

**CONNECTIVITY AND RELIABILITY MODELING
IN NEXT GENERATION VEHICULAR NETWORKS**

M.Sc. THESIS

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**GELECEK NESİL ARAÇLAR ARASI HABERLEŞME AĞLARINDA
BAĞLANTI VE GÜVENİLİRLİK MODELLEMESİ**

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To my family,

FOREWORD

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ABBREVIATIONS

AC	: Access Category
ACK	: Acknowledgment
AIFSN	: Arbitration Interframe Space Number
AP	: Access Point
App	: Appendix
BSS	: Basic Service Set
CCH	: Control Channel
CR	: Cognitive Radio
CR-VANET	: Cognitive Radio-Vehicular Ad hoc NETwork
CTS	: Clear-To-Send
CVN	: Cognitive Vehicular Network
DCF	: Distributed Coordination Function
DSA	: Dynamic Spectrum Access
DSRC	: Dedicated Short Range Communication
EDCA	: Enhanced Distributed Channel Access
EIRP	: Equivalent Isotropically Radiated Power
FCC	: Federal Communications Commission
FIFO	: First In First Out
GPS	: Global Positioning System
IEEE	: The Institute of Electrical and Electronics Engineers
ITS	: Intelligent Transportation System
LTE	: Long-Term Evolution
MAC	: Media Access Control
MANET	: Mobile Ad Hoc Networks
MSE	: Mean Squared Error
OBU	: On-Board Unit
OFDM	: Orthogonal Frequency Division Multiplexing
PDF	: Probability Density Function
PHY	: Physical
QoS	: Quality of Service
RTS	: Request-To-Send
RSU	: Road Side Unit
SCH	: Service Channel
SINR	: Signal-to-Interference-and-Noise Ratio
VANET	: Vehicular Ad hoc NETwork
VDSAN	: Vehicular Dynamic Spectrum Access Network
V2I	: Vehicle-to-Infrastructure
V2V	: Vehicle-to-Vehicle
WAVE	: Wireless Access for Vehicular Environments
WBSS	: WAVE Basic Service Set

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CONNECTIVITY AND RELIABILITY MODELING IN NEXT GENERATION VEHICULAR NETWORKS

SUMMARY

Due to the vehicular network technology which enables to obtain online and accurate information between vehicle to vehicle (V2V) and vehicle to infrastructure (V2I), the amount of safety applications has been increased. Thanks to safety applications, not only traffic safety and efficiency have been improved, but also driving comfort for drivers has been maintained such as monitoring, tracking, routing and solving congestion problem. Moreover, with recent advances in access technologies, such as WiMAX, 3G, infotainment applications have also emerged (e.g. video streaming, web browsing). To support these vehicular applications, The U.S. Federal Communications Commission has allocated 75 MHz in the 5.9 GHz frequency band for Dedicated Short Range Communication (DSRC) and this spectrum band consists of one control channel (CCH) and six service channels.

However, due to the increasing use of vehicular applications and high traffic density, specifically in urban environments, DSRC channels have not satisfied to growing bandwidth demands by causing a crucial problem; spectrum scarcity. This problem has been addressed by a new communication paradigm, called Dynamic Spectrum Access (DSA).

DSA is a potential approach which opportunistically enables to utilize vacant spectrum bands and improves spectrum utilization for unlicensed users. Therefore, in Vehicular Dynamic Spectrum Access Networks (VDSANs), vehicles as unlicensed users can have an opportunity to utilize available licensed spectrum band in order to supply increasing bandwidth requirements. However, in VDSANs, high fluctuation in the spectrum band occurs depending on not only channel usage pattern of licensed users but also relative motion between vehicles. Therefore, vehicles cannot continuously obtain a channel throughout all communication periods and this brings a crucial problem in terms of maintaining network connectivity. Establishing continuous communication and disseminating online information result with intermittent connectivity.

In addition to channel usage status (idle or busy) by licensed users, high mobility of vehicles and limited transmission range of roadside units (RSUs) cause dramatic changes in spatial and temporal behaviors of the network topology. All these challenges cause degradations both in the vehicle satisfaction and wireless communication quality in VDSANs by resulting with high number of channel switching. Therefore, continuous allocation of spectrum is more challenging in VDSANs to maintain network connectivity.

Hence, at first, we concentrate on the connectivity problem in VDSANs. Our objective is to determine best available channels to maintain full network connectivity. Due to the mobility of vehicles, each vehicle needs to characterize spatial and temporal

spectrum opportunities when they move into the transmission range of a RSU. Depending on channel usage pattern of licensed users and usage of other vehicular nodes in the topology, each vehicle chooses an appropriate channel -single or multiple channel selection- to satisfy Quality of Service (QoS) requirements by avoiding interference with licensed users.

In this thesis, we propose a novel queuing theory based framework for VDSANs. Two performance parameters in VDSANs, the number of channel switching and vehicle satisfaction ratio, are analyzed to maintain a continuous and robust connectivity. Specifically, our proposed framework uses queuing theory analytics to model the dynamic behaviors of vehicles and obtain high satisfaction ratio of vehicles. Moreover, we propose six novel dynamic channel selection algorithms to provide minimal channel switching ratio while conserving the network connectivity. The thorough evaluations show that the network connectivity can be enhanced while optimizing the channel switching with our proposed queuing theoretic VDSANs paradigm.

In addition to connectivity analysis and modeling in VDSANs, we also analyze the reliability of broadcast messages over CCH in vehicular networks. CCH enables to disseminate broadcast information. However, in IEEE 802.11p based broadcast vehicular communications, there are no traditional request-to-send (RTS)/clear-to-send (CTS) handshaking and acknowledgment mechanism to guarantee a reliable communication. Hence, hidden terminal problem, transmission collisions and channel fading arise as main communication challenges in vehicular networks and all these challenges dramatically reduce the reliability of broadcast vehicular communication.

Therefore, in this thesis, we also focus on the hidden terminal problem, transmission collisions and channel fading challenges by considering reliability requirements of broadcast messages. Our objective is to analyze the reliability of broadcast vehicular communication by proposing a novel power calibration model implemented into RSUs. More specifically, the proposed model is used to estimate the reliable and effective transmission power of hidden vehicles with Kriging spatial interpolation method. Kriging enables to find an optimal spatial prediction which estimates the unknown values from the observed data. Kriging interpolation method is used to predict the right amount of transmission power of hidden vehicles in vehicular networks so that we can calculate the hidden terminal radius depending on traffic density to prevent hidden terminal problem.

We also define a novel reliability coefficient in order to evaluate the impacts of discovered hidden terminals and calibration of their transmission power so that we can observe the correctness of broadcast messages receptions. Moreover, the proposed model enables to a semi-isolated mobility model by utilizing distance between vehicles to reflect a realistic 2D vehicular environment. One of the major novelty in our proposed implementation is that the proposed power management does stand as a software add-on on the top of the hardware communication infrastructure in RSU. Thus, the implementation becomes flexible and scalable.

As a result, to achieve these, we implement an analytical model consisting of Kriging spatial interpolation method by using semi-variogram analysis in 2D vehicular environment. The simulation results show the relationship among network parameters in terms of reliability, distance between receiver and transmitter, and hidden terminal radius with respect to traffic density.

GELECEK NESİL ARAÇLAR ARASI HABERLEŞME AĞLARINDA BAĞLANTI VE GÜVENİLİRLİK MODELLEMESİ

ÖZET

Araçlar arasında ve araçlar ile yol kenarı baz istasyonları arasında online ve güvenilir haberleşmeye imkan sağlayan araçlar arası haberleşme ağının gelişmesiyle, araç uygulamalarının sayısında artış gözlemlenmiştir. Mevcut araç uygulamaları ile trafik güvenliği ve etkinliğinin iyileştirilmesinin yanı sıra sürücüler için de trafiği izleme, yönlendirme, tıkanıklık problemlerini takip edebilme, durumsal farkındalık oluşturma açısından da bir çok kolaylık sağlamıştır. Özellikle, erişim teknolojilerindeki son gelişmelerle (örneğin; WiMAX, 3G), güvenlik maksatlı araç uygulamalarının yanı sıra eğlence amaçlı birçok araç uygulaması da ön plana çıkmıştır (örneğin; video akışı, internet tarayıcısı). Tüm bu uygulamaları desteklemek maksadıyla ABD Federal Haberleşme Komisyonu tarafından 5.9 GHz frekans bandında 75 MHz'lik spektrum aralığı kısa mesafeli araç iletişimi (Dedicated Short Range Communication) için tahsis edilmiştir. IEEE 802.11p ve IEEE 1609 standartları ile kısa mesafeli araç iletişimi için tahsis edilen spektrum bandı 1 kontrol kanalı ve 6 servis kanalı olmak üzere toplam 7 kanala ayrılmıştır.

Araçlar arası haberleşme ağında kısa mesafeli araç iletişimi için tahsis edilen kanalların, özellikle kentsel bölgelerde artan trafik yoğunluğu ve çok sayıda araç uygulamasının geliştirilmesi neticesinde yeterli olmadığı gözlemlenmiştir. Bu da araçlar arası haberleşmede yeni bir probleme neden olmaktadır: spektrum yetmezliği problemi (spectrum scarcity problem).

Bahse konu problemin etkilerini azaltmak maksadıyla, dinamik spektrum erişimi (Dynamic Spectrum Access), artan bant genişliği ihtiyacını karşılamak için araçlar arası haberleşmede potansiyel bir çözüm olmaktadır. Dinamik spektrum erişimi; lisansız kullanıcıların, spektrum boşluklarını tespit ederek, lisanslı kullanıcıların haklarına zarar vermeden ve ortamda bulunan diğer lisansız kullanıcılar ile spektrum paylaşımlarını öngörür. Araçlar arası haberleşmede, dinamik spektrum erişimi yaklaşımı ile araçların tahsisli 75 MHz'lik spektrum aralığı dışındaki spektrum bölgelerine erişim imkanı sağlanmıştır. Bununla birlikte, lisanslı kullanıcıların bölgelere göre spektrum kullanım karakteristiğindeki değişiklikler ve araçlar arası haberleşme ağında meydana gelen topoloji değişiklikleri, mevcut kullanılabilir spektrum bandında dalgalanmalara neden olmaktadır. Bu durum araçların haberleşme periyotları süresince aynı kanalda iletişim kurmasına imkan sağlamamakta ve haberleşme süresince kesikli bir bağlantıya neden olarak kanal değişimlerini gerektirmektedir. Bu maksatla, araçların en iyi kanalları tespit ederek mevcut spektrum bandının etkin kullanımına imkan sağlayacak ve böylelikle lisanslı kullanıcılar ile karışımı önleyecek bir model oluşturmak önem arz etmektedir.

Özet olarak, araçların hareketliliği, yol kenarı baz istasyonlarının sınırlı kapsama alanları ve lisanslı kullanıcılar tarafından kanalların kullanım karakteristiği, topolojide

uzaysal ve zamana bağılı değişikliklere neden olmaktadır. Değişken bir haberleşme ağı ortamı da lisanslı kullanıcılar ile karışımı, sık kanal değişikliklerini, sinyal gücünde azalmaları ve gecikmeleri tetiklemektedir. Tüm bu problemler, araçların spektrumu yeterince etkin kullanamaması ve sık kanal değişiklikleri ile sonuçlanarak dinamik spektrum erişimine dayalı araçlar arası haberleşme ağlarında bağlantı sorununu ortaya çıkarmaktadır.

Bu maksatla, çalışmanın ilk aşamasında, dinamik spektrum erişimine dayalı araçlar arası haberleşme ağlarında sürekli ve sağlam bir bağlantının kurulması problemini incelemekteyiz. Amacımız, araçlar ve yol kenarı baz istasyonları arasında sürekli ve güvenilir bağlantının kurulması için mevcut en iyi kanalları tanımlamaktır. Bunun için, her aracın yol kenarı baz istasyonunun kapsama alanına girdiğinde uzaysal ve zamansal olarak kullanılabilir spektrum aralıklarını karakterize etmesi gerekmektedir. Lisanslı kullanıcıların kanalları kullanım karakteristiği ve topolojideki diğer araçların kanallara erişimine bağlı olarak, her araç uygun bir spektrum bandı seçmektedir. Bu seçim haberleşme süresince servis ihtiyaçlarını karşılamak için tek bir kanal kullanımı olabileceği gibi, kanal değişimleri ile çoklu kanal kullanımı şeklinde de olabilir.

Sonuç olarak, tezin dinamik spektrum erişimine dayalı araçlar arası haberleşme ağları incelemesinde, araçlar ile yol kenarı baz istasyonları arasında sürekli ve sağlam bir bağlantının kurulabilmesi maksadıyla kuyruk teorisine dayalı bir model önerilmektedir. Mevcut kanalların araçlar arasında etkin bir şekilde kullanımına imkan sağlamak ve minimum sayıda kanal değişimi ile bağlantı kurulması hedeflenmektedir. Önerilen model, araçların hareketliliğinden kaynaklanan dinamik davranışları modelleyerek etkin bir kanal erişimine kuyruk teoreminden yararlanarak imkan sağlamaktadır. Bu maksatla, minimum kanal değişimini sağlayan 6 yeni kanal seçim algoritması önerilmiştir. Simülasyon sonuçlarında, önerilen algoritmalar yardımıyla minimum sayıda kanal değişimi ile araçlar ve yol kenarı baz istasyonları arasında sürekli ve sağlam bir bağlantı kurulabileceği gözlemlenmiştir.

Dinamik spektrum erişimine dayalı araçlar arası haberleşme ağlarında sürekli ve sağlam bir bağlantının kurulabilmesi maksadıyla önerilen modelin yanı sıra, çalışmanın ikinci aşamasında, kısa mesafeli araç iletişimi için tahsis edilen kontrol kanalı üzerinden gönderilen yayın (broadcast) mesajlarının güvenilirlik analizi incelenmiştir.

Kısa mesafeli araç iletişimi için tahsis edilen kontrol kanalı, güvenlik maksatlı araç uygulamalarında, araçlar arasında, mevki, hız, yön, hızlanma, yavaşlama bilgilerini içeren durum mesajlarının online olarak aktarılması maksadıyla kullanılabilmektedir. Bununla birlikte, IEEE 802.11p protokolüne dayalı araçlar arası yayın haberleşmesinde, muhtemel paket kayıplarını ve çatışmalarını önlemek maksadıyla kullanılan request-to-send (RTS)/clear-to-send (CTS) mesajları ve alıcıya mesajın başarılı bir şekilde teslim edildiğini bildiren paket alındı (acknowledgment) mekanizmalarının kullanımı söz konusu değildir. Bunun başlıca nedenleri arasında sürekli değişen topoloji ortamı, araçların hızlarından dolayı kısa ömürlü bağlantı gereksinimi, araçların sürekli kapsama alanlarını değiştirmesi gösterilebilir. Bunun için, gizli terminal problemi (hidden terminal problem), eş zamanlı haberleşmeden kaynaklanan çatışmalar (collision) ve kanal sönümlemesi (channel fading) birçok araç uygulamasında temel sorun olarak ortaya çıkmaktadır ve bu problemler, güvenlik maksatlı araç uygulamalarında en önemli unsur olan bilginin zamanında elde edilmesine dayanan güvenilirliği olumsuz etkilemektedir.

Bu maksatla, bu çalışmada amacımız; IEEE 802.11p protokolüne dayalı araçlar arası haberleşmenin mevcut özellikleri ile, gizli terminal problemi, eş zamanlı haberleşmeden kaynaklanan çatışmalar ve kanal sönümlemesi problemlerine çözüm bulamamasından dolayı ortaya çıkan araç uygulamalarındaki güvenilirlik gereksinimlerini iyileştirmeye yönelik bir model önermektir.

Temel hedefimiz, yol kenarı baz istasyonlarına uygulanacak yeni bir güç ayarlama modeli geliştirerek araçlar arası haberleşmenin güvenilirliğini artırmaktır. Bu model, 2 boyutlu hareketli haberleşme ağındaki potansiyel gizli terminalleri belirlemek ve semi-variogram analizinden yararlanarak Kriging uzaysal ara değer kestirim (spatial interpolation) yöntemi ile gizli terminallerin güvenilir ve etkin sinyal çıkış gücünü tespit etmek için kullanılmıştır. Kriging; elde edilen verilerden, bilinmeyen değerlerin optimum uzaysal tahminini bulmayı amaçlayan bir yöntemdir. Bu maksatla, Kriging ara değer kestirim yöntemi ile elde edilen optimum sinyal çıkış gücüyle gizli terminal problemi önlenabilmekte ve gizli terminallerin kapsama alanı hesaplanabilmektedir.

Bununla birlikte, bahse konu modeli test edebilmek maksadıyla; gizli terminaller arasındaki mesafe, araçların sinyal çıkış gücü ve kapsama alanına dayanan yeni bir güvenilirlik katsayısı tanımlanmıştır. Ayrıca bahse konu metod ile gözlemlenen en önemli sonuçlardan biri de, her araç çifti arasındaki kovaryans, sadece araçlar arasındaki mesafeye bağlıdır, araç yönlerinin hesaplamalarda etkisinin olmadığı tespit edilmiştir, bu da hareketli ağlarda araçlar arasında haberleşmeye imkan sağlamaktadır. Gizli terminal problemini önlemenin yanı sıra, bu uygulamanın getirdiği yeniliklerden biri de, yol kenarı baz istasyonlarının donanımsal iletişim altyapısının üzerine yazılım-tabanlı bir güç yönetiminin eklenmesidir. Bu da uygulamanın esnek ve ihtiyaçları karşılamaya uyumlu olmasına imkan sağlamaktadır. Simülasyon sonuçlarında, önerilen modelin güvenilirlik, gizli terminal kapsama alanı ve alıcı ve gönderici istasyonlar arasındaki mesafe üzerindeki etkisi trafik yoğunluğuna bağlı olarak gözlemlenmiştir.

