

**REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**

**A CROSS-LAYER DESIGN FOR NEXT GENERATION WIRELESS
NETWORKS:V2V PERSPECTIVE**

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**PH.D. THESIS
DEPARTMENT OF COMPUTER ENGINEERING
PROGRAM OF COMPUTER ENGINEERING**

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LIST OF SYMBOLS

n	Field n
\in	Element
$\in \cdot$	Set
\setminus	Difference (set)
\forall	For all (propositional logic)
T	Transmit pulse width
T_W	Transmit window length in time
N	Number of nodes
L	Window length
$f_{t_k}(t)$	PDF of k -th random variable in time
ρ	Overlap region in time
Δt	Difference in time
\mathbf{X}	Minimum of multiple random variables
$\Pr(\{x < \mathbf{X}\})$	Probability of \mathbf{X} being greater than x
$E\{\cdot\}$	Expected value
$\text{Var}(\cdot)$	Variance
$\text{Cov}(\cdot)$	Covariance
γ	Threshold
ρ	Correlation coefficient estimate
$D^{-1}(\cdot)$	First-order difference operator
\hat{d}_n^k	Predicted binary state of the k -th channel at the n -th step

LIST OF ABBREVIATIONS

ACI	Adjacent channel interference
AIC	Akaike information criteria
AM	Amplitude modulation
AR	Autoregressive
AWGN	Additive white Gaussian noise
AoA	Angle-of-arrival
BPSK	Binary phase shift keying
BSS	Basic service set
C2CCC	Car 2 Car - Communication Consortium
CCI	Co-channel interference
CC	Control channel
CDF	Cumulative distribution function
CLT	Central limit theorem
CR	Cognitive radio
CSMA/CA	Carrier sense multiple access/collision avoidance
DC	Direct current
DSRC	Dedicated short range communications
EMS	Electromagnetic spectrum
EU	European Union
FCC	Federal Communications Commission
GPS	Global Positioning System
GSV2VCN	Green and Secure Vehicle-to-Vehicle Communications Network
HMM	Hidden Markov model
I/Q	In-phase/quadrature
i.i.d.	Independent and identically distributed
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ISM	Industrial, scientific, and medical
ITS	Intelligent transportation system
ITS	Intelligent transportation system
ITU-R	International Telec. Union – Radiocommunications
LOS	Line-of-sight
MAC	Medium access control
MAI	Multi-access interference
MSE	Mean-squared-error
NBI	Narrow-band interference
NGWN	Next generation wireless network
NLOS	Non-line-of-sight

OBU	Onboard unit
OFDM	Orthogonal frequency division multiplexing
OSI	Open systems interconnection reference
PDF	Probability density function
PHY	Physical layer
PN	Pseudo noise
PSK	Phase shift keying
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
QoS	Quality of service
RF	Radio frequency
ROC	Receiver operating characteristic
SC	Service channel
SDR	Software-defined radio
SINR	Signal-to-interference-plus-noise ratio
SNR	Signal-to-noise ratio
UMTS	Universal Mobile Telecommunications System
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-Vehicle
VANET	Vehicular ad-hoc network
VSA	Vector signal analyser
VSG	Vector signal generator
VoIP	Voice over IP
WAVE	Wireless access in vehicular environments
WBI	Wide-band interference
WHO	World Health Organization
WSS	Wide-sense stationary

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A Cross-Layer Design for Next Generation Wireless Networks:V2V Perspective

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Recent advances in the automotive industry enabled us to build fast, reliable, and comfortable vehicles with various safety features. Roads are designed and made safer than ever before as well. Nevertheless, analyses and reports show that traffic accidents still remain one of the major causes of death and/or serious injuries around the globe. Intelligent transportation systems (ITSs) are expected to minimize the total number of accidents, if not prevent them completely.

Safety is not the sole objective of ITS. Routing optimization, green environments with reduced fuel consumption and carbon emission, and infotainment applications are also prominent targets of ITS. It is clear that all of these objectives, envisions, and services require some sort of a communications network structure. Note that two key components of any transportation system are vehicles and the transportation infrastructure. Therefore, it is easier to analyze the network structure required by ITS in terms of V2V and vehicle-to-infrastructure (V2I) networks. A V2V network in ITS represents a set of physically close-by vehicles which are communicating with each other within a local geographical region. V2I network, on the other hand, consists of vehicles that communicate with the transportation infrastructure. Due to the high-level mobility, signaling in both V2V and V2I networks is established via wireless links. Generally, ITS is considered to be supported by a backhaul over the V2I network so that it is connected to the core or backbone network.

