_($i) set Z_ 0
    $vehicle_($i) nodeid $ID_($i)
#              $ns_ initial_node_pos $vehicle_($i) X_
}

#END - node placement
#xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

#Start - Set & attach Agent

for {set i 0} {$i < 1240 } {incr i} {
    set agent_($i) [new Agent/PBC]
    $ns_ attach-agent $vehicle_($i)  $agent_($i)
    $agent_($i) set payloadSize 500
    $agent_($i) set periodicBroadcastInterval 0.25
    $agent_($i) set periodicBroadcastVariance 0.05
    $agent_($i) set modulationScheme 1
    $agent_($i) PeriodicBroadcast ON
    $ns_ at $val(stop).0 "$vehicle_($i) reset";
}

#END - Set & attach Agent
#xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

$ns_ at $val(stop).0002 "puts \"NS EXITING...\" ; $ns_ halt"
$ns_ at $val(stop).0003 "$ns_ flush-trace"
puts "Starting Simulation..."
$ns_ run

#$ns_ flush-trace
```

APPENDIX B

SAMPLE AWK SCRIPT

```
#close $tracefd

BEGIN {
# Initialize e2edelay variables
count = 0;
seqno = 0;
AGTcountS = 0;
PHYcountS = 0;

delay1 = 0;
delay2 = 0;
delay3 = 0;
delay4 = 0;
delay5 = 0;
delay6 = 0;
delay7 = 0;
delay8 = 0;
delay9 = 0;
delay10 = 0;

count100m = 0;
count200m = 0;
count300m = 0;
count400m = 0;
count500m = 0;
count600m = 0;
count700m = 0;
count800m = 0;
count900m = 0;
count1000m = 0;

# Initialize PDR variables
countR100m = 0;
```

```
countR200m = 0;
countR300m = 0;
countR400m = 0;
countR500m = 0;
countR600m = 0;
countR700m = 0;
countR800m = 0;
countR900m = 0;
countR1000m = 0;

# Initialize Throughput variables
TPcountR = 0;
pkt_size = 0;

# Misc variables
S = 0;
R = 0;
DND = 0;
PND = 0;
RXB = 0;
TXB = 0;
PXB = 0;
SXB = 0;
totalD = 0;
}

{
action = $1;
time = $2;
nodeid = $3;
layer = $4;
dropreason = $5;
type = $7;
size = $8;
txid1 = $10;
txid2 = $14;

#Throughput for current node
```

```
if(nodeid == "_150_" && action == "r" && layer == "AGT") {
        pkt_size = $8;
        TPcountR++;
        }
#Main body of the code
if((time > 1)&&(time < 21)&&((txid1 == "[150:0")||(txid2 ==
"[150:0"))){

        if(action == "s" && layer == "AGT") {
        AGTcountS++;
        seqno = $6;
        start_time[$6] = $2;
        }

        if(action == "s" && layer == "PHY") {
        PHYcountS++;
        }

        if(action == "r" && nodeid == "_403_") {
        countR100m++;
                end_time100m[$6] = $2;
                        delay1 = end_time100m[$6]-start_time[$6];
         }

        if(action == "r" && nodeid == "_406_") {
        countR200m++;
                end_time200m[$6] = $2;
                        delay2 = end_time200m[$6]-start_time[$6];
         }

        if(action == "r" && nodeid == "_410_") {
        countR300m++;
                end_time300m[$6] = $2;
                        delay3 = end_time300m[$6]-start_time[$6];
         }
        if(action == "r" && nodeid == "_413_") {
        countR400m++;
                end_time400m[$6] = $2;
                        delay4 = end_time400m[$6]-start_time[$6];
```

```
    }

    if(action == "r" && nodeid == "_416_") {
    countR500m++;
          end_time500m[$6] = $2;
                delay5 = end_time500m[$6]-start_time[$6];
    }

    if(action == "r" && nodeid == "_420_") {
    countR600m++;
          end_time600m[$6] = $2;
                delay6 = end_time600m[$6]-start_time[$6];
    }

    if(action == "r" && nodeid == "_423_") {
    countR700m++;
          end_time700m[$6] = $2;
                delay7 = end_time700m[$6]-start_time[$6];
    }

    if(action == "r" && nodeid == "_426_") {
    countR800m++;
          end_time800m[$6] = $2;
                delay8 = end_time800m[$6]-start_time[$6];
    }

    if(action == "r" && nodeid == "_430_") {
    countR900m++;
          end_time900m[$6] = $2;
                delay9 = end_time900m[$6]-start_time[$6];
    }

    if(action == "r" && nodeid == "_433_") {
    countR1000m++;
          end_time1000m[$6] = $2;
                delay10 = end_time1000m[$6]-start_time[$6];
    }