1. INTRODUCTION

Wireless communication systems explore innovative approaches and opportunities available in business and society through technology. Within the last 10 to 15 years, wireless communication networks got popular and common with the help of the idea of "*Internet of Things*" that all physical object could eventually communicate data over the internet to other connected devices, from automobiles to household devices.

These developments towards wireless networks have considerably attracted in automotive industries. One of the most important reason is that every year, traffic accidents occur casualty of unawareness of drivers, misjudgment or operation miss. In order to avoid traffic accidents, and improve traffic safety and efficiency, Vehicular Networks, also known as Vehicular Ad hoc NETWORKS (VANETs), have been a promising technology by offering many advantages not only safety issues but also entertainment issues.

Cars are no longer simply vehicles. They are fast becoming high-speed internet hot-spots. Audi and GM already have 4G Long-Term Evolution (LTE) capability in some of their vehicles, but it is a technology that is becoming increasingly mainstream. AT&T and Audi announced that they planned to work together to have 4G LTE in every Audi 2016 model that is equipped with Audi Connect-a navigation system, internet database and in-car WiFi. And ultimately, it means connected vehicles could communicate with each other and smart devices.

However, how can be vehicles connected and communicate with each other or infrastructure? More importantly, what are the advantages of all that connectivity in vehicular networks? AT&T's chief executive Glenn Lurie expressed that "better voice activation, better voice diagnostics-all the things you want so your hands stay on the wheel and your eyes stay on road".

As a result of these developments, the U.S. Federal Communications Commission (FCC) has allocated 75 MHz in the 5.9 GHz frequency band for Dedicated Short

Range Communication (DSRC) with the aim of usage in vehicular applications. These applications require information provided by other vehicles or road-side units (RSUs). Therefore, two main communication patterns can be taken into consideration in vehicular networks:

- Vehicle-to-vehicle (V2V) communication: The main goal of V2V communication is to improve traffic management by allowing short and medium range communications among vehicles.
- Vehicle-to-infrastructure (V2I) communication: The deployment of RSUs enables to improve network performance by extending wireless coverage area in vehicular networks. Similar to V2V communications, V2I communications generally include the provisioning of real time information related safety.

Moreover, the efficiency of vehicular applications depends on the reliable exchange of information on time and reliability is the main performance limiting factor in vehicular networks.

Therefore, here are two communication challenges of vehicular networks. (i) how can be vehicles connected with each other or infrastructure? (ii) what is the importance of reliability in vehicular applications?

In this thesis, we address the challenges of network connectivity and reliability in vehicular networks. First, in this chapter, we provide a brief overview of DSRC. We briefly describe the developments and standardization activities in vehicular networks. We investigate the usage of Dynamic Spectrum Access (DSA) techniques in vehicular networks. Then we define the challenges of connectivity and reliability issues by offering our motivation and contributions.

1.1 Background Information

Vehicular networks are of paramount importance to drivers due to the improving traffic safety and efficiency and provide a wide range of applications with different purposes. While safety is major factor behind V2V and V2I communications, applications related to entertainment have also become popular in vehicular networks. Vehicular applications are generally divided into two main categories:

- **Safety applications:** Providing safety is the main objective in vehicular networks. Warning messages, forward collision avoidance, approaching emergency vehicle assistant, optimal speed advisory can be listed as leading examples.
- **Infotainment applications:** With the recent advances in access technologies, such as WiMAX, 3G, WiFi, infotainment applications have also emerged (e.g. video streaming, web browsing, voice over IP). Especially, these applications have become more popular with the emerging applications with the aid of *mobile internet access*.

With this purpose, at first, we overview the details of DSRC which supports many vehicular applications. Then we outline the standardization activities of vehicular networks and finally, we review the usage of DSA techniques in vehicular networks.

1.1.1 Dedicated Short Range Communication

DSRC provides short and medium range communication among vehicles and between vehicles and RSUs in order to support public safety and private operations [1]. DSRC enables to data exchange with high data rates, especially in situations where requiring low latency and high reliability. In 1999, FCC has allocated 75 MHz in the 5.9 GHz frequency band for DSRC which consists of one control channel (CCH) and six service channels (SCHs).

To support many vehicular applications, Figure 1.1 shows the list of channels and also power limit of these channels for dedicated band. The usage of these channels is explained as follows:

- Channel 178 is control channel that supports safety applications which consist of V2V broadcast-type traffic. This channel is monitored by each vehicle and RSU with the help of on-board units (OBUs). Broadcast messages are delivered over CCH interval by the Wireless Access for Vehicular Environments (WAVE) draft standard as seen in Figure 1.2. The beginning of each channel interval (CCH interval or SCH interval) is a guard interval, shown in Figure 1.2, used to account for radio switching and timing inaccuracies among different devices [2]. Vehicles periodically switch to the CCH, every 100 ms, to receive safety messages from the surrounding vehicles. When vehicles and RSUs listen to CCH for a transmission, they have to wait ongoing transmission. However, high priority messages are

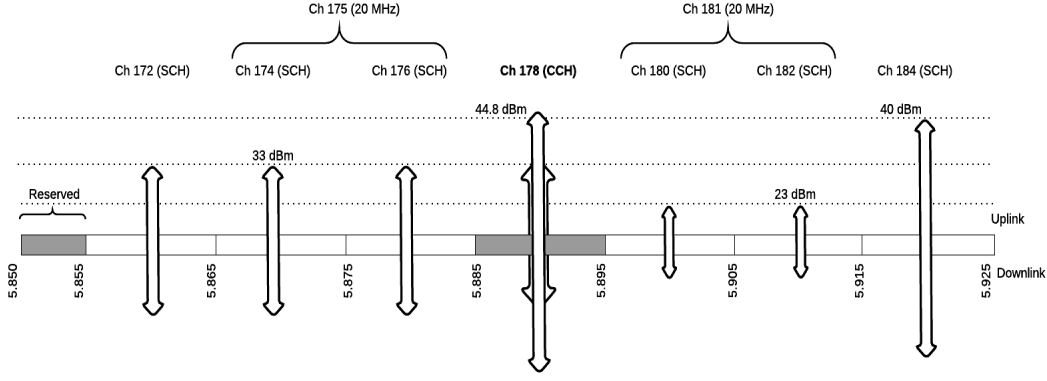


Figure 1.1: 5.9 GHz DSRC channels.

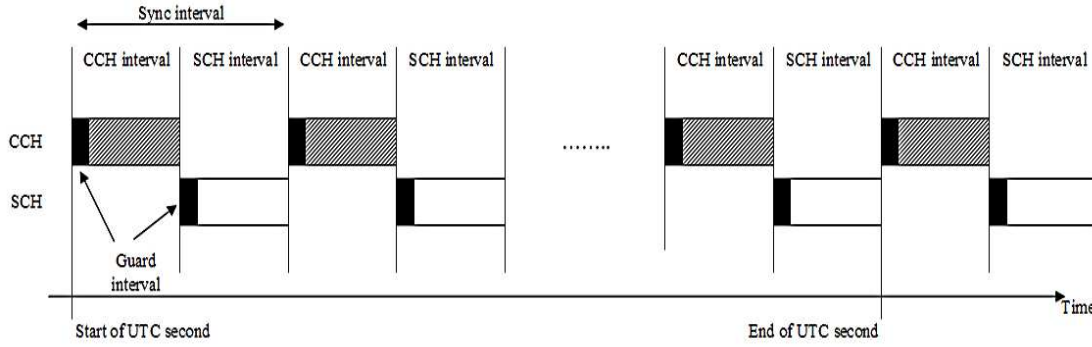


Figure 1.2: Synchronization interval, guard interval, CCH and SCH interval.

guaranteed to accept, then lower priority messages. Synchronization for switching to CCH is maintained via time received from a GPS receiver. Moreover, Table 1.1 shows the system characteristics of channel 178. The maximum EIRP for this channel is 33 dBm for non-government services, but could be as high as 44.8 dBm for government services.

- Channel 172, 174, 176, 180, 182, 184 are service channels. Vehicles switch over to one of available SCHs to support public safety and private operations. In addition, channels 174 and 176 can be combined to produce channel 175, and channels 180 and 182 can be combined to produce channel 181 so that channels 175 and 181 are 20 MHz channels.

Table 1.1: System characteristics of control channel.

Characteristic	Value
OperatingClass (CCH)	17
ChannelNumber (CCH)	178
CchInterval	50 ms
SchInterval	50 ms
SyncTolerance	2 ms
MaxChSwitchTime	2 ms

1.1.2 Standardization Activities

A set of DSRC standards is developed to satisfy Quality of Service (QoS) requirements of vehicular applications. The goal of this section is to explain the content and status of the standardization activities that support vehicular communications. Figure 1.3 shows the Intelligent Transportation System (ITS) protocol stack with the associated specifications for the layers. At the physical (PHY) and Medium Access Control (MAC) layers, DSRC utilizes IEEE 802.11p WAVE, a modified version of the familiar IEEE 802.11 (WiFi) standard. In the middle of the stack DSRC employs a suite of standards defined by the IEEE 1609 Working Group [1].

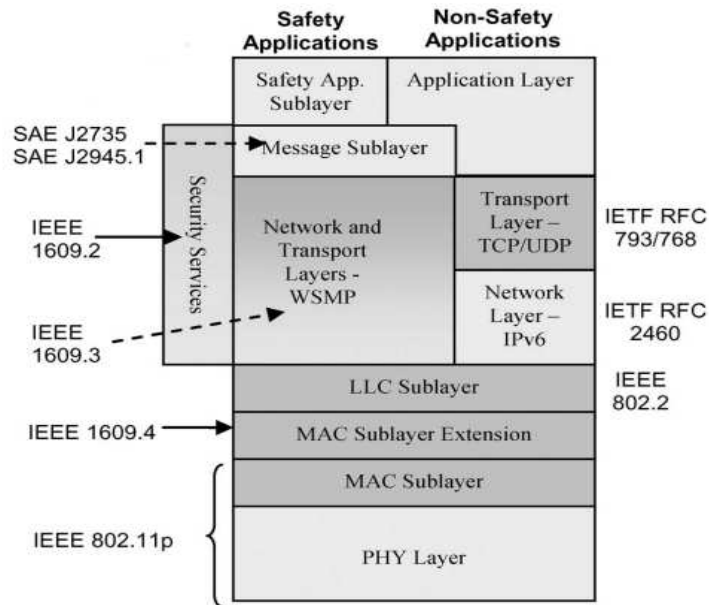


Figure 1.3: ITS (DSRC/WAVE) protocol stack [1].

1.1.2.1 IEEE 802.11p

IEEE 802.11p is an approved amendment to the IEEE 802.11 standard to add WAVE. It defines enhancements to 802.11 required to support ITS applications. This includes data exchange among high-speed vehicles and between vehicles and RSUs in the licensed ITS band of 5.9 GHz [3].

The IEEE 802.11p defines PHY layer and MAC layer amendments to the IEEE 802.11 standards to allow for efficient vehicular communications. In this respect,

the following description of 802.11p PHY and MAC layers are briefly explained with differences from traditional 802.11.

- **PHY layer:** PHY layer is based on the 802.11a standard and uses Orthogonal Frequency Division Multiplexing (OFDM) modulation. Table 1.2 shows the IEEE 802.11p modulation, coding rate, data rate as specified in the standard. Here, Signal-to-Interference-and-Noise Ratio (SINR) threshold values are obtained in [4] to determine the optimal data rate in V2V safety communications and achieve successful packet reception. Higher data rates are more efficient and require more SINR thresholds. However, higher data rates will be prone to more interference and noise. When compared with the traditional 802.11, 802.11p uses 10 MHz bandwidth instead of 20 MHz as defined in 802.11a in order to decrease delay spread in vehicular networks. Also, adjacent and non-adjacent channel rejection requirements are defined to reduce cross channel interferences in 802.11p.
- **MAC layer:** Due to the short amount of contact time between vehicles, the IEEE 802.11p amendment defines a new type of basic service set (BSS). The key purpose of this is to enable efficient communication by avoiding overhead in 802.11 MAC. BSS mechanism controls to access an access point's (AP) resource, and allows for a radio to remove the transmissions from other unrelated radios nearby. A radio first listens for beacons from an AP and then joins the BSS through a number of interactive steps, including authentication and association [5]. Therefore, in traditional IEEE 802.11, devices need to define BSS to establish connection and also wait an authentication process. On the other hand, a new type of BSS, known as WAVE BSS (WBSS) is defined in 802.11p which has a fixed identifier and transmits beacons on demand without authentication procedure. However, authentication and data confidentiality are provided by higher network layers.

1.1.2.2 IEEE 1609

IEEE 1609 is a higher layer standard based on the IEEE 802.11p. IEEE 1609 defines the architecture, communications model, network management, security mechanisms, and physical access for wireless communications in vehicular networks [6].

The IEEE 1609.4 is one of the standards of the IEEE 1609 protocol family, which describes multi-channel operation in vehicular environments without requiring any

Table 1.2: IEEE 802.11p modulation, coding rate, data rate, SINR threshold.

Modulation	Coding Rate	Data Rate	SINR Threshold (dB)
BPSK	1/2	3	5
BPSK	3/4	4.5	7
QPSK	1/2	6	8
QPSK	3/4	9	11
16-QAM	1/2	12	15
16-QAM	3/4	18	20
64-QAM	2/3	24	25
64-QAM	3/4	27	N/A

knowledge of physical layer parameters based on the IEEE 802.11p MAC layer. IEEE 802.11p MAC uses carrier sense multiple access with collision avoidance and some concepts from the Enhanced Distributed Channel Access (EDCA) mechanism in order to access the channels.

EDCA is a new wireless technology which is an enhanced version of IEEE 802.11 distributed coordination function (DCF) for WAVE. It describes seven channels (CCH and SCHs) with different features and usage. Each channel is classified according to access categories (AC), denoted by AC0-AC3. Here, while AC3 is the highest priority, AC0 is the lowest priority. In EDCA mechanism, each message according to priorities enters different queues to support the QoS requirements.

1.1.3 Dynamic Spectrum Access

Due to the increasing bandwidth requirement in wireless communication systems, researchers have tried to seek possibilities in all areas throughout communication system. Recent measurements showed that the wireless spectrum resource is underutilized in most parts of the spectrum and according to FCC [7], the usage of spectrum ranges from 15% and 85%. Therefore, the inefficiency in the spectrum usage has been addressed by a new communication paradigm, called Dynamic Spectrum Access (DSA).

Dynamic Spectrum Access (DSA) enables to utilize vacant licensed spectrum bands by unlicensed users and improves spectrum utilization for unlicensed users so that inefficient usage of existing spectrum can be prevented.

In vehicular networks, after FCC has allocated bandwidth of 75 MHz in the 5.9 GHz frequency band for DSRC, many attractive applications have become more popular

in transportation system. Although new applications and innovations have emerged in transportation system, growing bandwidth demands in vehicular applications have caused "*spectrum scarcity problem*". To overcome this spectrum scarcity problem, DSA is a potential approach in order to supply increasing bandwidth requirements. Therefore, in Vehicular Dynamic Spectrum Access Networks (VDSANs), vehicles as secondary users can have an opportunity to utilize licensed spectrum holes. However, high fluctuation in the available spectrum band occurs depending on not only channel usage pattern of primary users but also relative motion between vehicles. Therefore DSA techniques in vehicular networks should analyze effectively by preventing interference with primary users.

DSA techniques mainly focus on spectrum sensing, spectrum decision, spectrum sharing, spectrum mobility functionalities [8] for an efficient spectrum management so that available spectrum resources can be used as efficiently as possible among vehicles and network performance can be improved. An efficient mechanism enables to utilize spectrum resources with a continuous and robust connectivity among vehicles. These functions can be summarized in VDSANs as follows:

- Spectrum sensing: Detecting spectrum opportunities in order to avoid interference with primary users.
- Spectrum decision: Deciding best available channels to satisfy QoS requirements of vehicles based on vehicular applications.
- Spectrum sharing: Providing a fair share of available spectrum resources among vehicles.
- Spectrum mobility: Switching channel due to the existence of primary users or better channel conditions to maintain continuous network connectivity.

In this thesis, based on the background information, we look into the two main communication challenges in vehicular networks.

- Network connectivity in VDSANs
- Reliability analysis of broadcast messages over CCH in vehicular networks

1.2 Network Connectivity

Connectivity means that all nodes within the transmission range can be connected and communicate with each other on the same channel and spectrum band for a successful transmission. In VDSANs, connectivity can be achieved if and only if this channel and spectrum band are not used by a primary user and then a reliable communication is provided among vehicles. In VDSANs, network connectivity mainly depends on the transmission range of primary users and vehicles, distance among nodes, the number of available channels and activities of primary users. Especially, primary user activities affect the connectivity of vehicular networks. Hence, the density of primary users, the probability of primary users' activities for each spectrum band should analyze in an efficient manner. Moreover, due to the existence of primary users with heterogeneous QoS requirements, each channel characterization changes spatially and temporally so that network connectivity will be more challenging when compared to traditional wireless ad hoc networks.