Among V2I and V2V networks, V2V networks receive slightly more attention compared to V2I networks due to the following reasons: First of all, network topology for V2V networks is dynamic and of transient nature because of high-level of mobility. This implies that network entry, establishing connection, and maintaining a high-level of quality of service (QoS) are relatively difficult tasks as compared to those in traditional terrestrial

communications networks such as cellular networks. Second, network traffic consists of several types of messages including emergency-related data with various QoS requirements. From this perspective, information flow, data integrity, authorization, and security become life-critical concerns. In addition, in case there are multiple V2V networks in the vicinity, relaying especially the critical emergency-related messages from one node to another needs to be considered very carefully. In this regard, establishing a connection between transient networks along with the aforementioned information flow, data integrity, and security concerns is a serious challenge for the V2V networks. Note that none of the concerns listed here poses severe problems for the V2I networks given that the transportation infrastructure can handle the signaling seamlessly.

In order to tackle the problems and concerns listed above, generally the traditional layered architecture is adopted in the literature for V2V networks. Although it is a very powerful and successful strategy, layered architecture falls short in solving some critical issues especially in V2V networks such as dynamic resource allocation. This points out that a cross-layer approach could provide different perspectives while benefiting from the layered architecture. At the end, it should be stated here that the standardization efforts are not mature enough yet for V2V networks. For instance, network entry procedures and the non-emergency/service channel selection mechanisms are not explicitly defined in the draft version of the standard. This automatically indicates that there are some design gaps which could be supported by the findings of research carried out in this field especially with the cross-layer support. Hence, in this dissertation, a novel cross-layer predictive channel selection mechanism is proposed for V2V networks in order to minimize the average number of collisions. Both physical layer (PHY) and medium access control (MAC) layers are incorporated into the cross-layer design. At PHY layer, first a novel, fractional rate sensing mechanism is proposed, which reduces the total number of computations in order to obtain sufficient statistics for the decision. Next, the necessary condition for the optimum predictive sensing strategy is derived and validated by the empirical data obtained by field measurements. It is also shown that any linear predictive strategy outperforms the general Markovian-based prediction schemes under various traffic load scenarios in case the derived necessary condition is satisfied. Finally, a protocol which is developed based on master-slave architecture along with a nomination procedure operating on a single universal broadcast channel is proposed at the MAC layer. The proposed protocol is fed with the output of the PHY layer predictive channel selection mechanism and completes the network entry procedure for V2V networks.

Keywords: cross-layer design, 802.11p, Vehicle-to-vehicle networks, Predictive channel selection, communications network, vehicle-to-vehicle communications

AR-AR Bakış Açısıyla Yeni Nesil Kablosuz Ağlar için Katmanlar Arası Tasarım

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Otomobil endüstrisindeki gelişmeler, pek çok güvenlik önlemi olan hızlı ve konforlu araçlar üretilmesini sağlamıştır. Bu sayede otoyolların daha güvenli hale getirilmesi amaçlanmıştır. Fakat yayınlanan raporlara göre trafik kazaları, halen dünya çapında en fazla can kaybı sebeplerinden biridir. Trafik kazalarını azaltmak için, araçları ve iletişim altyapısını birbiri ile haberleştiren akıllı taşıma sistemleri (ATS) kullanılabilir.

Güvenlik odaklı tasarlanan ATS'lerin; rota optimizasyonu, eğlence uygulamaları, azaltılan yakıt tüketimi ve buna bağlı karbon emisyonunu düşürmek gibi başka hedefleri de bulunmaktadır. Tüm bu hedefler ancak araçların birbirleri ve çevreleriyle haberleşmesi ile gerçekleştirilebilir. Bu haberleşme sistemi, belirli bir yerel bölgede fiziksel olarak yakın olan araçların kendi aralarında araçtan-araca (AR-AR) haberleştiği ve bu araçların çeşitli iletişim altyapıları ile araçtan-altyapıya (AR-ALT) haberleştiği ağlar olmak üzere iki ana kısımda değerlendirilebilir. Kablosuz olarak iletişim sağlayan bu ağlar, hareket halinde olan araçlardan ötürü çoğu zaman yüksek devingenliğe sahiptir. Bu devingenlik, özellikle AR-AR ağlarının topolojilerinin süreklilik arz etmemelerine neden olur. Bu yüzden, hücresel ağlar gibi geleneksel kara yayınlarına kıyasla, AR-AR bağlantılarının oluşturulması, devam ettirilmesi ve servis kalite gereksinimlerinin (SKG) sağlanması çok daha zordur.