# BLR-breakup calculations
```

```
        if(action == "r" && layer == "AGT") {
        R++;
        }

        if(dropreason == "DND") {
        DND++;
        }

        if(dropreason == "PND") {
        PND++;
        }

        if(dropreason == "RXB") {
        RXB++;
        }

        if(dropreason == "TXB") {
        TXB++;
        }

        if(dropreason == "PXB") {
        PXB++;
        }

        if(dropreason == "SXB") {
        SXB++;
        }

DinCR = RXB+TXB+PXB+SXB;
totalD = DND+RXB+TXB+PXB+SXB;
allReventsinCR = DinCR+R;
  }
}
END # End main body
#end-to-end delay calculations
{

    for(i=0; i<=seqno; i++) {
        if(end_time100m[i] > 0) {
```

```
        delay100m[i] = end_time100m[i] - start_time[i];
            count100m++;
    }

if(end_time200m[i] > 0) {
        delay200m[i] = end_time200m[i] - start_time[i];
            count200m++;
    }

if(end_time300m[i] > 0) {
        delay300m[i] = end_time300m[i] - start_time[i];
            count300m++;
    }

if(end_time400m[i] > 0) {
        delay400m[i] = end_time400m[i] - start_time[i];
            count400m++;
    }

if(end_time500m[i] > 0) {
        delay500m[i] = end_time500m[i] - start_time[i];
            count500m++;
    }

if(end_time600m[i] > 0) {
        delay600m[i] = end_time600m[i] - start_time[i];
            count600m++;
    }

if(end_time700m[i] > 0) {
        delay700m[i] = end_time700m[i] - start_time[i];
            count700m++;
    }
if(end_time800m[i] > 0) {
        delay800m[i] = end_time800m[i] - start_time[i];
            count800m++;
    }
if(end_time900m[i] > 0) {
        delay900m[i] = end_time900m[i] - start_time[i];
```

```
                count900m++;
        }
      if(end_time1000m[i] > 0) {
            delay1000m[i] = end_time1000m[i] - start_time[i];
                count1000m++;
        }
}

for(i=0; i<=seqno; i++) {

        if(delay100m[i] > 0) {
            e2e100m = e2e100m + delay100m[i];
      }

        if(delay200m[i] > 0) {
            e2e200m = e2e200m + delay200m[i];
      }

        if(delay300m[i] > 0) {
            e2e300m = e2e300m + delay300m[i];
      }

        if(delay400m[i] > 0) {
            e2e400m = e2e400m + delay400m[i];
      }

        if(delay500m[i] > 0) {
            e2e500m = e2e500m + delay500m[i];
      }

        if(delay600m[i] > 0) {
            e2e600m = e2e600m + delay600m[i];
      }

        if(delay700m[i] > 0) {
            e2e700m = e2e700m + delay700m[i];
      }

        if(delay800m[i] > 0) {
```

```
            e2e800m = e2e800m + delay800m[i];
        }

          if(delay900m[i] > 0) {
            e2e900m = e2e900m + delay900m[i];
        }

          if(delay1000m[i] > 0) {
            e2e1000m = e2e1000m + delay1000m[i];
        }
    }
#final print command for output
printf("%d %d %d %d %d %d %d %d %d %d %d %3.2f %3.2f %3.2f %3.2f
%3.2f %3.2f %3.2f %3.2f  %3.2f %3.2f %3.2f %3.2f %3.2f %3.2f %3.9f
%3.9f %3.9f %3.9f %3.9f %3.9f %3.9f %3.9f %3.9f %3.9f\n",DND, PND ,
RXB, TXB, PXB, SXB, totalD, AGTcountS, PHYcountS, R, allReventsinCR,
(allReventsinCR/PHYcountS), (DinCR/PHYcountS), (R/PHYcountS),
((TPcountR*pkt_size)/20)*(8/1000), (countR100m/PHYcountS)*100,
(countR200m/PHYcountS)*100,(countR300m/PHYcountS)*100,(countR400m/PHY
countS)*100,(countR500m/PHYcountS)*100,(countR600m/PHYcountS)*100,(co
untR700m/PHYcountS)*100,(countR800m/PHYcountS)*100,(countR900m/PHYcou
ntS)*100,(countR1000m/PHYcountS)*100, (e2e100m/count100m)*1000,
(e2e200m/count200m)*1000, (e2e300m/count300m)*1000,
(e2e400m/count400m)*1000, (e2e500m/count500m)*1000,
(e2e600m/count600m)*1000, (e2e700m/count700m)*1000,
(e2e800m/count800m)*1000, (e2e900m/count900m)*1000,
(e2e1000m/count1000m)*1000);
}
```