To support many vehicular applications, continuous transmission and network connectivity are needed. For example, in United States, an average commuter drives approximately 26 km per day and spectrum occupancy characteristics vary while traveling on the road [9]. In such a case, establishing continuous communication and disseminating online information can be achieved with a robust network connectivity. In addition to changing channel characterization, limited transmission range of RSUs and high mobility of vehicles cause dramatic changes in spatial and temporal behaviors of the network topology. These dynamic topological changes bring a crucial problem in terms of network connectivity maintenance and this problem causes expressive degradations both in vehicle satisfaction and wireless communication quality in vehicular networks. Therefore, in this section, the following challenges peculiar to network connectivity are analyzed:

- High vehicular mobility
- The increasing use of vehicular applications
- Spatial and temporal changes of available channels
- Limited transmission range

1.2.1 High Vehicular Mobility

Mobility arises as one of the distinct characterization in VDSANs. Depending on traffic density, informations of vehicles including position, speed, direction change over time and space, and these cause dramatic changes in vehicular network topology. As shown in Figure 1.4(a), vehicles can communicate with each other or RSUs within the transmission range of each other. After a time period, as seen in Figure 1.4(b), due to the movement of vehicles, available channels, QoS requirements and communication requests of current vehicles and the distribution of vehicles may vary by resulting with dynamic topology changes.

Although the movements of vehicular nodes are predictable, which are constrained to physical environment such as buildings, obstacles, trees, each geographic region shows different characteristics. More specifically, spatial and temporal changes, relative speeds of vehicles, even when moving in the same direction, geographic conditions, changing radio propagation effects lead to attenuation of the signal and intermittent connectivity in VDSANs.

In addition, vehicular mobility strongly influences over spectrum management in terms of the correctness of the sensing information. For example, while low mobility enables to collect more samples per unit area, high mobility allows to vehicles to move away from a shadow region as quickly as possible. Thus, spectrum management in VDSANs may vary based on the characteristics of environment and the speed of vehicles. A vehicle can collect signal samples at the different locations. Many collected samples by all vehicles are utilized in the function of spectrum decision and it helps to reduce the risk of incorrect decision caused by shadowing effects [10].

Moreover, the selection of mobility model is a great importance in order to maintain robust and continuous network connectivity. Vehicular networks are separated from traditional mobile ad hoc networks (MANETs) with the property of high mobility. Therefore, commonly used mobility models in MANETs, such as Random Walk, Random Waypoint, are insufficient not to reflect a realistic vehicular environment due to the changes of node mobility depending on traffic density. In this respect, there exist many mobility models in literature for vehicular networks such as Manhattan mobility

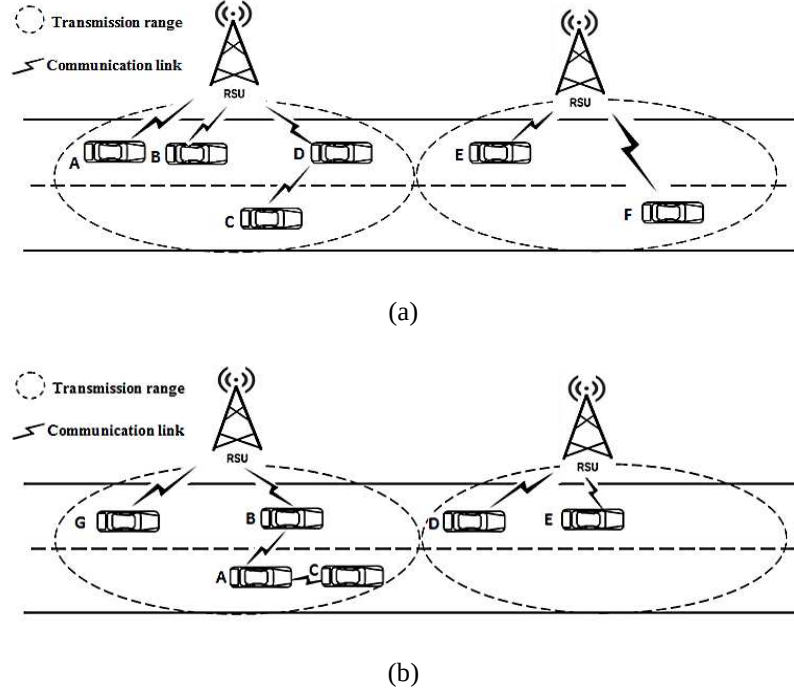


Figure 1.4: Dynamic topology changes (a) Example of showing vehicles within the transmission range of RSUs (b) Example of showing vehicles as a result of changing network topology.

model, Freeway mobility model. However, these models also restrict vehicular mobility. For example, Freeway mobility model uses bi-directional multi-lane freeways and the movement of vehicles is restricted by lanes. Manhattan mobility model uses the grid road topologies and probabilistic approach in the choice of direction. Therefore, novel analytical mobility models are proposed [11] [12] in many researches.

In literature, mobility models are generally divided into two main categories; *macroscopic description* involves restricted vehicle movements. To analyze the correlation between vehicular mobility and network connectivity, traffic stream models relate among speed of vehicles, traffic density and traffic flow. *Microscopic description* models each vehicle behaviors as a distinct entity, but computationally more expensive [13].

1.2.2 The Increasing Use of Vehicular Applications

Due to the vehicular network technology which enables to obtain online and accurate information between V2V and V2I, the amount of safety applications has been increased. Thanks to safety applications, not only traffic safety and efficiency have

been improved, but also driving comfort for drivers has been maintained such as monitoring, tracking, routing, solving congestion problem and situation awareness. Moreover, with recent advances in access technologies, such as WiMAX, WiFi, 3G, infotainment applications have also emerged (e.g. video streaming, web browsing).

The consequences of these emerging applications also triggers to growing bandwidth demands by resulting spectrum scarcity problem. Although DSA is a potential solution to utilize unused spectrum band for vehicles as secondary users, available spectrum resources cannot be used throughout whole communication duration due to the primary user activities and there is a strong need to maintain connectivity for these vehicular applications in VDSANs.

1.2.3 Spatial and Temporal Changes of Available Channels

The utilization of each spectrum band changes spatially and temporally due to the primary users and vehicles in VDSANs. Depending on primary user activities and wireless communication quality, vehicles can dynamically need to switch current channel. Vehicles should adapt changing network environment by detecting best available channels and avoiding interference with primary users.

Channel switching is required when a primary user activity is detected or a better channel condition is needed. Therefore, vehicles need to exploit to channel status to check the availability of channels at all times. High fluctuation in the available spectrum band causes frequent channel switching by affecting the network performance and the quality of network connectivity adversely in VDSANs. Each channel switching results with intermittent connectivity and communication duration continuously changes depending on network topology. When the number of channel switching increases, the quality of network connectivity will be effected by causing communication disruptions. Therefore, the quality of communication is related to determine best available channels dynamically.

Dynamic channel selection is affected by channel availability depending on primary user activities. Channel availability is defined as available or unavailable according to spatial and temporal changes of channels. Dynamic channel selection algorithms can be divided into two main categories in order to maintain full network connectivity:

- Multi-channel selection: Vehicles can sense multiple channels by using traditional sensing techniques in the literature of DSA technology such as matched filter detection, energy detection, transmitter detection etc. [14] in order to obtain the information of channel availability. Vehicles can access one channel at a time when the channel is detected as available and switch to another suitable channel dynamically when the channel is detected as unavailable.
- Single-channel selection: Vehicles can access only one channel throughout entire communication period depending on the availability of channels.

Depending on channel selection, vehicles should share available resources in an efficient manner. Queuing theory is one of the used techniques in vehicular networks. In queuing disciplines, the most common used approach is First In First Out (FIFO). However, especially, when considered to safety applications, this is not only possible approach. Messages are categorized depending on types of vehicular applications. For example, a warning message in safety applications is higher priority than video streaming in infotainment applications. Moreover, in emergency situations, the message with highest priority is immediately transmitted even if a message with lower priority is already in transmission. Here, two priority discipline can be considered in VDSANs: preemptive and non-preemptive. In preemptive case, while the message with highest priority is allowed to transmit immediately, the lower priority message is preempted and then retransmitted after message with highest priority is transmitted. The second situation, in non-preemptive case, the message with highest priority enters the head of the queue but this message does not serve until ongoing transmission is completed. Figure 1.5 generally represents a multi-channel queuing system. Here, channels are modeled as servers and communication requests of vehicles are evaluated according to availability of channels.

1.2.4 Limited Transmission Range

Transmission ranges of vehicles and RSUs have a major impact by affecting the communication duration in VDSANs. Limited transmission range causes short communication duration among vehicles and between vehicles and RSUs by resulting with intermittent connectivity and this brings major challenges such as degradation of wireless communication quality and frequent channel switching. Moreover, rapid

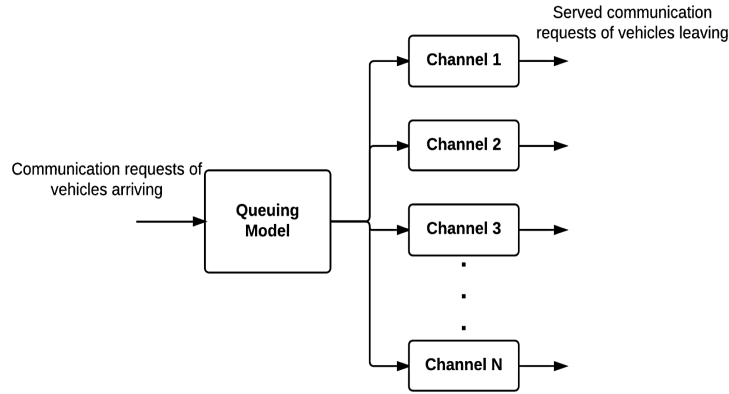


Figure 1.5: Multi-channel queuing system.

changes in network topology result with short link lifetimes and while utilizing the spectrum opportunities, continuous connectivity cannot be achieved due to the movement of vehicles.

V2V communications allow short and medium range communications among vehicles as seen in Figure 1.6(a). In addition to limited transmission range, due to the primary user activities, many critical V2V applications can be interrupted after a short communication period. Nevertheless, this drawback of V2V communications can be solved with the integration of RSUs. The deployment of RSUs enables to improve network performance by extending wireless coverage area as seen in Figure 1.6(b). Here, RSU plays a significant role in the topology by gathering all global and local informations on traffic and road conditions such as position, speed, direction, acceleration of vehicles, channel availability status, and also RSU may propose some behaviors to vehicles within the geographical area of itself. Therefore, each vehicle registers to RSU when they come into the transmission range of it.

1.2.5 Motivation

Due to the aforementioned challenges, vehicles cannot continuously obtain a channel throughout all communication period and establishing continuous communication and disseminating online information result with an intermittent connectivity in VDSANs. All these challenges cause degradations both in the vehicle satisfaction and wireless communication quality by resulting with high number of channel switching.

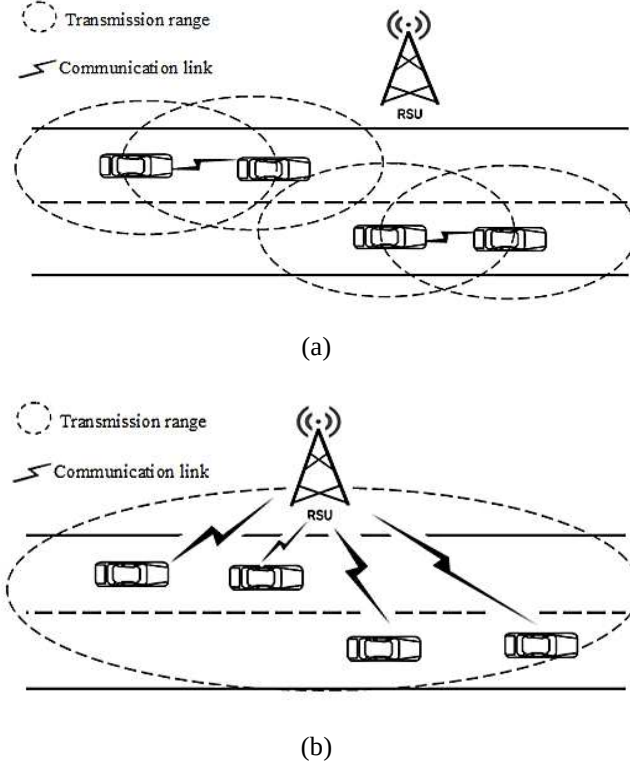


Figure 1.6: Connectivity analysis for two different VDSAN patterns (a) V2V communication (b) V2I communication.

Therefore, based on establishing continuous network connectivity between vehicles and RSUs, this thesis gives a deep understanding to show the relationship between network connectivity and channel switching with the proposed dynamic channel selection algorithms with a queuing theory approach in VDSANs.

1.2.6 Contributions

In this research, we analyze connectivity problem under different traffic densities in VDSANs. In our work, selection of a channel is related to the quality of connectivity and the number of channel switching. Our approach is to solve network connectivity problem by proposing dynamic channel selection algorithms in terms of satisfaction ratio (total usage ratio of channels) and the number of channel switching. Therefore, at first, we propose a channel utilization table and then implement six novel channel selection algorithms. We model vehicular communication by using queuing analytics and schedule communication requests accordingly. Finally we compare the results with different approaches including single channel switching and multi-channel switching. Our objective is to maximize satisfaction ratio while minimizing the number of channel switching.

Specifically, this thesis makes the following main contributions and the details will be described in Chapter 3.

- We model communication requests with a queuing model and we propose a channel utilization table for VDSANs.
- According to the proposed utilization table, we derive dynamic channel selection algorithms to enhance connectivity between vehicles and RSUs.
- We evaluate simulation environment in terms of satisfaction ratio and number of channel switching with a queuing approach by calculating average waiting time and queue length, and without queuing approach.
- We evaluate the performance of the channel selection algorithms by including multi-channel and single channel selection.

In this thesis, in addition to connectivity analysis and modeling, reliability of broadcast messages is also analyzed in vehicular networks.

1.3 Reliability Analysis

Safety applications are deployed to mitigate safety problems by decreasing traffic accidents and their severity in vehicular networks. When considered to V2V communications potentially address about 4,409,000 crashes annually in [15], the need of safety applications is clear.

In safety applications, delivery of a message in a timely manner and reliable information play a significant role. For example, in emergency situations, crashes are only prevented by the driver's quick reactions and obtained reliable warning messages on time assist to improve personnel response time and avoid traffic crashes. Hence, safety applications provide critical and important informations collected by all vehicles.

Safety applications intensively use broadcast vehicular communication and CCH enables to disseminate broadcast messages. The efficiency of safety applications depends on reliable exchange of broadcast messages on time. Therefore, reliability of safety applications arises as an another main communication challenge in vehicular networks.

In this section, we analyze the reliability requirements of broadcast messages over CCH in vehicular networks. With this purpose, the following challenges are described:

- Hidden terminal problem and transmission collisions
- Channel fading

1.3.1 Hidden Terminal Problem and Transmission Collisions

Safety applications intensively use IEEE 802.11p based broadcast vehicular communication. Vehicles periodically broadcast status messages including position, speed, direction, acceleration informations to nearby vehicles.

In Figure 1.7, vehicle B and C are out of transmission range of each other. However, they are within the transmission range of vehicle A. They are hidden nodes that are out of the carrier sensing range but can still interfere the nodes in the transmission range of vehicle A. Therefore, they can access the channel at the same time to communicate with vehicle A and collision can cause due to the hidden terminal problem.

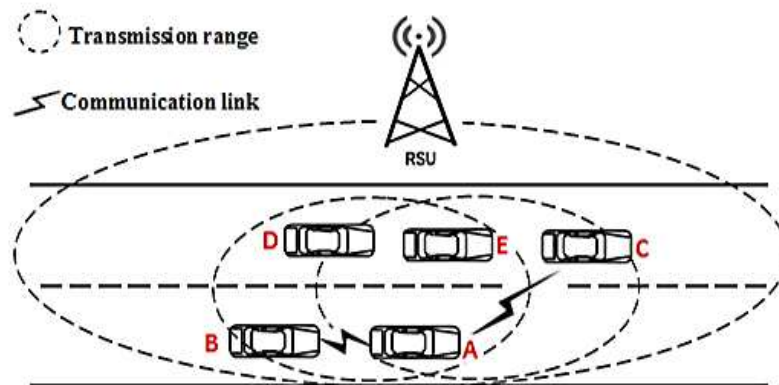


Figure 1.7: Example of showing hidden terminal problem.

IEEE 802.11 protocol addresses the hidden terminal problem with an optional mechanism, request-to-send (RTS)/ clear-to-send (CTS) exchange. RTS/CTS exchange occurs before any data is transferred to avoid collisions caused by hidden nodes. As seen in Figure 1.8, when a source node wants to send a packet to destination node, it initially sends a small packet called RTS. Upon correctly receiving the RTS, destination node responds with another small packet called CTS. After receiving the CTS, source node sends the DATA packet to destination node. If destination node receives the DATA packet correctly, it sends an Acknowledgment (ACK) back to

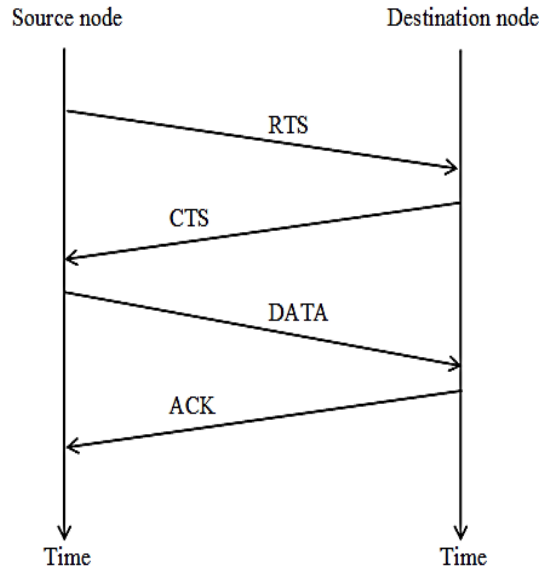


Figure 1.8: RTS/CTS handshake.

source node. Any node that hears a RTS or CTS is prohibited from transmitting any signal for a period that is encoded in the duration field of the received RTS or CTS.