AR-AR haberleşmesi acil durum mesajları dahil olmak üzere pek çok SKG'ye sahip farklı mesaj türlerini içinde barındırır. Acil durum mesajlarının birbirine yakın araçlar arasında hızlı ve doğru bir biçimde iletilmesi büyük bir öneme sahiptir. Bu durum bilgi akışının sağlanması, veri bütünlüğünün korunması, yetkilendirme ve güvenlik konularını hayati kılar. Olası hataların can ve mal kaybına sebep olabileceği hassas bir yapıya sahip olan AR-AR ağları için iletişim aksaklıkları ciddi sorunlar teşkil etmektedir. Bu sorunların AR-ALT ağlarında, kablolu iletişim altyapısının sinyalleşmeyi kesintisizce yapabildiği

varsayıldığı için nispeten daha kolay çözülebileceği düşünülmektedir. AR-AR ağlarında ise bu sorunları çözmek için genellikle literatürde katmanlı yapılar tercih edilmektedir. Bu yapılar çok güçlü ve başarılı olmalarına rağmen, devingen olarak kaynak tahsisi yapan AR-AR ağlarında gecikmelere sebep olmakta ve bu ağlara has bazı sorunlarının çözümü için yetersiz kalmaktadır. Katmanlar-arası bir tasarım, daha esnek bir yapı sağladığından dolayı sözü edilen sorunlar için uygun bir çözüm adayı olabilir.

AR-AR ağları için standartlaştırma çalışmaları henüz tamamlanmamış olup mevcut standartlaştırma çalışmalarında ağa dahil olma prosedürleri ve servis kanalı seçme yöntemlerinden bahsedilmemektedir. Bu durum standartlarda, çeşitli katmanlarda tasarım boşluklarının olduğunu ortaya koymaktadır. Doğal olarak bu boşluklar özellikle katmanlar-arası araştırma çözümleri ile desteklenip tamamlanabilir.

Bu tezde AR-AR ağları için ortalama çakışma sayısını en aza indirecek yeni bir katmanlar-arası tahmine dayalı kanal seçme mekanizması önerilmiş ve hem fiziksel katmanı hem de ortam-erişim katmanını içeren tümleşik katmanlar-arası bir yapı ortaya koyulmuştur. Öncelikle fiziksel katmanda karar verebilecek kadar yeterli istatistiğin toplanması için gereken hesaplama sayısını azaltan yeni bir basamaklı algılama yöntemi geliştirilmiştir. Daha sonra tahmine dayalı algılama stratejisi için gereken koşullar kuramsal olarak türetilmiş ve sonuçlar toplanan saha verileri ile karşılaştırılmıştır. Gerekli koşulların sağlandığı çeşitli trafik senaryolarında önerilen doğrusal tahmin stratejilerinin, genel Markov tabanlı tahmin stratejilerine oranla daha iyi performans sağladığı görülmüştür. Son olarak ortam-erişim katmanında evrensel yayın kanalı üzerinde çalışan adaylık sistemine bağlı sunucu-istemci mimarisini kullanan bir protokol geliştirilmiştir. Bu protokol fiziksel katmanın tahmine dayalı kanal seçme yöntemi verileri ile beslenerek olası en uygun kanal seçilmiş ve ağa giriş prosedürleri tamamlanmıştır.

Anahtar Kelimeler: katmanlar-arası tasarım, 802.11p, araçlar arası ağ, tahmine dayalı kanal seçimi, iletişim ağları, araçlar arası iletişim

CHAPTER 1

INTRODUCTION

Recent advances in the automotive industry enabled us to build fast, reliable, and comfortable vehicles with various safety features as well as assistive technologies. Roads are designed and made safer than ever before as well. Nevertheless, traffic accidents still remain one of the major causes of death and/or serious injuries around the globe according to reports and statistical data [1, 2]. Even though there is a strong push toward making safer vehicles and infrastructures, it is observed that these efforts yield a limited decrease in the total number of casualties in traffic accidents. In order to dramatically minimize the total number of casualties, a communications network for the transportation system is required, which allows information exchange between vehicles, infrastructures, and related technologies.