However, in IEEE 802.11p based broadcast vehicular communications, there are no traditional RTS/CTS handshaking to detect the collisions and ACK packets to control whether packet is received successfully or not. For this reason, hidden terminal problem and collisions due to the concurrent transmissions arise as main communication challenges in vehicular networks by resulting in degradation of reliability.

1.3.2 Channel Fading

The signal received by the vehicles may consist of many reflected signals due to the reflection, diffraction and scattering depending on distance between vehicles. It is well known that the wireless multi-path channel causes an arbitrary time dispersion, attenuation, and phase shift, known as fading, in the received signal. The received signals from these undesired effects and also interfering transmitters also effect the quality of communication by causing packet loss and power leakage.

In vehicular networks, due to the high mobility of vehicles and limited communication range of vehicles, dramatic changes in spatial and temporal behaviors of the network topology occur and such a highly fluctuating network triggers the challenge of channel fading.

In general, in the literature, Rician distribution for short distances and Rayleigh distribution for large distances are used for fading channel modeling. However, it is shown that Nakagami distribution is more efficient and flexible than current distributions for urban propagation environments [16]. This distribution can model the rapid fluctuations of the received signal envelope, which is transmitted over fading wireless channel. Therefore, since Nakagami fading can reflect many fading condition in a wireless channel, it can provide a better explanation in real-time safety applications. As special cases, Nakagami-m includes Rayleigh distribution when $m=1$, and for the values of $m>1$, Nakagami-m distribution closely approximates Rician distribution.

The probability density function (PDF) of signal power, P_r , for Nakagami-m fading channel [17] can be defined in Eq.1.1:

$$Pdf(P_r) = \frac{2m^m P_r^{2m-1}}{\Omega^m \Gamma(m)} \exp\left(-\frac{mP_r^2}{\Omega}\right) \quad (1.1)$$

where the channel amplitude $P_r \geq 0$, $\Omega = E(P_r^2)$ is average fading power, $E(.)$ is the expectation operator and $\Gamma(.)$ is gamma function. The parameter m expresses the severity of the fading as described in Eq.1.2.

$$m = \frac{(E(P_r^2))^2}{Var(P_r^2)} \quad (1.2)$$

1.3.3 Motivation

Since the current specifications of IEEE 802.11p based broadcast vehicular communication do not propose a solution for the challenges of hidden terminal problem, transmission collisions and channel fading, reliability is main performance limiting factor in safety applications.

Therefore, in this research, we propose an analytical model to analyze broadcast vehicular communication and also enhance the reliability of broadcast communication in safety applications.

1.3.4 Contributions

In this research, our objective is to analyze the reliability of broadcast vehicular communications by proposing a novel power calibration model implemented into RSU. More specifically, the proposed model is used to estimate the reliable and effective

transmission power of hidden vehicles with Kriging spatial interpolation method. Kriging enables to find an optimal spatial prediction which estimates the unknown values from the observed data. Kriging interpolation method is used to predict the right amount of transmission power of hidden vehicles in vehicular networks. With this method, we can calculate the hidden terminal radius depending on traffic density to prevent hidden terminal problem. We also define a novel reliability coefficient to analyze the proposed model depending on distance between vehicles, signal power and transmission range so that we can observe the correctness of broadcast messages receptions. Moreover, we consider a semi-isolated mobility model by utilizing distance between vehicles to reflect a realistic 2D vehicular environment.

We investigate over the proposed model with a Nakagami fading channel model with the aim of decreasing interference and increasing reliability. One of the major novelty in our proposed implementation is that the proposed power management does stand as a software add-on on the top of the hardware communication infrastructure in RSUs. Thus, the implementation becomes flexible and scalable.

Specifically, this thesis makes the following main contributions and the details will be described in Chapter 4.

- We present a novel power calibration model implemented into RSU to detect potential hidden vehicles and then estimate reliable and accurate amount of transmission power of these hidden vehicles in 2D vehicular environment.
- Our proposed model consists of a semi-isolated mobility model by utilizing the distance between vehicles to reflect a realistic vehicular environment and to model highly dynamic vehicular network topology.
- We define a novel reliability coefficient in order to observe the correctness of broadcast messages receptions by using three spatial schemes (Exponential, Gaussian and Linear model) so that we can evaluate the impacts of discovered hidden terminals and calibration of their transmission power and we can manage the efficiency of the spatial estimation method. Then, we demonstrate the trade-off between reliability and distance between receiver and transmitter depending on traffic density.

- We calculate hidden terminal radius depending on traffic density dynamically so that we enhance the reliability of the network performance by mitigating the impacts of hidden terminal problem.

The outline of this thesis is organized as follows.

Related Work (Chapter 2). In this chapter, related work is reviewed based on the challenges of network connectivity in VDSANs and reliability of broadcast messages in vehicular networks.

Connectivity Modeling (Chapter 3). In this chapter, we propose a novel queuing theory based framework for VDSANs to model the dynamic behaviors of vehicles and obtain high satisfaction ratio of vehicles. Moreover, six novel dynamic channel selection algorithms are proposed to provide minimal channel switching ratio while conserving the network connectivity.

Reliability Management (Chapter 4). In this chapter, a novel power calibration model implemented into RSUs is proposed by using a spatial estimation model with the aim of enhancing the reliability of broadcast vehicular communication. The proposed model is used to detect potential hidden vehicles in the topology and then estimate the reliable and accurate amount of transmission power of hidden vehicles in order to guarantee a reliable communication in vehicular networks.

Conclusions (Chapter 5). In this chapter, we summarize our work.

2. RELATED WORK

This chapter provides a taxonomy of the existing literature on network connectivity in VDSANs and reliability analysis of broadcast messages in vehicular networks. Related work is reviewed based on the challenges of network connectivity in VDSANs and reliability issues in vehicular networks.

2.1 Network Connectivity

In this section, we review the network connectivity in VDSANs based on the challenges as described in Chapter 1. First, the studies related to dynamic channel selection, including multi-channel selection and single channel selection approaches, are investigated. Next, the usage of TV White Spaces are described in DSA and then existing works are explained. Finally, researches about spectrum coordination and queue analytics are analyzed to maintain network connectivity.

Maintaining robust and continuous connectivity can be achieved with detecting spectrum opportunities, deciding best available channels to satisfy QoS requirement of vehicles based on vehicular applications and using the available spectrum resources in a fairly manner among vehicles.

In this respect, dynamic channel selection algorithms are proposed to detect spectrum opportunities and determine best available channels for data communication in many works. The number of channel switching as a performance parameter is also calculated to perform an efficient spectrum management.

Cheng et al. [11] propose a non-cooperative congestion game to exploit channel access opportunities. Spatial distribution and temporal channel usage of primary transmitters and mobility pattern are modeled. A distributed spectrum access algorithm is derived to access multiple channels from a game-theoretic perspective and the existence of the pure Nash equilibrium is also proved. Moreover, the proposed model is analyzed with uniform MAC and slotted ALOHA. Niyato et al. [12] analyze the problem of

optimal channel access by presenting a framework for cluster based communication in Cognitive Vehicular Networks (CVNs). Share-use channels and exclusive-use channels are considered to access the channels opportunistically and the reservation of a channel for dedicated access by vehicles. Moreover, cluster size control is adapted to maximize the utility of data transmission. Choi et al. [18] focus on exploiting available channels and then propose a cognitive channel hopping protocol to maintain network connectivity. Multiple channel selection and single channel selection are evaluated over proposed protocol and multi-channel hopping improve network performance over single channel hopping with the proposed model. Rocke et al. [19] propose a channel selection algorithm and a distance-based multi-dimensional indexing approach in order to enable learning of vehicular environment in VDSANs. In this way, the experience about the location and requirements of vehicular applications are used to manage the resources efficiently. Tsukamoto et al. [20] propose a dynamic channel selection scheme in order to maximize data transmission within the period in multi-hop VANET using DSA techniques.

In addition, VDSANs are deployed over a wide range of the spectrum bands. One of the candidate of usable spectrum band is UHF television frequency, as often termed *TV white spaces*. FCC has allowed to vehicles to operate in the television spectrum when the spectrum is not being used by primary users and this band, which is between 470-698 MHz (Channel 14-Channel 51), is often analyzed in many researches based on VDSANs due to the static channel usage pattern.

In this respect, in [21], reinforcement learning is used to achieve dynamic channel selection in VDSA environment. Number of channel switching, interference and throughput are analyzed by utilizing TV whitespace. Pagadarail et al. [22] [23] describe the available TV channels in a specific geographic area and present the implications of the non-contiguous channel availability in TV spectrum on the design of a CR transceiver and devise a quantitative model based on spectrum measurements. One of the observation is that spectral occupancy changes various locations along the highway. However, this change is acceptable level so that it allows the vehicles to sense the frequency of TV broadcasts and change the frequency in order to avoid interruption or interference with TV signals.

Moreover, spectrum coordination is required to provide a fair share of available spectrum resources among vehicles. Therefore, an efficient spectrum access mechanism enables an efficient spectrum utilization and fair share of spectrum resources by avoiding interference with primary users.

In this respect, Li and Irick [24] apply Belief Propagation model for collaborative spectrum sensing in CVNs. In addition to local observation of vehicles, the informations received from other vehicles in the topology are utilized to obtain a stable information about the existence of primary users. Then, this spectrum sensing mechanism helps to vehicles by making decisions for appropriate spectrum bands. Wang and Ho [25] propose a framework for spectrum sensing coordination in CR-VANETs. Each vehicle defines its spectrum sensing activity and fine sensing activities of nearby vehicles are coordinated and scheduled in order to obtain an efficient sensing mechanism in CR-VANETs. Felice et al. [26] propose a collaborative spectrum management framework in order to determine the accuracy of spectrum sensing, share spectrum information and detect spectrum opportunities at future locations. Han et al. [27] analyze the channel allocation problem for multi-channel CVNs to maximize throughput for all vehicles. Silva et al. [28] present a mechanism for connectivity management on CVNs which enables the usage of channels according to the movement of vehicles and application requirements for reliable data delivery.

Moreover, queuing theory in terms of connectivity modeling has been extensively investigated in many researches to share available spectrum band among vehicles in a fair and efficient manner. Sultana and Kwak [29] examine VDSA system by using queuing theory via multi server multi priority approaches and calculate transmission latency and the probability of all channels is busy over TV white space. Khabbaz et al. [30] propose M/M/1+G queuing model to analyze service requests of vehicles and characterize the dynamics of the communication system under limited spectrum resources scenario in DSA based vehicular communication. Average number of service requests, average waiting time, the probability of expiry as performance parameters are evaluated in the proposed queuing model. Chen et al. [31] present a feasibility analysis based on queuing theory approach for VDSANs. Vacant TV channels are modeled as available servers and M/M/m and M/G/m queuing system with FIFO queue and

priority queue approaches are evaluated in terms of the probability that all channels are busy and response time.

2.2 Reliability Analysis

In this section, we review the reliability of broadcast messages in vehicular networks based on the challenges as described in Chapter 1. Since the current specifications of DSRC do not propose a solution for the challenges of hidden terminal problem, transmission collisions and channel fading, reliability based on IEEE 802.11p broadcast vehicular communication has been extensively researched in many studies analytically and by simulations.

Ma et al. [32] [33] introduce four reliability metrics including packet reception rate, packet delivery ratio, packet delivery probability and effective range, and evaluate the performance and reliability of broadcast communication for safety applications in VANETs. Hafeez et al. [34] analyze the reliability and delay of DSRC over CCH by considering a new mobility model in safety applications for VANETs. Vehicles change their parameters such as sending rate, communication range, carrier sense range depending on traffic density and speed to increase the success probability. Khabazian et al. [35] evaluate the performance of safety broadcast messages including low-priority periodic messages and high-priority event-driven messages in VANETs and demonstrate the relationship among transmission range of vehicles, traffic generation rate and MAC parameters. Ye et al. [36] show the relationship between broadcast reliability and broadcast efficiency, and propose a power control and congestion control mechanism in order to increase broadcast efficiency. Jaber et al. [37] propose a repetition based broadcast model under hidden terminal problem to meet DSRC reliability and delay requirements in terms of probability of successful reception and delay depending on repetitions. The effect of hidden nodes on the performance is analyzed in repetition-based protocol. Cheng and Yamao [38] propose an analytical model for V2V broadcast communication of CSMA/CA relay network to increase reliability by considering fading, shadowing and hidden terminal problem.

3. CONNECTIVITY MODELING

In vehicular networks, limited transmission range of RSUs, high mobility of vehicles and channel status (busy or idle) cause dramatic changes in spatial and temporal behaviors of the network topology. These dynamic topological changes bring a crucial problem in terms of network connectivity maintenance. Moreover, the high number of channel switching becomes also a problem due to the dynamic topology changes in vehicular networks. These challenges cause expressive degradations both in the user satisfaction and wireless communication quality in vehicular networks. To overcome these challenges, in this thesis, we propose a novel queuing theory based framework for VDSANs. Specifically, our proposed framework uses queuing theory analytics to model the dynamic behaviors of vehicles and obtain high satisfaction ratio of vehicles. Moreover, we propose six novel dynamic channel selection algorithms to provide minimal channel switching ratio while conserving the network connectivity.

3.1 Network Architecture and Assumptions

In this section, we propose a network architecture supporting DSA for V2I communication pattern as seen in Figure 3.1. In this architecture, RSUs are centralized coordinators which can be located at known positions. Vehicles and RSUs can communicate with each other within a limited transmission range, α , and vehicles can be register only one RSU at a time.

As shown in Figure 3.1(a), vehicle B, C and D, which are located within the transmission range of a RSU, access available channels, channels 1, 2 and 3 respectively. After a time period, while vehicle D is out of transmission range, vehicle A, B and C access available channels. However, vehicle B and C need to switch another channel, channels 3 and 5 respectively, due to the movement of vehicles and channel status as shown in Figure 3.1(b).

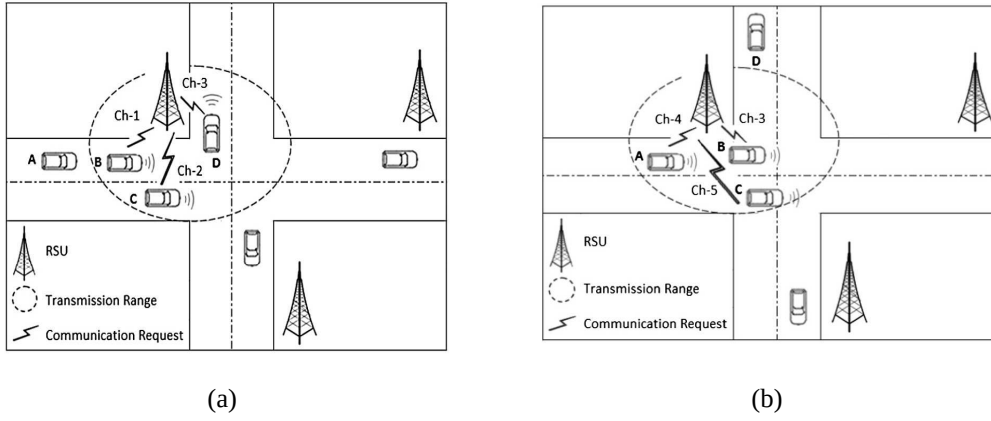


Figure 3.1: Changing network topology due to the vehicular mobility and channel condition (a) Example of showing the vehicles within the transmission range of a RSU in the first situation (b) Example of showing as a result of changing network topology in the second situation.

Limited transmission range, channel status (busy or idle) and velocity of vehicles will cause highly dynamic network topology. As a result, communication duration between vehicles and RSU will result with intermittent network connectivity.

To overcome this challenge, we assume that there are c channels that are divided into fixed time slots, t , as seen in Figure 3.2. Vehicles can opportunistically access to channels depending on communication requests. Communication request describes entire transmission demands of vehicle within the transmission range of a RSU. Moreover, RSUs store the channel availability status regarding its geographical area. Channel availability is defined as available or unavailable for each time slot. When the selected channel is unavailable, vehicles can dynamically switch to another suitable channel in response to network conditions. Each vehicle can be used only one channel at a time slot.

Vehicles move at variable velocity, v' , which are between $[v_{min} \leq v' \leq v_{max}]$ depending on traffic density, ρ . The movement of vehicles is considered normally distributed zero mean and unit variance. The time between arrival and departure point, $t_2 - t_1$, within transmission range of a RSU is calculated for each vehicle separately. A detailed explanation of mobility pattern will be described in the following section and mathematical notations used in this chapter is given in Table 3.1.

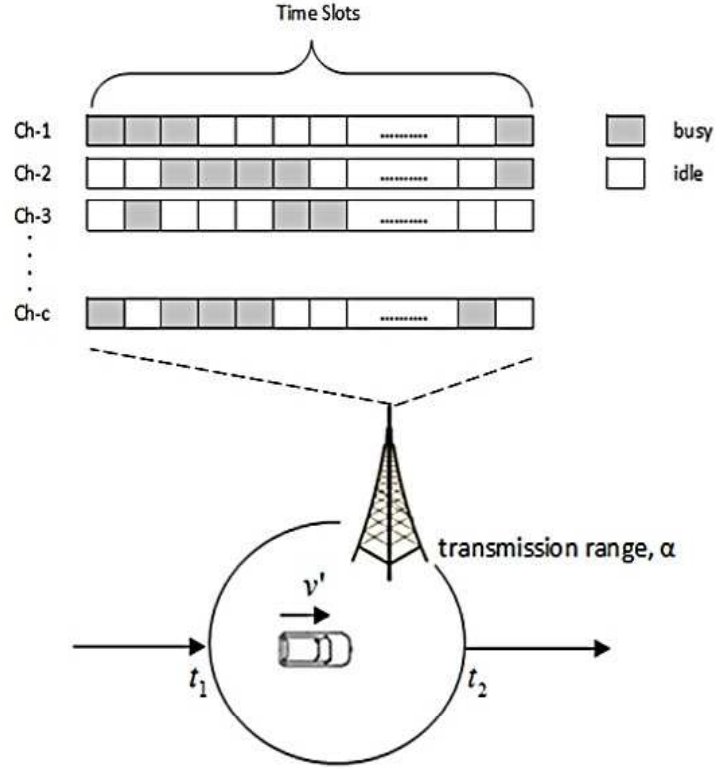


Figure 3.2: Multiple channel structure within transmission range.

Table 3.1: Mathematical notations for connectivity modeling.

Notation	Description
α	Transmission range of a RSU
v'	Velocity of vehicles
t	Total number of time slot
t_1, t_2	Arrival and departure time
m	Number of vehicles
$[U_{cxt}]$	Utilization matrix
$U_{c_i}^m$	Utilization ratio of channel i for m^{th} vehicle
$R(t)$	Communication request
$C(t)$	Channel availability status
c	Number of channels (servers)
n	Total number of communication requests in each time slot
ρ	Traffic intensity
P_0	The probability of queue being empty
P_n	The probability of all channels being busy
$E(W)$	Average waiting time spent in the queue by a vehicle
$E(L^q)$	Mean queue length
$[\xi]$	Satisfaction matrix
ξ	Satisfaction ratio
χ	Number of channel switching

3.2 System Model

In this work, our main objective is to maintain robust and continuous connectivity in VDSANs. We consider communication between vehicles and RSUs. RSUs gather all communication requests of vehicles within its transmission range. With the help of obtained information by vehicles and stored channel availability status, connectivity problem is analyzed in the proposed system models, as shown in Figures 3.3 and 3.4. The proposed system models are embedded in RSU and each module is modeled as follows.

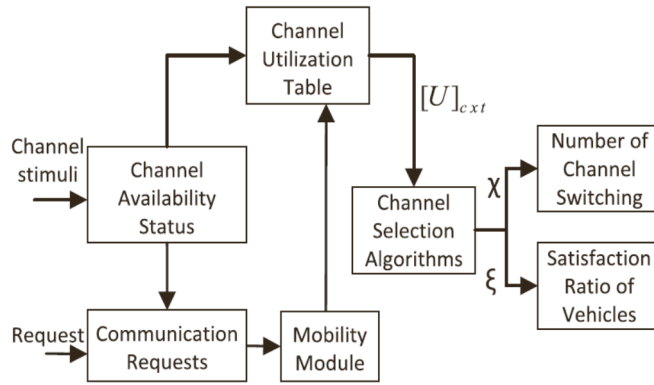


Figure 3.3: Proposed system model without a queuing approach.

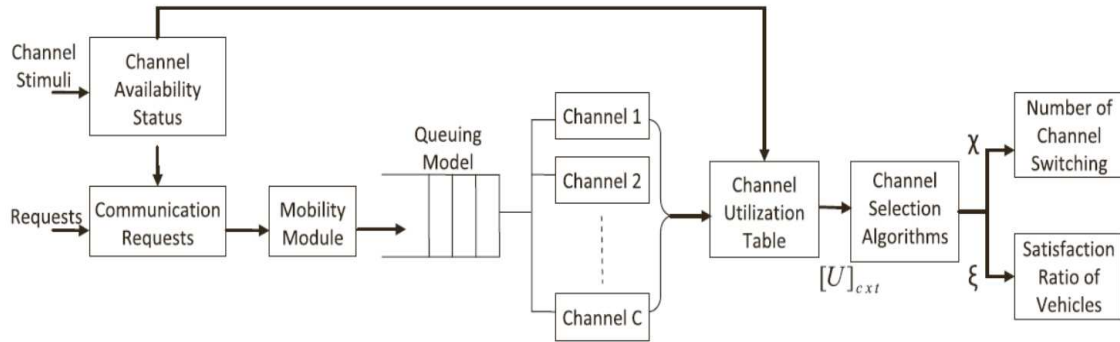


Figure 3.4: Proposed system model with a queuing approach.

3.2.1 Channel Availability Status

In this module, each channel is characterized as idle or busy in each time slot which is represented with binary variables, $C(t)$, and distributed according to Poisson process with the arrival rate λ_C in time interval $[1, t]$.

RSU gathers the information of all channels and according to channel availability status, communication requests are evaluated in RSU in order to obtain proposed channel utilization table as seen in Figure 3.6.

3.2.2 Communication Requests

This module characterizes vehicles according to their communication requests. Communication requests describe entire transmission demands of vehicles within the transmission range of a RSU in each time slot. Requests, $R(t)$, are represented with binary variables, and distributed according to Poisson process with the arrival rate λ_R in time interval $[1, t]$ similar to channel availability status module.

3.2.3 Mobility Module

To reflect a real traffic scenario as closely as possible, mobility parameters such as traffic density, velocity of vehicle, arrival and departure time, are defined in this module. Here, an interaction between traffic density and velocity of vehicles is analyzed in simulation environment to obtain a realistic vehicular mobility pattern. RSUs have a limited transmission range, α . According to traffic density, ρ , each vehicle moves along its transmission range at variable velocity, v' , which are between $[v_{min} \leq v' \leq v_{max}]$, and depending on traffic density, vehicular flow changes by effecting arrival and departure time. Velocity and direction of vehicles are considered independently of each other. Thanks to this module, RSU determines time period of vehicles how long will remain in its transmission range, $t_2 - t_1$, considering velocity of vehicle, assuming that $\frac{\alpha}{v'}$ as shown in Figure 3.2. Upon reaching to arrival point in t_1 , simulation begins for vehicles separately. It is assumed that vehicles are inside transmission range of RSU in t_1 .

3.2.4 Queuing Model

Vehicles within transmission area share suitable channels and there is no priority among vehicles. In the first proposed system model, as shown in Figure 3.3, when more vehicles detect the same channel as available, one of the vehicles is randomly selected and the other communication requests are dropped. This situation caused performance degradation in the network. However, we observe that the satisfaction

ratio is acceptable and the number of channel switching is minimal depending on communication requests without queuing approach.

Moreover, with the aim of improving performance, we modeled the communication requests by using queuing model as shown in Figure 3.4.

M/M/m queuing model with FIFO approach is considered to analyze the system. The state of the system is characterized with respect to the number of communication requests in each time slot. Channels are modeled as servers. The total number of communication requests in each time slot is compared with the number of available channels in the same time slot. If there is no available channel to serve, requests are waited until next time slot to check availability of channels. Average waiting time in the queue and queue length are calculated with M/M/m queuing approach.

We get the basic equation with the help of state diagram as shown in Figure 3.5. c and n represent the number of channels and the number of vehicles which has communication requests, respectively. If there is available channel for each communication request to serve ($n \leq c$), all requests are accepted or otherwise ($n > c$) requests until available channels are served and the remaining requests are waited in the queue.

$$\lambda_R P_{n-1} = \min(n, c) \mu P_n \quad \forall n \in [1, 2, \dots, m] \quad (3.1)$$

where λ_R represents arrival rate of communication requests, μ is the service rate of a channel for each request and a function of time, m is the total number of vehicles and P_n is the probability of all channels being busy is given by Eq.3.2 as defined in [39]:

$$P_n = \frac{(c\rho)^n}{n!} P_0 \quad \forall n \in [0, \dots, c] \quad (3.2)$$

To calculate P_n in Eq.3.2, traffic intensity ρ and P_0 are defined in Eqs.3.3 and 3.4 respectively as follows:

$$\rho = \frac{\lambda}{c\mu} \quad (3.3)$$

$$P_0 = \left(\sum_{n=0}^{c-1} \frac{(c\rho)^n}{n!} + \frac{(c\rho)^c}{c!} + \frac{1}{1-\rho} \right)^{-1} \quad (3.4)$$

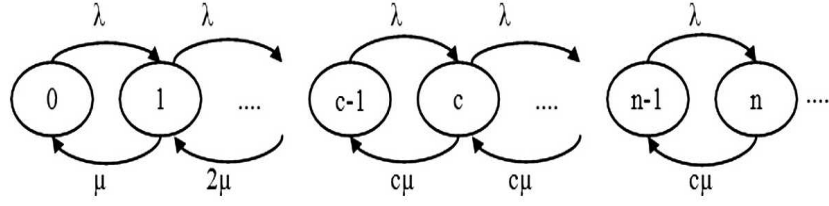


Figure 3.5: State diagram.

The probability that a request has to wait is defined in Eq.3.5:

$$\begin{aligned}
 P_{\text{queuing}} &= P_c + P_{c+1} + P_{c+2} + \dots + P_m \\
 &= \frac{P_c}{1 - \rho} \\
 &= \frac{(c\rho)^c}{c!} \left((1 - \rho) \sum_{n=0}^{c-1} \frac{(c\rho)^n}{n!} + \frac{(c\rho)^c}{c!} \right)^{-1}
 \end{aligned} \tag{3.5}$$

From the equilibrium probabilities, the mean queue length with respect to time is obtained by Eq.3.6:

$$E(L^q) = P_{\text{queuing}} \frac{\rho}{1 - \rho} \tag{3.6}$$

and then average waiting time in the queue with respect to number of vehicle is defined from *Little's law* in Eq.3.7:

$$E(W) = P_{\text{queuing}} \frac{1}{1 - \rho} \frac{1}{c\mu} \tag{3.7}$$

However, we observed the following situations with the queuing model. Firstly, when the satisfaction ratio increases, the number of channel switching also increases 12% in queuing model when compared with the without queuing approach. Secondly, in particular, in a high traffic density, more vehicles spent more time to serve in the network and the opportunity to access the channels cannot be achieved in the end of the transmission range of RSU. Therefore, without queuing approach can also be considered to model the system.

3.2.5 Channel Utilization Table

We modeled each channel for each vehicle by creating utilization table. When a new vehicle comes into the transmission range of a RSU, it defines communication request. The information of available channels is collected and stored by RSU. According to these requests and information of channel usage, channel utilization table is derived in RSU as shown in Figure 3.6.

	Time Slots			
Communication Request $R(t)$	no request	requested	no request	requested
Channel Availability $C(t)$	idle	idle	busy	busy
Utilization Table ($[U]_{cxt}$)	N/A	occupied	N/A	N/A

Figure 3.6: Channel utilization table.

When the channel is idle, then the channel can be occupied by a vehicle. It can be formulated by Eq.3.8 as follows:

$$[U_{cxt}] = \begin{cases} 1, & R(t) = 1, C(t) = 0 \\ 0, & otherwise \end{cases} \quad (3.8)$$

where $[U_{cxt}]$ is utilization matrix for each vehicle, $R(t)$ and $C(t)$ represent communication request and channel availability, respectively.

Then, channel utilization ratios are calculated for each vehicle in Eq.3.9 as follows:

$$U_{c_i}^m = \frac{\sum_{j=1}^t [U]_{c_i}^m}{t} \quad \forall i \in [1, 2, \dots, c], \forall j \in [1, 2, \dots, t] \quad (3.9)$$

where $U_{c_i}^m$ is utilization ratio of channel i for vehicle m , $c_i \in c$ and $[U]_{c_i}^m$ is the utilization matrix of i^{th} channel for vehicle m .

After obtaining the utilization table for each vehicle by RSU, each vehicle decides a channel selection algorithm according to these channel utilization table to maintain connectivity with the minimal channel switching and determine best available channels.

3.2.6 Channel Selection Algorithms

We defined six novel dynamic channel selection algorithms (multi-channel and single channel selection) to maintain network connectivity. We define two main communication performance parameters and then elaborated them with different traffic densities.

- Satisfaction ratio, ξ : Total usage ratio of channels with respect to proposed channel selection algorithms.
- The number of channel switching, χ : The total number of channel switching throughout entire communication period.

In this module, our aim is to maximize satisfaction ratio while minimizing the number of channel switching with the proposed algorithms.

Algorithm 1 is based on multiple channel selection approach by maintaining maximum connectivity with maximum channel switching. In Algorithm 1, vehicles switch to another suitable channel whenever channel is detected as unavailable and all idle time slots are used to obtain maximum satisfaction ratio resulting with frequent channel switching.

Algorithm 1 Connectivity Maximization

Require: $[U]_{cxt}$
Ensure: ξ, χ
Temp. Variables: $\gamma, \Psi, C, C_{index}$

- 1: $\xi, \chi \leftarrow 0$
- 2: **for** $i \leftarrow 1$ to m **do**
- 3: **for** $j \leftarrow 1$ to c **do**
- 4: $\gamma \leftarrow$ Specify beginning index of consecutive available and unavailable transmission periods corresponding to $[U]_{cxt}$
- 5: **end for**
- 6: **end for**
- 7: **for** $i \leftarrow 1$ to m **do**
- 8: **for** $j \leftarrow 1$ to c **do**
- 9: Eliminate unavailable intervals in γ and $[U]_{cxt}$
- 10: **end for**
- 11: **end for**
- 12: **for** $i \leftarrow 1$ to m **do**
- 13: **while** true **do**
- 14: **for** $j \leftarrow 1$ to c **do**
- 15: $\Psi \leftarrow$ Calculate consecutive available transmission periods according to γ and $[U]_{cxt}$
- 16: $C \leftarrow \max \{\Psi\}$
- 17: $C_{index} \leftarrow$ beginning index of selected C
- 18: **end for**
- 19: **for** $i \leftarrow 1$ to m **do**
- 20: **if** no vehicle is using the channel in the specified time slots **then**
- 21: Wait until next slot
- 22: **end if**
- 23: $\xi \leftarrow \xi \cup \{C\}$
- 24: $\chi \leftarrow \chi \cup \{C_{index}\}$
- 25: **end for**
- 26: **end while**
- 27: **end for**

Each vehicle determines the beginning indices of available and unavailable transmission periods in its utilization table as shown in the example Figure 3.7 and calculates consecutive available transmission intervals. Here, 1 and 0 values represent available and unavailable transmission interval in utilization table, respectively. The beginning indices of consecutive 1 and 0 values for each channel are specified as shown in Figure 3.7. Indices represent the time slots. Then, available transmission intervals are only considered such that unavailable transmission periods and their indices are eliminated. This process enables to calculate the amount of consecutive available transmission periods.

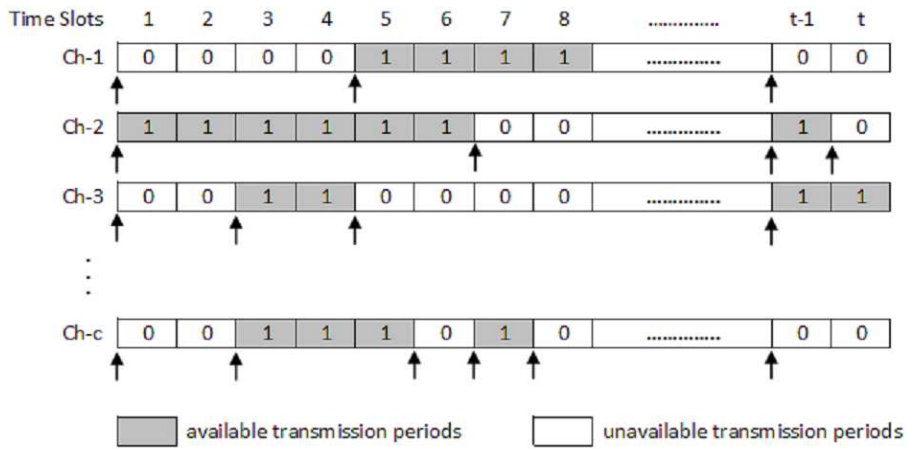


Figure 3.7: Consecutive available and unavailable transmission periods and indices in utilization table.

At the end of the each transmission period, available channels are determined and then a large amount of transmission interval is selected for the next channel switching. Every selection is based on higher utilization in order to minimize channel switching. If there is no available channel in a specified time slot, vehicle has to wait until next slot. The process is repeated in each channel switching. Satisfaction ratio and number of channel switching are calculated in the end of the algorithm.

In proposed system models, we also evaluated the results which include single channel selection as given in Algorithms 2, 3 and 4.

Vehicles use the same channel throughout all communication period after selecting to use a channel. When a channel is unavailable for a vehicle, vehicle waits for same channel to transmit until channel is available. Due to the usage of only one channel, channel selection is the more significant than multi channel operations.

Channel utilization ratios, $U_{c_i}^m$, are calculated for each vehicle as given in Eq.3.9. In Algorithm 2, each vehicle selects a channel that has maximum utilization ratio throughout entire communication period in order to utilize the channel as long as possible. However, if the number of vehicle is higher than the number of channels, all vehicles cannot be access the channels.

Algorithm 2 Maximum Channel Utilization Ratio

Require: $U_{c_i}^m$
Ensure: ξ, χ

```

1: for  $i \leftarrow 1$  to  $\min\{m, c\}$  do
2:   Select vehicles randomly until  $m$ 
3:    $\xi \leftarrow \max\{U_{c_i}^m\}$ 
4:   if  $m > c$  then
5:      $\xi \leftarrow 0$  for vehicles which has not chosen
6:      $\chi \leftarrow 0$ 
7:   end if
8:    $\chi \leftarrow 1$ 
9: end for

```

In Algorithm 3, vehicles check their utilization tables until obtaining initial channel that is available. Then vehicles randomly select a channel among available channels in this time slot and this channel is used throughout all communication periods.