Such a communications network provides not only extra safety measures for the entire transportation system, but also paves the way for green environments. Vehicles could share their instantaneous fuel consumption, carbon emission, speed, acceleration, location/position information; whereas weather, traffic, road/highway accessibility status such as road work and accident data could be broadcast or disseminated on demand. As can be inferred, once there is a communications infrastructure to exchange such a vast variety of data, energy efficiency, route optimization, and smart transportation become globally available. The concept of intelligent transportation systems (ITSs) seems to be a promising candidate towards the aforementioned idealized scenario since it aims to establish a smart transportation network which employs both computational and communications technologies together. It is clear that once the ITS concept meets the recently emerging

technology called Internet of Things (IoT), a paradigm shift will be experienced in the understanding of next-generation transportation systems. Indeed, such a shift should be considered as a mandatory step rather than a vision, because deployment of smart and green cities requires a smart transportation infrastructure. From this perspective, ITS cannot be designed and implemented as a separate, isolated concept, because collaboration, coordination, and cooperation with other already-existing and emerging communications infrastructures are required.

There are two essential components of any transportation system: *vehicles* and *the transportation infrastructure*. Therefore, an ideal ITS design and implementation should include a communications network which enables information exchange between vehicles and the transportation infrastructure. This implies that the communications network of ITS should support two modes of information exchange: Vehicle-to-Vehicle (V2V) and vehicle-to-infrastructure (V2I). It is important to keep in mind that these two modes of operation exhibit two different topological and behavioral characteristics. For instance, V2V is of highly dynamic and transient nature due to the high-level mobility pattern of the vehicles, whereas V2I could be considered to be of quasi-static and stable nature. There are differences in terms of quality of service (QoS) requirements of the two modes as well. For example, emergency messages in V2V mode generally contain delay-sensitive, life-critical, and high assurance data. On the other hand, general signaling in V2I mode include relatively relaxed versions of the QoS requirements compared those in V2V mode. Hence, it is easier and reasonable to break ITS into parts and analyze it from the perspectives of V2V and V2I modes separately.

V2V mode could be contemplated as a specific network type operating under ITS. Therefore, it is referred to as “V2V network” in the literature. In this regard, a V2V network in ITS represents a set of physically close-by vehicles which are communicating with each other within a local geographical region. Due to the inherent nature of V2V networks mentioned above, there are several concerns regarding network entry, establishing connection, and maintaining a high-level of QoS requirements, since they are relatively difficult tasks as compared to those in traditional terrestrial communications networks such as cellular networks. Furthermore, emergency-related data with various QoS requirements impose an extra burden on V2V networks, because failure to achieve these requirements

cause hazardous situations in traffic. Also, dynamic and transient topology put extra burden on V2V networks because relaying and exchanging the messages between close-by networks with stringent delay, integrity, authenticity, and security requirements are difficult tasks. Note that none of the concerns listed here poses severe problems for the V2I networks given that the transportation infrastructure can handle the signaling seamlessly. Therefore, one can conclude that V2V networks is the most challenging component in ITS. In light of the aforementioned discussions, in this dissertation, a detailed investigation on V2V communications and its current status, underlying technology and its critical issues and challenges are identified and addressed. Considering the safety-critical nature of V2V communications, cross-layer and adaptive strategies are examined from the perspective of vehicular ad-hoc networks (VANETs).