Algorithm 3 Checking Channel Utilization Table

Require: $[U]_{cxt}, U_{c_i}^m$
Ensure: ξ, χ

Temp. Variables: t', γ

```

1: for  $i \leftarrow 1$  to  $\min\{m, c\}$  do
2:   for  $j \leftarrow 1$  to  $t$  do
3:      $t' \leftarrow$  Check the channel availability status
4:     if  $t'$  is not empty then
5:       Select a channel index,  $\gamma$ , randomly among available channels
6:        $\xi \leftarrow U_{c_i}^m$ 
7:        $\chi \leftarrow 1$ 
8:     end if
9:   end for
10: end for

```

As seen in the example Figure 3.8, 0 and 1 represent the channel availability status. 0 means that channel is unavailable in the specified time slot while 1 means that channel can be occupied by a vehicle. According to Algorithm 3, vehicle i checks its utilization

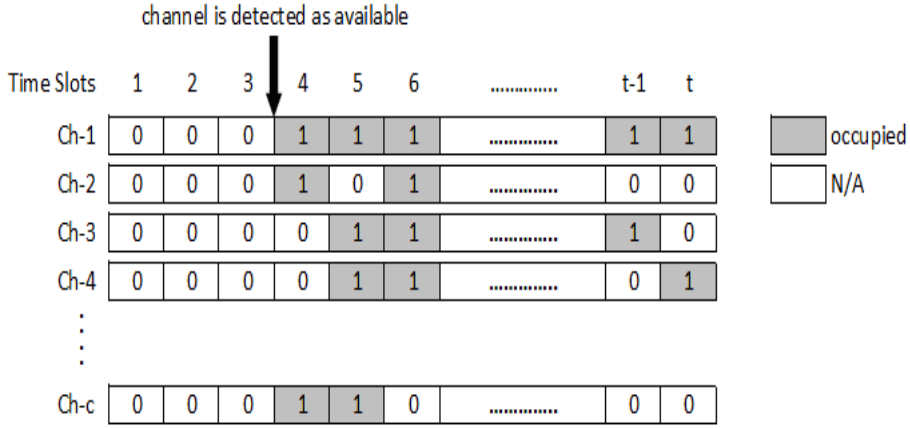


Figure 3.8: The structure of Algorithms 3 and 4.

table by starting from initial time slot. In the 4th time slot, vehicle i detects channels 1, 2 and c as available and selects one of them randomly.

In Algorithm 4, vehicles check their utilization tables until obtaining initial channel that is available similar to Algorithm 3. The only difference from Algorithm 3, after vehicle detects channels as available at a time, it selects a channel that has maximum utilization ratio among available channels.

As we shown in Figure 3.8, vehicle i selects the channel with maximum utilization ratio among channels 1, 2 and c.

Algorithm 4 Checking Channel Utilization Table by Selecting Maximum Channel Utilization Ratio

Require: $[U]_{cxt}, U_{c_i}^m$
Ensure: ξ, χ
 Temp. Variables: t', γ

- 1: **for** $i \leftarrow 1$ to $\min\{m, c\}$ **do**
- 2: **for** $j \leftarrow 1$ to t **do**
- 3: $t' \leftarrow$ Check the channel availability status
- 4: **if** t' is not empty **then**
- 5: Select a channel index, γ , that has max utilization ratio among available channels
- 6: $\xi \leftarrow U_{c_i}^m$
- 7: $\chi \leftarrow 1$
- 8: **end if**
- 9: **end for**
- 10: **end for**

Algorithms 5 and 6 are based on multiple channel selection similar to Algorithm 1 and proposed to avoid frequent channel switching in Algorithm 1.

Therefore, in Algorithm 5, at first, Algorithm 1 is run to obtain satisfaction matrix and the number of channel switching so that total amount of transmission periods in satisfaction matrix is calculated in each channel switching. With the help of obtaining these transmission intervals in each channel switching, the mean of all periods is calculated to compare with each transmission period. If the amount of transmission period is lower than the mean value, this transmission period is eliminated to decrease channel switching. We can expect that, while decreasing number of channel switching, satisfaction ratio is also decreased. However, we observe that satisfaction ratio and number of channel switching are optimized by conserving full network connectivity.

As an example, Figure 3.9 shows the satisfaction matrix of vehicle i and transmission periods in each channel switching. At first, vehicle i accesses to channel 2 at initial 3 time slots, then switches to channel 1 and accesses this channel at 4^{th} time slot and then again switches to another channel depending on network conditions. Mean of these transmission periods in each channel switching is calculated and then according to mean transmission period, it is determined whether to use or not.

Algorithm 5 Optimization Between Satisfaction Ratio and Channel Switching

Require: $[U]_{cxt}$
Ensure: ξ, χ
Temp. Variables: γ, ε, μ

- 1: Run Algorithm 1 and obtain the satisfaction matrix $[\xi]$ number of channel switching, χ in Algorithm 1
- 2: **for** $i \leftarrow 1$ to m **do**
- 3: $\gamma \leftarrow$ Specify beginning indices of transmission periods in $[\xi]$
- 4: $\varepsilon \leftarrow$ Calculate transmission period in each channel switching according to γ
- 5: **end for**
- 6: **for** $i \leftarrow 1$ to m **do**
- 7: **for** $j \leftarrow 1$ to c **do**
- 8: $\mu \leftarrow$ Calculate the mean of transmission periods
- 9: **if** $\varepsilon < \mu$ **then**
- 10: $\varepsilon \leftarrow 0$
- 11: $[\xi] \leftarrow$ Update satisfaction matrix according to ε
- 12: $\chi \leftarrow \chi - 1$
- 13: **end if**
- 14: **end for**
- 15: **end for**

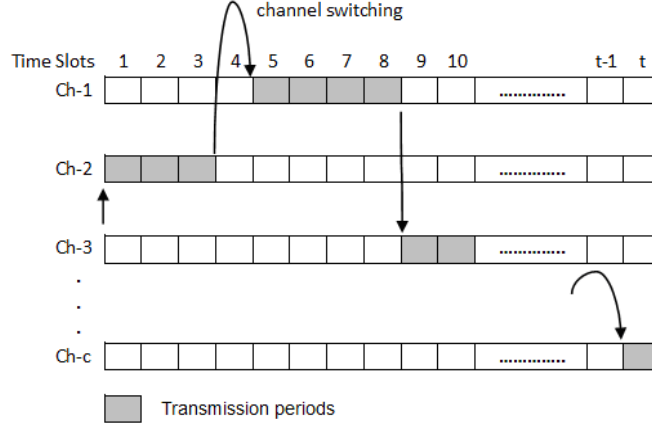


Figure 3.9: The structure of Algorithms 5 and 6.

Unlike the other proposed algorithms, the number of channel switching is assigned by each vehicle in the beginning of Algorithm 6. Then, depending on assigned number, vehicles switch the channel by starting from maximum transmission period.

The first step in Algorithm 6 is similar to Algorithm 5 as shown in Figure 3.9. Therefore, Algorithm 1 is run again to obtain satisfaction matrix and the number of channel switching so that transmission periods in each channel switching can be calculated. Then calculated transmission periods are sorted in a descending order and selected maximum transmission periods in each channel switching until assigned number of channel switching.

Algorithm 6 Assigning Number of Channel Switching by Vehicles

Require: $[U]_{cxt}, \chi'$
Ensure: ξ, χ
 Temp. Variables: γ, ε

- 1: **for** $i \leftarrow 1$ to m **do**
- 2: Assign the number of channel switching, χ'
- 3: **end for**
- 4: Run Algorithm 1 and obtain the satisfaction matrix $[\xi]$ number of channel switching, χ in Algorithm 1
- 5: **for** $i \leftarrow 1$ to m **do**
- 6: $\gamma \leftarrow$ Specify beginning indices of transmission periods in $[\xi]$
- 7: $\varepsilon \leftarrow$ Calculate transmission period in each channel switching according to γ
- 8: **end for**
- 9: **for** $i \leftarrow 1$ to m **do**
- 10: **for** $j \leftarrow 1$ to c **do**
- 11: sort ε values in descending order
- 12: select maximum ε values in order until χ'
- 13: $[\xi] \leftarrow$ Update satisfaction matrix according to ε
- 14: **end for**
- 15: **end for**

3.3 Simulation Results

In this section, we evaluate the performance of the proposed six dynamic channel selection algorithms in terms of network connectivity. The results of the proposed algorithms and all system modules are obtained using MATLAB environment. We consider two different approaches which are with queue and without queue. Moreover, we obtain the results with different traffic densities, low, medium and high. The number of vehicles varies between 1–10, 10–15 and 15–20 in low, medium and high traffic densities, respectively. The parameters used in the simulation are shown in Table 3.2.

We use a VDSANs with one RSU and between 1 and 20 vehicles with variable velocity between 10 and 20 m/s. Moreover, the movement of vehicles is considered normally distributed zero mean and unit variance. We assume that all vehicles are registered and connected to RSU when they come into its transmission range.

A total number of 10 channels are divided into 1000 time slots and vehicles opportunistically access to channels by utilizing channel utilization table which is derived by RSU.

We compare the proposed algorithms in terms of satisfaction ratio and the number of channel switching according to two different approaches and the results highlight with these approaches:

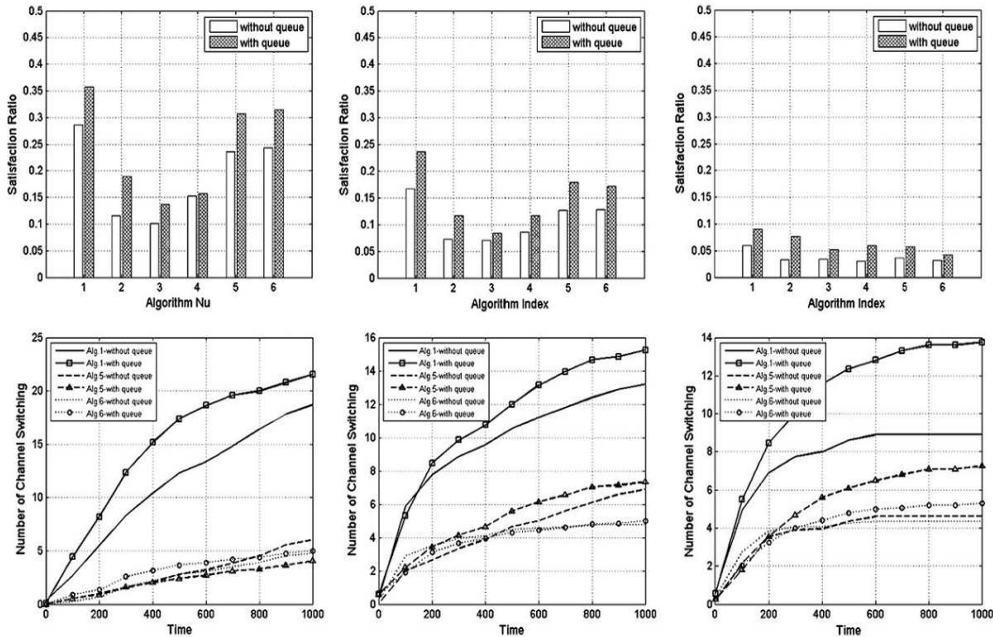
- Without queue: In the first approach, we consider communication requests in each time slot separately. When a vehicle needs to access a channel at a time, available channels are determined spontaneously at this specific time period. However, if there is no available channel, communication requests are dropped. Moreover, when more vehicles detect the same channel as available, one of the vehicles is randomly selected and the other communication requests are also dropped.
- With queue: In this approach, we model the communication requests with M/M/m queuing model. If there is no available channel for communication requests at a time, requests are waited in the queue to serve next slots.

Table 3.2: Simulation parameters for connectivity modeling.

Parameter	Value
Transmission range of a RSU, α	5000m
Velocity of vehicles, v'	10-20 m/s
Number of channels, c	10
Number of vehicles, m	1-20
Total number of time slot, t	1000

In this respect, Figure 3.10 shows the relationship between satisfaction ratio and number of channel switching depending on traffic density. With queuing approach, more connectivity is achieved for vehicles in each traffic density. We enhance the connectivity 26% with queuing model. However, while enhancing connectivity, number of channel switching also increases 12% with queuing model. In particular, we observe that maintaining connectivity is more challenging in high traffic density.

Moreover, the satisfaction ratios of Algorithms 2, 3 and 4 are less than the other algorithms due to the usage of only one channel. Algorithm 1 enables to maximum connectivity resulting with frequent channel switching. While the number of channel switching decreases in Algorithms 5 and 6, the satisfaction ratios are also decreased. However, simulation results show that satisfaction ratio and number of channel switching are optimized by conserving full network connectivity in Algorithms 5 and 6.

**Figure 3.10:** Satisfaction ratio and the number of channel switching w.r.t. low, medium and high traffic density, respectively.

It is clearly showed that the performance of the queuing model enables higher utilization. However, queuing approach causes waiting time in the queue. Figures 3.11 and 3.12 show the performance of each traffic density in terms of queue length and waiting time, respectively.

Figure 3.11 shows the queue length over the simulation time. Queue length is the number of vehicles waiting in the queue to serve. Due to the limited number of channels and also channel status (available or unavailable), a limited number of vehicles serves at a time in each traffic density. When the traffic density increases, average number of vehicles waiting in the queue increases. Specifically, in a high traffic density, a large amount of vehicles need to wait more time before being served.

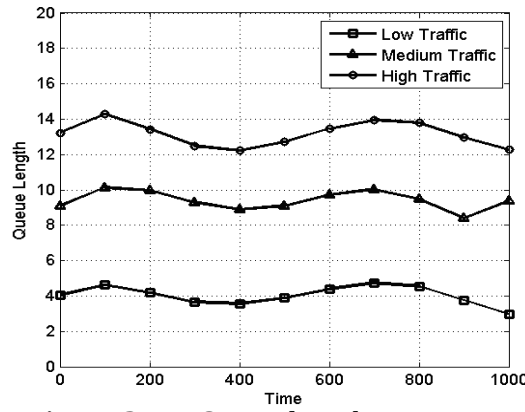


Figure 3.11: Queue length w.r.t. time.

Figure 3.12 shows the time spent waiting depending on number of vehicles. When the number of vehicles increases, time spent waiting before being served increases for each vehicle. In particular, in medium and high environment, more vehicles will spend more time in the queue due to the traffic density.

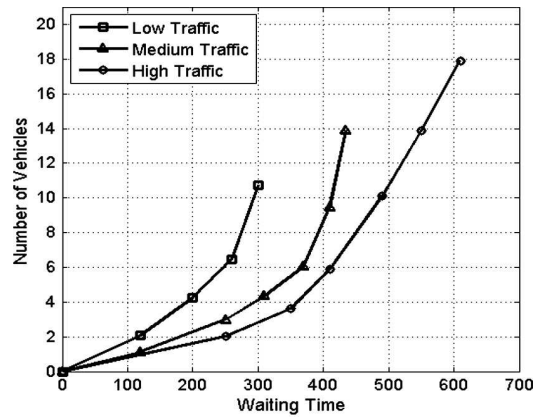


Figure 3.12: Waiting time w.r.t. number of vehicles.

3.4 Summary

In this chapter, we analyze and model network connectivity in VDSANs. We propose a robust and continuous connectivity maintenance system between RSU and vehicles in terms of satisfaction ratio and number of channel switching. We design six dynamic channel selection algorithms. Queuing model is analyzed to enhance connectivity and also queue length and waiting time of vehicles are evaluated in simulation environment. We observe in the proposed algorithms that multi-channel selection can significantly improve the network performance when compared with single-channel selection. Simulation results show that there is a significant relationship between satisfaction ratio and the number of channel switching to maintain connectivity and connectivity can be enhanced 26% with a queuing model and the proposed dynamic channel selection algorithms.

4. RELIABILITY MANAGEMENT

Vehicular applications intensively use broadcast vehicular communication and reliability is the main performance limiting factor in vehicular networks. However, in IEEE 802.11p based broadcast vehicular communications, there are no traditional RTS/CTS handshaking and acknowledgment mechanisms to guarantee a reliable communication. Hence, hidden terminal problem, transmission collisions and also channel fading arise as main communication challenges in vehicular networks and all these challenges dramatically reduce the reliability of broadcast vehicular communication. Therefore, in this chapter, we propose a novel power calibration model consisting of Kriging spatial interpolation method that RSU determines the potential hidden vehicles in the vehicular network topology. Then by calibrating transmission power of hidden vehicles, a dynamic communication range, named as hidden terminal radius, is obtained. This enables to enhance reliability by preventing aforementioned challenges in vehicular networks.

4.1 Network Architecture and Assumptions

In vehicular network topology, we consider one single RSU with N vehicles within its transmission range for DSRC broadcast messages over CCH. In this topology, each vehicle registers to RSU whenever they come into the transmission range of it. Then depending on distance between vehicles, they can communicate with each other, which is represented with a connectivity matrix. All informations of vehicles including position, speed, direction, distance between transmitter and receiver, are stored in RSU.

In this section, we make some trivial assumptions to model vehicular network topology so that we can build a more accurate and efficient model to track the hidden terminal radius depending on transmission power. These assumptions are as follows:

- Vehicles are equipped with OBU and GPS to share information of their position, speed and direction with the other nearby vehicles and RSU.

- Vehicles are located on a 2D urban vehicular environment, which are distributed according to Poisson distribution with traffic density β .
- At initial situation of simulation, all vehicles have equal transmission range and transmission power.

4.2 System Model

In this work, our main objective is to establish a reliable communication and enhance the reliability of broadcast vehicular communication by proposing an analytical model implemented into RSUs. We consider a centralized network topology between RSU and vehicles.

To calculate hidden terminal radius of hidden vehicles, we focus on signal power since the degradation of signal strength occurs depending on long distances between vehicles. Therefore, signal attenuation and interference effect the communication range and communication duration. The proposed system model as seen in Figure 4.1 is implemented into RSU and each module is modeled as follows.

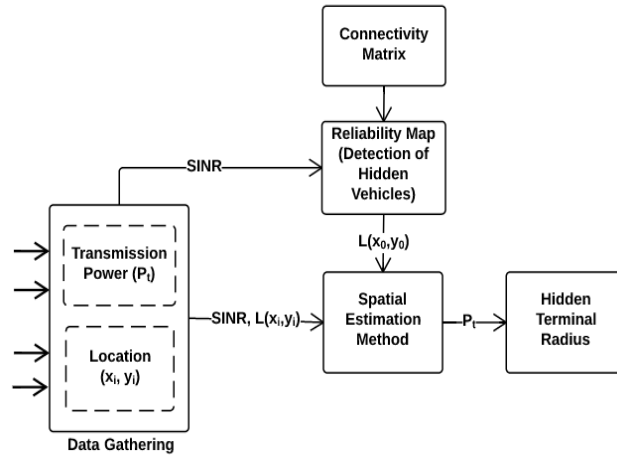


Figure 4.1: Proposed system model.

4.2.1 Connectivity Matrix

We create a connectivity matrix by determining trade-off between vehicles. A communication link between vehicles (v_i, v_j) may exist if the Euclidean distance between vehicles v_i and v_j is less than or equal to transmission range as specified in IEEE 802.11p standard.

$$[C]_{N \times N} = \begin{cases} 1, & \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \leq R \\ 0, & \text{otherwise} \end{cases} \quad (4.1)$$

where (x_i, y_i) is the position of vehicle v_i and R is the transmission range which is initially defined as static for all vehicles. $[C]_{N \times N}$ represents the connectivity matrix.

4.2.2 Data Gathering

In this analysis, we use a 2D vehicular network model and we assume that all vehicles broadcast their status messages to RSU which is obtained via GPS periodically. Therefore, the performance of vehicular network topology depends on the Signal-to-Interference-and-Noise Ratio (SINR) level at the hidden vehicles.

Hence, first signal power is analyzed to our proposed model over the communication channel. Therefore, RSU calculates SINR level, denoted as $Z^0(t, x_i, y_i)$ for all vehicles at different positions in order to estimate the quality of the link as given in Eq.4.2.

$$SINR = Z^0(t, x_i, y_i) = \frac{P_t}{I + P_n} \quad \forall i \in N \quad (4.2)$$

where P_t and I are the transmission power and the received interference power within the range of each vehicle respectively, P_n is the noise power and N is the number of vehicles.

In this work, we use Nakagami-m channel model to reflect many fading condition in a wireless channel. The probability density function (PDF) of signal power, P_r , for Nakagami-m fading channel [17] can be defined in Eq.4.3:

$$Pdf(P_r) = \frac{2m^m P_r^{2m-1}}{\Omega^m \Gamma(m)} \exp\left(-\frac{mP_r^2}{\Omega}\right) \quad (4.3)$$

where the channel amplitude $P_r \geq 0$, $\Omega = E(P_r^2)$ is average fading power, $E(.)$ is the expectation operator and $\Gamma(.)$ is gamma function. The parameter m expresses the severity of the fading as described in Eq.4.4.

$$m = \frac{(E(P_r^2))^2}{Var(P_r^2)} \quad (4.4)$$

SINR level and also position of vehicles are given as input to the spatial estimation method and reliability map module as seen in Figure 4.1.

4.2.3 Reliability Map

This module analyzes the connectivity matrix by calculating the Euclidean distances between vehicles and creates a reliability map in order to determine potential hidden vehicles in the topology as given in the following algorithm.

Algorithm 7 Reliability Map Creation to Detect the Hidden Vehicles

Require: $[C]_{N \times N}, R, Z^0(t, x_i, y_i), d v_i, v_j, v_k$ Ensure: v_{hidden} <pre> 1: for $i \leftarrow 1$ to N do 2: Choose a vehicle i such that 3: $\{(v_i, v_j) \leftarrow 1 \wedge (v_i, v_k) \leftarrow 1\} \subset [C]_{N \times N}$ 4: $\{(v_j, v_k) \leftarrow 0\} \subset [C]_{N \times N}$ 5: $R_I \leftarrow (Z^0(t, x_i, y_i))^{1/\ell} R$ 6: Check $(v_j \wedge v_k) \subset R_I$ 7: if v_j and v_k transmit to v_i at the same time, and $d v_i, v_j \geq d v_i, v_k$ then 8: $v_{hidden} \leftarrow v_j$ 9: else 10: $v_{hidden} \leftarrow v_k$ 11: end if 12: return v_{hidden} 13: end for </pre>
--

This algorithm finds hidden terminals that are two nodes which are outside the interference range of each other but within the transmission range of a set of terminals as given in line 2-6. Here, interference range, R_I , is defined in line 5. Then, in order to adjust transmission range of hidden terminals, one of the discovered hidden terminals is selected by comparing distances between receiver and broadcast sender as seen in line 7-11. The terminal, which is farthest away from receiver is assigned and its transmission power is calibrated in the proposed spatial estimation method.

We assume that all vehicles have same transmission range and transmission power at initial situation. Therefore we use the interference model in [40]. Therefore a vehicle can interfere if and only if the following condition is satisfied as given in Eq.4.5.

$$P_j d|v_k - v_i|^\ell > Z^0(t, x_i, y_i) P_k d|v_j - v_i|^\ell \quad (4.5)$$

Since the transmission power of vehicle j and vehicle k are equal to each other, the equation can be expressed as follows:

$$d|v_k - v_i| \leq (Z^0(t, x_i, y_i))^{1/\ell} R \quad (4.6)$$

where ℓ is the path-loss exponent and R is the transmission range. $d|v_k - v_i|$ represents to distance between transmitter and receiver. Here, interference range, R_I , is defined as $(Z^0(t, x_i, y_i))^{1/\ell} R$.

Then we define a reliability coefficient, ρ , as performance parameter as follows:

$$\rho^{802.11p} = \frac{d|v_k - v_i|}{\sum_{i=1}^N (Z^0(t, x_i, y_i))^{1/\ell} R} \quad \forall i \in N \quad (4.7)$$

Reliability coefficient is defined as the ratio of distance between transmitter vehicle and receiver vehicle to the SINR level of vehicles and transmission range. This is used for measuring how discovered hidden terminals and calibration of their transmission power effect the correctness of broadcast messages receptions. Here, when traffic density increases, the number of receivers within the senders' transmission range shows an increase depending on distance between receiver and broadcast sender. Vehicles can be obtained more status messages at the different locations in order to utilize in vehicular applications and this helps to reduce the risk of incorrect decision. However, an increasing traffic density will reduce the reception of broadcast messages due to the undiscovered hidden terminals. Hence, one of the critical factors is to detect hidden terminals so that the higher the reliability, the lower the undiscovered hidden terminals. Therefore, an analytical model is derived to evaluate the reliability in terms of transmission power, number of vehicles and distance between transmitter and receiver nodes.

After detecting potential hidden terminals in the vehicular network topology, the positions of hidden terminals are given to the proposed estimation method as an input.

4.2.4 Spatial Estimation Method

We use Ordinary Kriging method as spatial estimation method. Kriging is a interpolation technique which observed values are weighted to estimate the value for an unknown location in geostatistics. Weights are based on the distance between the known locations by estimating spatial distribution of predicted values. We use the distances between vehicles to predict optimum weights. In this module, our aim is to find reliable and accurate amount of transmission power of hidden vehicles so that we can calculate the hidden terminal radius of hidden vehicles.

Ordinary Kriging estimates the weighted linear combinations of the measured data with the aim of minimizing variance of the errors [41]. This method uses semivariogram analysis to determine the spatial correlation of the obtained signals from surrounding nodes. For further information about this method, [41], [42], [43] can be referred.

We will estimate the right amount of transmission power of hidden vehicles using a weighted linear combination of the available data. We assume that there are N vehicle locations $(x_i, y_i; i = 1, \dots, N)$ and a known value $Z^0(t, x_i, y_i)$ at this location (x_i, y_i) . Vehicles are distributed according to Poisson distribution with traffic density β .

To keep the estimate unbiased, we need to decide weight of the nearby vehicles. The Kriging estimator calculates by linear combination of the known values as defined in Eq.4.8.

$$Z^*(t, x_0, y_0) = \sum_{i=1}^N \lambda_i Z^0(t, x_i, y_i) \quad (4.8)$$

where $Z^*(t, x_0, y_0)$ represents SINR level at location (x_0, y_0) of hidden vehicle at time t . Weight, λ_i , is the Kriging coefficient and $\sum_{i=1}^N \lambda_i = 1$ for unbiasedness. However, this unbiasedness condition does not give any information about how to determine the weights. Therefore, mean squared error (MSE) is minimized in order to obtain optimum weights as defined in Eq.A.1 of Appendix. The obtained general formulas are given as follows:

$$\begin{aligned} \sum_{j=1}^N \lambda_j \gamma(h_{i,j}) + \mu &= \gamma(h_{i,0}) \quad \forall i \in N \\ \sum_{i=1}^N \lambda_i &= 1 \end{aligned} \quad (4.9)$$

This system of equations can be written in a matrix notation as follows:

$$\gamma(h_{i,j}) \lambda_i = \bar{\gamma}(h_{i,0}) \quad (4.10)$$

Matrix form in Eq.4.11 is used to determine optimal weights in order to satisfy conditions in Eq.4.9.

$$\begin{pmatrix} \gamma(h_{1,1}) & \cdots & \gamma(h_{1,N}) & 1 \\ \gamma(h_{2,1}) & \cdots & \gamma(h_{2,N}) & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \gamma(h_{N,1}) & \cdots & \gamma(h_{N,N}) & 1 \\ 1 & \cdots & 1 & 0 \end{pmatrix} \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_N \\ \mu \end{pmatrix} = \begin{pmatrix} \bar{\gamma}(h_{1,0}) \\ \bar{\gamma}(h_{2,0}) \\ \vdots \\ \bar{\gamma}(h_{N,0}) \\ 1 \end{pmatrix} \quad (4.11)$$

where γ is the semivariogram which is a function of distance between vehicles. Therefore, ordinary Kriging analyzes the estimation problem in terms of distance between vehicles. Semivariogram is used to determine spatial covariance of variables as seen in Eq.4.12.

$$\begin{aligned} \gamma(h_{i,j}) &= \gamma(x_i y_i - x_j y_j) \\ &= \frac{1}{2} E[(Z^0(t, x_i, y_i) - Z^0(t, x_j, y_j))^2] \end{aligned} \quad (4.12)$$

To solve the weights, we multiply Eq.4.10 on the both sides by γ^{-1} and Eq.4.13 is obtained.

$$\begin{aligned} \gamma(h_{i,j}) \lambda_i &= \bar{\gamma}(h_{i,0}) \\ \lambda_i &= \gamma^{-1}(h_{i,j}) \bar{\gamma}(h_{i,0}) \end{aligned} \quad (4.13)$$

In ordinary Kriging, the key approach depends on the selective of semivariogram model. Therefore, most commonly used semivariogram models are analyzed in the proposed model: Exponential model, Gaussian model, Linear model as given in Eqs.4.14, 4.15 and 4.16, respectively:

$$\gamma^{exp}(h_{i,j}) = \begin{cases} 0, & h_{i,j} = 0 \\ C_0 + C_1(1 - \exp(\frac{-3h_{i,j}}{a})), & h_{i,j} > 0 \end{cases} \quad (4.14)$$

where C_0 is the nugget effect, which provides a discontinuity at the origin. The semivariogram value at the origin should be zero in theory ($C_0=0$). a is the range which represents covariance value as constant at a time which the longest Euclidean distance between vehicles. $C_0 + C_1$ is called as sill value, which represents the variogram value for very large distances.

$$\gamma^{gauss}(h_{i,j}) = \begin{cases} 0, & h_{i,j} = 0 \\ C_0 + C_1(1 - \exp(\frac{-3h_{i,j}^2}{a^2})), & h_{i,j} > 0 \end{cases} \quad (4.15)$$

and,

$$\gamma^{lin}(h_{i,j}) = \begin{cases} 0, & h_{i,j} = 0 \\ C_0 + C_1 a h_{i,j}, & h_{i,j} > 0 \end{cases} \quad (4.16)$$

After weight λ_i^{exp} is calculated for exponential semivariogram model by inserting Eq.4.14 into Eq.4.13, the spatially estimated SINR of hidden vehicle at location (x_0, y_0) , can be expressed as follows:

$$Z^{exp}(t, x_0, y_0) = \sum_{i=1}^N \lambda_i^{exp} Z^0(t, x_i, y_i) \quad \forall i \in N \quad (4.17)$$

After weight λ_i^{gauss} is calculated for Gaussian semivariogram model by inserting Eq.4.15 into Eq.4.13. The spatially estimated SINR of hidden vehicle at location (x_0, y_0) , can be expressed as follows:

$$Z^{gauss}(t, x_0, y_0) = \sum_{i=1}^N \lambda_i^{gauss} Z^0(t, x_i, y_i) \quad \forall i \in N \quad (4.18)$$

After weight λ_i^{lin} is calculated for linear semivariogram model by inserting Eq.4.16 into Eq.4.13. The spatially estimated SINR of hidden vehicle at location (x_0, y_0) , can be expressed as follows:

$$Z^{lin}(t, x_0, y_0) = \sum_{i=1}^N \lambda_i^{lin} Z^0(t, x_i, y_i) \quad \forall i \in N \quad (4.19)$$

Then we calculate the reliability coefficient in Eq.4.7 for Exponential model, Gaussian model and Linear model after the spatially estimated SINR is obtained as given in Eqs.4.17, 4.18 and 4.19. These are expressed respectively by the Eqs.4.20, 4.21 and 4.22 as follows:

$$\rho^{exp} = \frac{d|v_k - v_i|}{\sum_{i=1}^N (Z^{exp}(t, x_0, y_0))^{1/\ell} R} \quad (4.20)$$

$$\rho^{gauss} = \frac{d|v_k - v_i|}{\sum_{i=1}^N (Z^{gauss}(t, x_0, y_0))^{1/\ell} R} \quad (4.21)$$

and

$$\rho^{lin} = \frac{d|v_k - v_i|}{\sum_{i=1}^N (Z^{lin}(t, x_0, y_0))^{1/\ell} R} \quad (4.22)$$

Moreover, the main characterization of vehicular networks is vehicular mobility and its main parameters are velocity and direction. Therefore, this is an another reason to select Kriging estimation method since the proposed spatial estimation method enables to a semi-isolated mobility model. It means that we only consider the distance between vehicles as a function of velocities of vehicles and we neglect direction of vehicles. The reason of this can be explained as follows: we observe that the covariance between data values at any two vehicle locations depends only the distance between them and not on the direction. Therefore, our proposed model supports two main characteristics of vehicular networks: 2D urban vehicular environment and mobility model.

4.2.5 Hidden Terminal Radius

We determine hidden terminal radius by obtaining the right amount of transmission power of hidden vehicles with the proposed model in order to avoid hidden terminal problem. After detecting potential hidden vehicles in the topology, instead of assigning a static transmission range, we calculate a dynamic hidden terminal radius while minimizing adverse effects of hidden vehicles. Moreover, we take the advantages of power saving by calibrating transmission power and maximizing network reliability.

Adjusting a dynamic hidden terminal radius mitigates interference occurred due to high transmission power. Especially, because of the rapidly changes in vehicular network topology, assigning a dynamic hidden terminal radius depending on traffic density directly effects the network connectivity and also duration time of connection between vehicles.

In the proposed model, RSU determines the right amount of transmission power of hidden vehicles by collecting network information as defined in the previous sections. Then, the theoretical hidden terminal radius, r_{hidden} , can be calculated by using *free space loss* equation as given in Eqs.4.23, 4.24 and 4.25, respectively.

$$r_{hidden}^{exp} = 10^{\frac{\sum_{i=1}^N (\lambda_i^{exp} (Z^0(t, x_i, y_i)) (I + P_h) - P_r + G_t + G_r - 20 \log_{10}(\frac{c}{4\pi})) - 20}{20}} \quad (4.23)$$

$$r_{hidden}^{gauss} = 10^{\frac{\sum_{i=1}^N (\lambda_i^{gauss} (Z^0(t, x_i, y_i)) (I + P_h) - P_r + G_t + G_r - 20 \log_{10}(\frac{c}{4\pi})) - 20}{20}} \quad (4.24)$$

$$r_{hidden}^{lin} = 10^{\frac{\sum_{i=1}^N (\lambda_i^{lin} (Z^0(t, x_i, y_i)) (I + P_h) - P_r + G_t + G_r - 20 \log_{10}(\frac{c}{4\pi})) - 20}{20}} \quad (4.25)$$

where G_t and G_r are antenna gains of transmitter and receiver, respectively, c is the speed of light, f_c is the carrier frequency.

The steps of adjusting communication range of hidden vehicle can be seen in Figure 4.2.