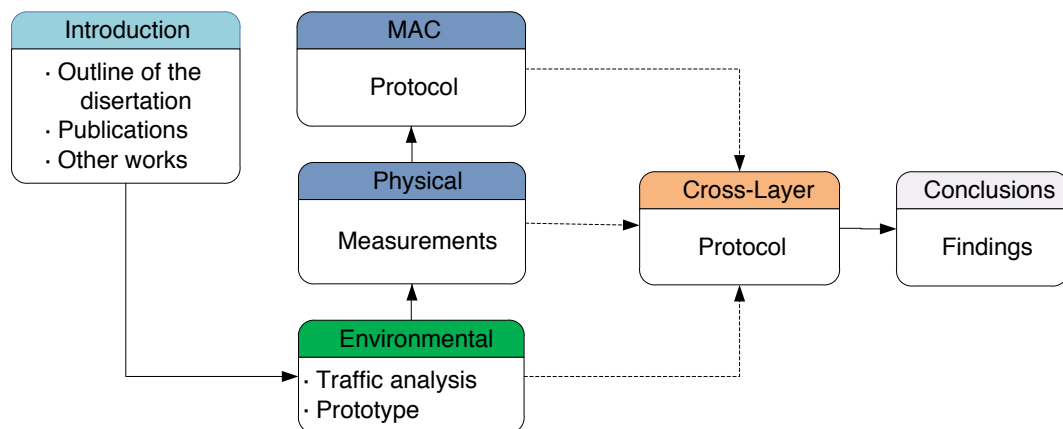


Figure 1.1 The organization chart of the dissertation.

Following the introduction (Chapter 1), the dissertation is organized in (see Figure 1.1) a bottom up approach starting with environmental layer. The important aspects and challenges about vehicles are listed in Chapter 2: *Intelligent Transport Systems*. After a brief description of the problem, the underlying environmental challenges are listed and a measurement prototype is defined in Chapter 3: *Analyzing the Environment*. Next, physical layer (PHY) studies are given in Chapter 4: *PHY-Related Studies*. Once preliminaries of PHY layer-related issues are established, the MAC layer is investigated in Chapter 5: *Green and Secure Vehicle-to-Vehicle Communications Network Protocol*. Finally, cross-layer design is given after both PHY-MAC layer findings in Chapter 6: *A Cross-layer Adaptive Channel Selection Mechanism for IEEE 802.11P Suite*. The results and discussions are given in Chapter 7: *Results and Discussions*.

1.1 Literature Review

Transportation is by far one of the most important features in mankind's entire history. Especially in today's busy world, transportation is not only a necessity for personal travel, it is also necessary for the shipment of goods across the globe. All these needs require infrastructure, planning and optimization to run safely and smoothly.

Recent advances in the automotive industry have enabled us to build fast, reliable, and comfortable vehicles with numerous safety features. At the same time, roads are designed and built safer than ever before. However, traffic accidents remain one of the major causes of death. Intelligent vehicles are the top candidates to prevent accidents. The objectives of ITS is not limited to safety; a more green environment is another priority. With dynamically planned vehicular network information flow, gas consumption and carbon emission will be reduced.

Although the primary intent for V2V networks is safety, like other communications platforms, the driving force is expected to be entertainment. Most of the entertainment applications like gaming and multimedia require a significant bandwidth to satisfy customers with a seamless performance. The most critical and scarce resource in such wireless vehicular networks is the electromagnetic spectrum (EMS). The allocated radio frequencies must be used in such a way that the most important emergency messages should always delivered in the shortest time possible. This potentially lifesaving aspect of this technology necessitates applications requiring high bandwidth to work in low priorities.

IEEE defines vehicular network standards with IEEE 802.11p. The allocated bandwidth is divided in several channels for different purposes. Even though the standards are mature enough, the channel selection mechanism is not explicitly defined. Selecting a random channel is the most widely adapted and simplest solution, but due to congestion the performance in busy network traffic is quite low. To increase the performance, a better channel selection mechanism is required.

In the literature, there are mainly four categories in selecting a service channel for VANET systems: *pre-allocation based* [3–7], *randomized rotation based* [8], *minimum duration*