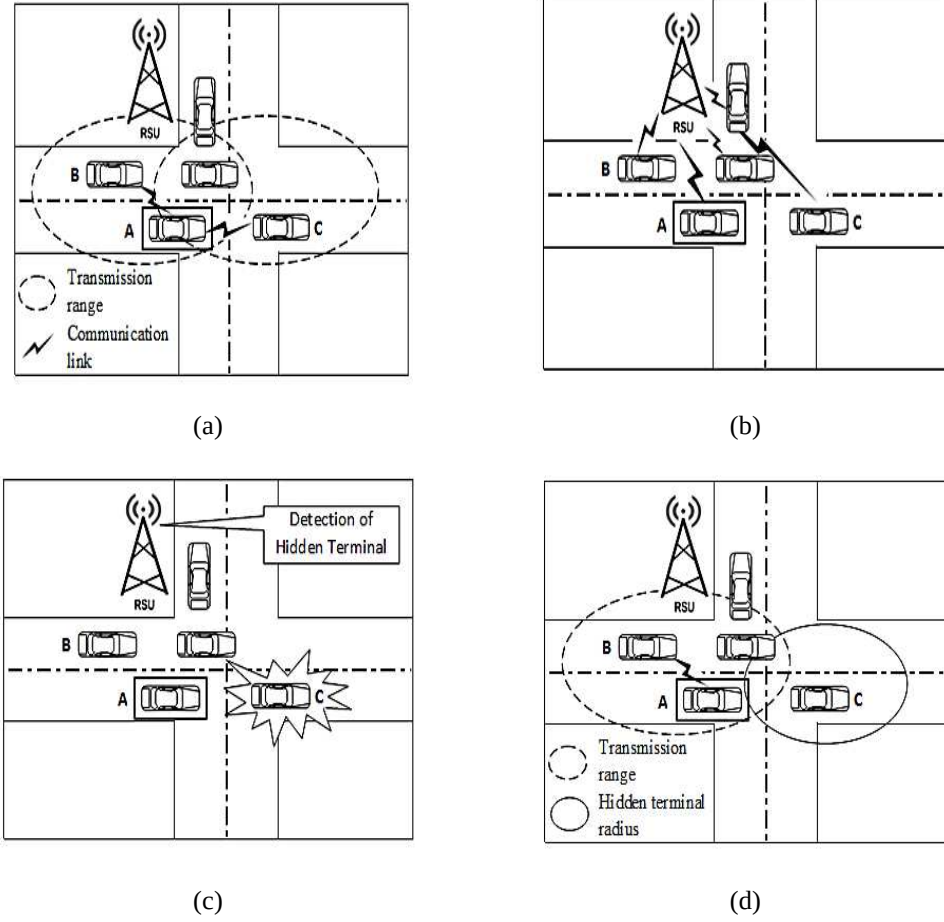


Figure 4.2: The steps of adjusting hidden terminal radius of hidden vehicles. (a) Example hidden terminal problem (b) RSU collects all network information to discover hidden vehicles (vehicles B and C) (c) RSU detects the hidden vehicles within the transmission range of it and selects the vehicle C, which is farthest away from vehicle A, to coordinate its transmission power (d) Example of showing the adjusted hidden terminal radius of hidden vehicle C to prevent hidden terminal problem in the last situation.

4.3 Simulation Results

In this section, we evaluate the performance of the proposed power calibration model with 3 estimation methods which are Exponential Model, Gaussian Model and Linear Model. Kriging spatial interpolation method is used to estimate the reliable and accurate amount of transmission power of hidden vehicles. Depending on obtained transmission power, reliability, hidden terminal radius and distance between transmitter and receiver as performance parameters are analyzed. The simulation results and system modules are applied in MATLAB environment. The parameters used in the simulation are shown in Table 4.1.

Table 4.1: Simulation parameters for reliability analysis.

Parameter	Value
Carrier frequency	5.890 GHz
Bandwidth	10 Mhz
Noise power	-99 dBm
Transmission power	33 dBm
Antenna gains of transmitter and receiver	1
Transmission range	1000m

We consider one single RSU with varying number of vehicles according to traffic density. We define the transmission range as 1000m at initial situation for IEEE 802.11p based broadcast vehicular communication. Then, each hidden vehicle adapts the changing network conditions by adjusting the communication range in order to establish reliable and robust broadcast vehicular communication. Here, RSU plays a significant role by gathering all global and local informations on traffic and road conditions including position, direction, speed, distance between transmitter and receiver. RSU coordinates to each vehicle with the help of power calibration model by proposing some behaviors to vehicles within the transmission range of itself.

The impacts of hidden terminal problem can be reduced with calibration of transmission power. At initial situation of simulation, it is assumed that all vehicles have allocated 33 dBm power in order to use in broadcast message transmission. After deciding to hidden vehicles as explained in the previous sections, vehicles calibrate transmission power with a centralized power control mechanism and adapt

the changing network conditions. This mechanism enables to prevent hidden terminal problem, transmission collisions and channel fading challenges by mitigating interference caused from hidden vehicles.

In this work, reliability is defined as the percentage of discovered hidden terminals that managed to calibrate their transmission power so that the correctness of broadcast messages receptions is analyzed depending on traffic density. Hidden terminal radius is defined as the right amount of communication range of discovered hidden terminals.

In this respect, Figure 4.3 demonstrates the increase of reliability with the proposed power calibration model depending on traffic density. Reliability coefficient is calculated in Eq.4.7 for IEEE 802.11p, then each spatial scheme is evaluated by utilizing Eqs.4.20, 4.21 and 4.22. When compared to current specifications of DSRC, each model guarantees to reach the broadcast messages with a high reliability. More reliable communication is achieved after the right amount of transmission power of hidden vehicles is obtained instead of assigning same transmission power for all vehicles. It is shown that in all cases, low traffic density leads to higher reliability due to the high percentage of discovered hidden terminals. This means that more vehicle access the channel without collision and send their status messages. As seen in Figure 4.3, Exponential model is more accurate in predicting hidden terminals and obtains the highest reliability with increase of 13% when compared to IEEE 802.11p.

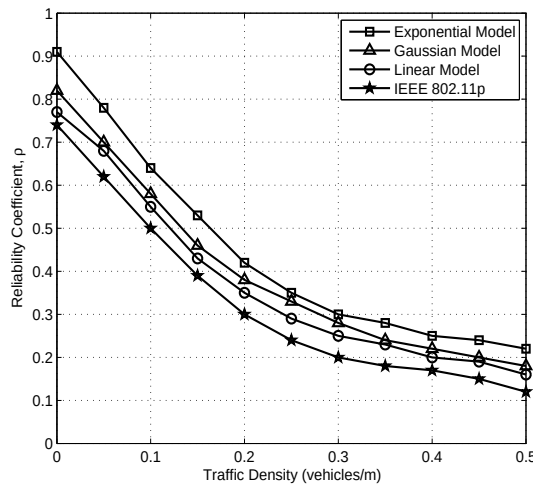


Figure 4.3: Reliability coefficient w.r.t. traffic density (vehicles/m).

Figure 4.4 shows the obtained hidden terminal radius, as given in Eqs.4.23, 4.24 and 4.25, corresponding to traffic density for each model. It is evident that as traffic density increases, hidden terminal radius will decrease. Here, transmission power effects the communication range and high transmission power enables to increase of communication range. However, at the same time, interference occurs by decreasing wireless communication quality. Therefore, Figure 4.4 shows the right amount of communication range depending on traffic density. For example, with a 0.2 traffic density, the optimal hidden terminal radius to guarantee a reliable communication should be adjusted to 250m, 380m, 430m in Exponential, Gaussian and Linear model, respectively.

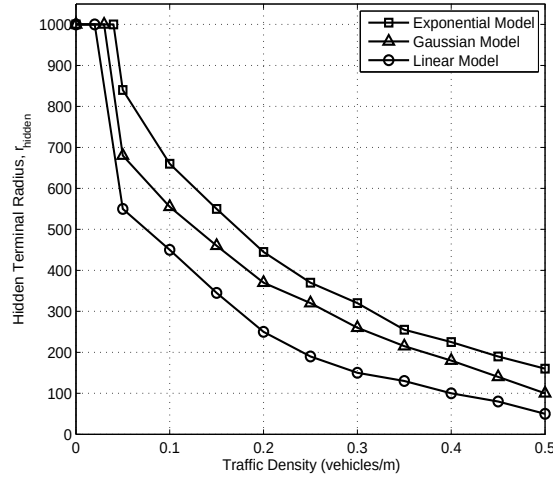


Figure 4.4: Hidden terminal radius w.r.t. traffic density (vehicles/m).

In addition, in Figure 4.5, reliability is analyzed in terms of distance between transmitter and receiver for each estimation method. There is a direct relation between traffic density and the transmission power as explained in Eqs.4.20, 4.21 and 4.22. Here, we consider two analyses, vertical analysis and horizontal analysis.

In vertical analysis, reliability is evaluated in terms of distance between receiver and broadcast sender in each model, separately. From Figure 4.5(a) to Figure 4.5(c), it is clearly showed that as distance between receiver and broadcast sender increases, reliability will decrease in each proposed spatial scheme. The explanation for the observation is that when vehicles move away from each other, they need to increase transmission power in order to obtain information from nearby vehicles and this causes an increase in the coverage area by enabling to access more vehicles. This means that

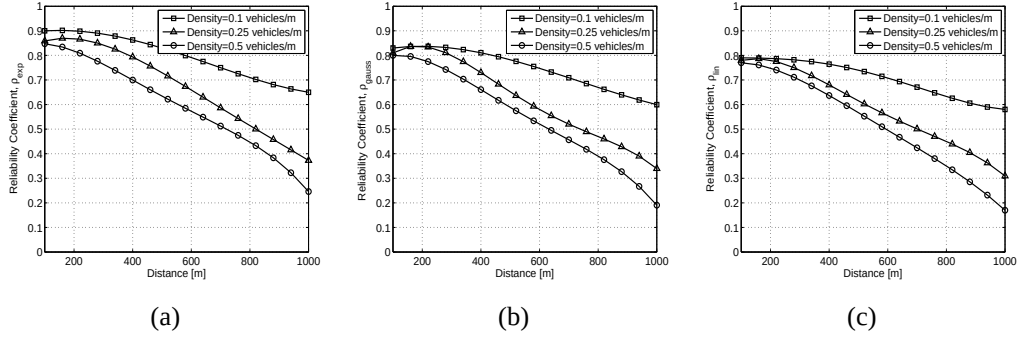


Figure 4.5: The relationship between reliability coefficient and distance between transmitter and receiver depending on traffic density for each model. (a) Exponential model (b) Gaussian model (c) Linear model.

the number of potential hidden vehicles will seriously show an increase by causing degradation of reliability of the vehicular network. For example, when the distance between sender and receiver is 600m, Exponential model obtains 80%, 67% and 58% reliability to send status messages successfully in low, medium and high traffic density (0.1 vehicles/m, 0.25 vehicles/m, 0.5 vehicles/m), respectively. While, in Gaussian model, the ratio of reliability is 75%, 59% and 52%, in Linear model, reliability changes to 71%, 56% and 50% low, medium and high traffic density, respectively. It is clearly showed that low traffic density achieves more reliable broadcast vehicular communication as observed in each model.

In horizontal analysis, we compare to proposed spatial schemes with each other. Exponential model achieves an average of 10% more reliable communication in each traffic density. In this work, semivariogram models are used to determine spatial covariance and we only consider to meet the unbiasedness condition in each model. Here, broadcast senders that far from the receiver significantly impact the reliability and Exponential model slightly better than Gaussian and Linear Model.

4.4 Summary

In this chapter, we present a novel power calibration model implemented into RSUs to enhance reliability of broadcast vehicular communication. In the proposed model, we use Kriging spatial interpolation method by utilizing three spatial schemes, which are Exponential Model, Gaussian Model and Linear Model, to estimate the right amount of transmission power. The challenges of hidden terminal problem, transmission collisions and channel fading are taken into the consideration in the evaluation of

reliability. It is analyzed that how transmission power can be calibrated by considering vehicle informations including position, speed, direction, distance between vehicles. Simulation results show the trade-off among network parameters in terms of reliability coefficient, hidden terminal radius and distance between transmitter and receiver with respect to traffic density. We observe that Exponential model is the most suitable option to achieve more reliable broadcast vehicular communication. Reliability is enhanced an average of 10% with Exponential model in each traffic density.

5. CONCLUSIONS

This thesis presented an overview of network connectivity and reliability in vehicular communication systems. The state of the art and challenges of both were discussed.

With recent advances in online embedded mobile applications, vehicular applications have gained major importance in order to improve traffic safety and efficiency. However, the increasing use of vehicular applications triggered to growing bandwidth requirements. Thus, the limited spectrum resources and the inefficiency in the spectrum usage necessitated a new communication paradigm, called Dynamic Spectrum Access. This key enabling technology provides additional bandwidth to vehicles by enabling to access licensed bands. However, due to the existence of primary users activities, unused spectrum bands should detect, use by defining best channels, share among vehicles and vacate when a primary user is detected. In addition to achieving all these functionalities, high mobility of vehicles, limited transmission range of Road-Side Units, and channel status (busy or idle) cause dynamic topological changes in vehicular networks. Due to these dynamic topological changes, maintaining full connectivity arises as one of the main communication challenge in vehicular networks. Moreover, the high number of channel switching also effects the quality of network connectivity causing an another significant problem in vehicular networks.

First, in this thesis, in order to overcome these challenges, we analyzed the full connectivity provisioning in vehicular networks by proposing six dynamic channel selection algorithms, parameterizing the vehicle satisfaction ratio and the number of channel switching. Specifically, our proposed framework used queuing theory analytics to model the dynamic behaviors of vehicles and obtain high satisfaction ratio of vehicles. Here, we proposed six novel dynamic channel selection algorithms to provide minimal channel switching ratio while conserving the network connectivity. We also compared the results of multi-channel selection and single channel selection.

We observed in the proposed algorithms that multi-channel selection can significantly improve the network performance when compared with single-channel selection. The

thorough evaluations showed that there is a significant relationship between satisfaction ratio and the number of channel switching to maintain connectivity and connectivity was enhanced 26% with our proposed queuing theoretic vehicular dynamic spectrum access networks paradigm.

Second, in this thesis, we also concentrated on the performance evaluation of broadcast vehicular communication. We analyzed the reliability of broadcast messages over control channel for dedicated short range communication.

The efficiency of vehicular applications depends on the reliable exchange of information on time and reliability is the main performance limiting factor in vehicular networks. Vehicles intensively use broadcast communication due to the dramatic changes in spatial and temporal behaviors of the network topology, vehicular mobility and limited communication range. However, in IEEE 802.11p based broadcast vehicular communications, there are no traditional request-to-send/clear-to-send handshaking and acknowledgment mechanism. For this reason, hidden terminal problem, transmission collisions and channel fading arise as main communication challenges in vehicular networks by resulting in degradation of reliability.

Therefore, an analytical model was proposed for reliability evaluation, consisting of analysis, modeling, simulation and assessment. We presented a novel power calibration model implemented into Road-Side Units to enhance the reliability of broadcast vehicular communication. In the proposed model, we used Kriging spatial interpolation method by utilizing three spatial schemes, which are Exponential Model, Gaussian Model and Linear Model. Kriging enables to find an optimal spatial prediction which estimates the unknown values from the observed data. Kriging interpolation method was used to predict the right amount of transmission power of hidden vehicles in vehicular networks. It was analyzed that how transmission power can be calibrated by considering vehicle informations including position, speed, direction, distance between vehicles.

We also defined a novel reliability coefficient to analyze the proposed model depending on distance between vehicles, signal power and transmission range. Here, we defined reliability as how discovered hidden terminals and calibration of their transmission power effect the correctness of broadcast messages receptions. Moreover, our

proposed spatially estimation model consisted of a semi-isolated mobility model by utilizing the distance between vehicles to reflect a realistic vehicular environment and to model highly dynamic vehicular network topology.

Simulation results showed the trade-off among network parameters in terms of reliability coefficient, hidden terminal radius and distance between transmitter and receiver with respect to traffic density. We observed that Exponential model is the most suitable option to achieve more reliable broadcast vehicular communication. Reliability was enhanced an average of 10% with Exponential model in broadcast vehicular communications.

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APPENDIX

APPENDIX : Finding Optimal Weights

APPENDIX

Our goal is to find optimal weights, λ_i , of the nearby vehicles by minimizing MSE so that we can obtain the general formulas in Eq.4.9. To achieve this, we look the following minimization problem.

$$\begin{aligned}
MSE &= E[(Z^*(t, x_0, y_0) - Z(t, x_0, y_0))^2] \\
&= \text{Var}(Z^*(t, x_0, y_0) - Z(t, x_0, y_0)) \\
&= \text{Var}(Z^*(t, x_0, y_0)) + \text{Var}(Z(t, x_0, y_0)) - 2\text{Cov}(Z^*(t, x_0, y_0), Z(t, x_0, y_0)) \\
&= \text{Var}\left(\sum_{i=1}^N \lambda_i Z^0(t, x_i, y_i)\right) + \text{Var}(Z(t, x_0, y_0)) - 2\text{Cov}\left(\sum_{i=1}^N \lambda_i Z^0(t, x_i, y_i), Z(t, x_0, y_0)\right) \\
&= \sum_{i=1}^N \sum_{j=1}^N \lambda_i \lambda_j \gamma(h_{i,j}) + \sigma^2 - 2 \sum_{i=1}^N \lambda_i \gamma(h_{i,0}) \tag{A.1}
\end{aligned}$$

Then we apply the Lagrange multiplier method by adding a new term for constrained optimization problem as given in Eq.A.2.

$$\begin{aligned}
MSE &= \sum_{i=1}^N \sum_{j=1}^N \lambda_i \lambda_j \gamma(h_{i,j}) + \sigma^2 - 2 \sum_{i=1}^N \lambda_i \gamma(h_{i,0}) + 2\mu \left(\sum_{i=1}^N \lambda_i - 1\right) \\
\varphi(\lambda_i, \mu) &= MSE + 2\mu \left(\sum_{i=1}^N \lambda_i - 1\right) \tag{A.2}
\end{aligned}$$

where μ is the Lagrange parameter. In order to minimize the function $\varphi(\lambda_i, \mu)$, we take the derivatives with respect to λ_i and μ , respectively and then equate them to 0 as follows:

$$\frac{\partial \varphi(\lambda_i, \mu)}{\partial \lambda_i} = 0 \tag{A.3}$$

which yields

$$\sum_{j=1}^N \lambda_j \gamma(h_{i,j}) + \mu = \gamma(h_{i,0}) \quad \forall i \in N \tag{A.4}$$

and,

$$\frac{\partial \varphi(\lambda_i, \mu)}{\partial \mu} = 0 \tag{A.5}$$

which yields

$$\sum_{i=1}^N \lambda_i = 1 \tag{A.6}$$

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