based [9] and *predictive based schemes* [10]. Pre-allocation based schemes employ a static database and then select a channel based on that database. Despite its simplicity, such an approach evidently yields a poor performance under dynamic access. Furthermore the database itself should be updated frequently. The randomized rotation based algorithms take advantage of a different version of frequency hopping. Therefore, they inherently adopt both advantages and disadvantages of frequency hopping approaches such as improved fairness and lack of knowledge regarding the state of the medium. Minimum duration based methods need to store the occupancy durations of each channel so that the least used can be identified. However, performance of these methods converge with those of pure random channel selection schemes. Predictive algorithms seem to fit best for the channel selection task, but they lack cross-layer and adaptive design leading to poor and unsatisfactory performances [11]. On the other hand, studies that focus on predictions taking advantage of Markovian assumption rely heavily on selecting the appropriate length of both prediction period and history. In the absence of historical data (past observations), it is reported that prediction accuracy degrades dramatically [10]. Studies which follow decision-making processes based on *a posteriori* probabilities of the occupancy state of a channel could also be considered in this manner. Nevertheless, such attempts require some sort of collaboration and coordination [12]. It is worth mentioning at this point that there are also studies in the literature which aim to be aware of spectrum conditions on future positions along the path of any vehicle. Yet, such a strategy mandates obtaining the location of each vehicle via an already-existing reference such as Global Positioning System (GPS) and an infrastructure which allows the vehicles to share the digital maps across the network [13, 14]. Therefore in this study, a novel cross-layer, adaptive channel selecting mechanism is proposed. Even though several predictive channel selecting mechanisms presently exist, to the best knowledge of the author, this study is pioneering the incorporation of cross-layer architecture with predictive strategy into vehicular networks.

1.2 Objective of the Thesis

The VANETs are an emerging technology. Despite that they are fairly old, they were never applied globally before. It is expected the V2V communications to be mandatory for new

manufactured cars in 2017. The standardization bodies are working on the standards and governments are allocating parts of the EMS for vehicular use only. In the near future with autonomous cars, the infrastructure, vehicles and services are expected to be interlinked.

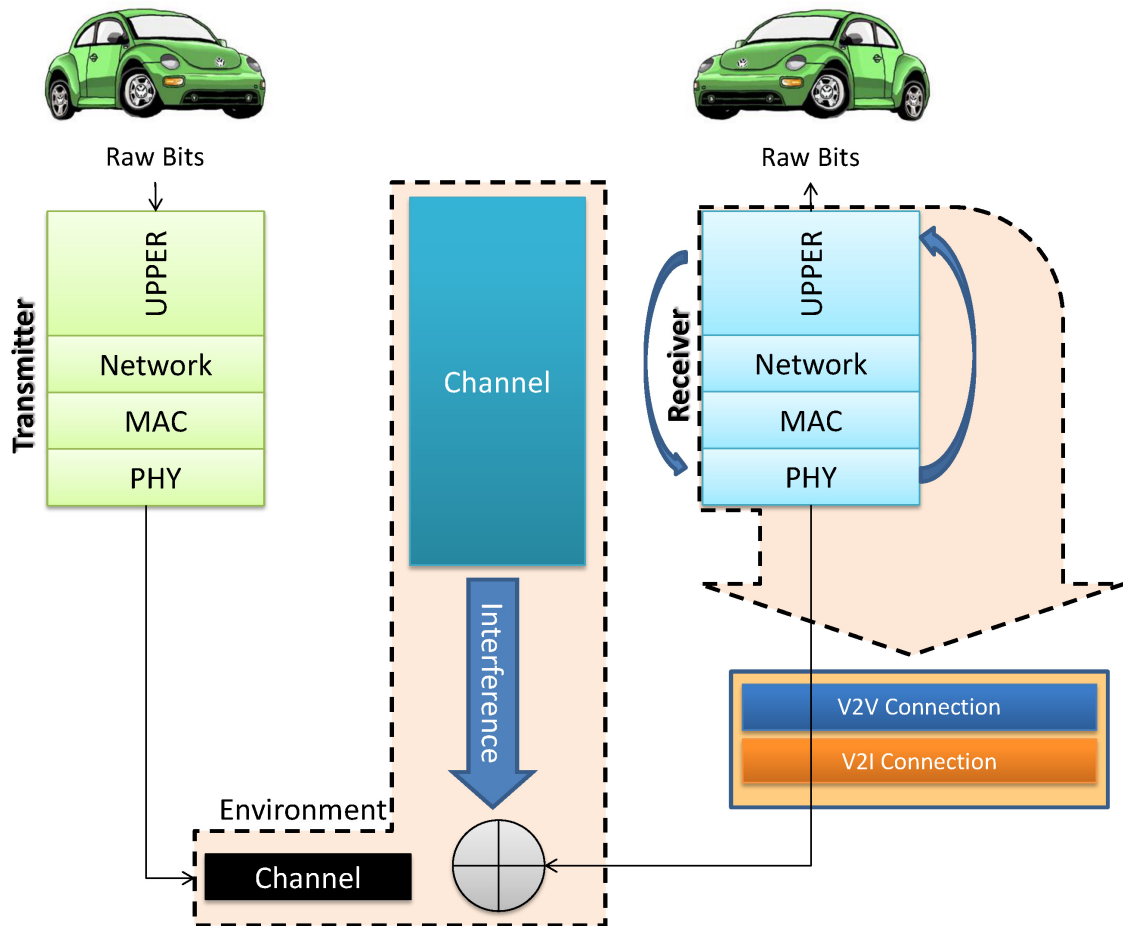


Figure 1.2 The conceptual relations between elements studied in this dissertation.

The conceptual relations between environmental, PHY and medium access control (MAC) are given in Figure 1.2.

The preparation and standardization efforts for this technology need much attention. In this dissertation, improvements for the statistical modeling, cross-layer design and channel selection mechanisms aimed to be improved. The objectives of this work are listed below with affiliated chapter numbers:

- Identifying the characteristics of the traffic and underlying environmental data (Chapter 3).
- Developing novel methods for identification of co-channel interference (CCI) for

next generation wireless networks (NGWNs) (Chapter 4) ¹

- Improving MAC layer protocol for V2V networks in such a way that the improved protocol takes into consideration multiple speed classes simultaneously and developing a novel MAC layer protocol for V2V networks (Chapter 5) ²
- Developing a cross-layer channel selection mechanism to decrease collision possibility for wireless communications (Chapter 6) ³

1.3 Hypothesis

Recently the automotive industry has advanced nearly to produce flying cars envisioned in science-fiction movies. Autonomous cars are already on the roads, traveling the world without any driver intervention. However, the improvements in vehicles alone only lead us to the local optimum in vehicular transportation. To reach the global maxima of transportation, efficiency of the vehicles must be improved via a cooperative and collective vehicular information network.

VANETs are expected to be the next big step after combustion engines for transportation. As the vehicles are mostly moving, the communication system needs to be wireless.

Wireless systems are widely used in many ways in our daily lives. However this technology is not used very effectively. Especially the EMS can be used more efficiently with simple intelligent solutions.

VANETs are designed for safety and emergency situations. Also there are some room left for user applications for infotainment services. However these services require a significant amount of bandwidth to operate.

IEEE 802.11p allocates 4 channels for infotainment applications. These channels seems to be inadequate for large number of users and must be used highly efficiently to serve everyone.

¹ Certain parts of the content of this chapter are published in [15].

² Certain parts of the content of this chapter are published in [16].

³ Certain parts of the content of this chapter are published in [17].

In this dissertation, the empirical analysis of real time traffic flow is measured and statistical investigations are carried and the abstract environment layer, which does not exist in OSI reference model, is defined. A general purpose 802.11p prototype is developed for measurement and demonstration. Spectrum sensing and measurements for VANETs are made to find the optimum values and create a statistical model for communications parameters. The MAC and upper-layers are studied. With the developed methods in this dissertation, it is shown that the efficiency of VANETs can be increased further.

1.4 Other Works Done

Apart from the work discussed above, there are some major topics present in the literature that are not directly included into this dissertation, such as cognitive radio (CR) and software-defined radio (SDR). While they are related to V2V communications, in order to keep the integrity of the text and flow, these works are not included in this dissertation.

INTELLIGENT TRANSPORT SYSTEMS

2.1 Introduction

Without a doubt, the automobile is one of the most important inventions of modern times. From the steam engines to the electric cars, the automobile industry made significant technological progress. In parallel, mankind built magnificent infrastructures, roads and highways. However traffic accidents remain one of the major causes of death [1, 2](see Figure 2.2). The current situation implies that further improvements in technology for each individual vehicle will not provide extra safety measures for transportation on the whole. Thus, deployment of cooperative and coordinated designs seems to be inevitable in order to extend contemporary safety measures. Even though preventing accidents entirely is a difficult task, cooperative and coordinative approaches provide a promising solution to make transportation safer. Motivated by these, ITS envisage a network topology consisting of interconnected vehicles and infrastructures [19, 20]. In this regard, vehicles that are aware of each other and of their surrounding environment will form an intelligent, dynamic subnetwork which can be used in several ways ranging from safety to infotainment. Early warning, intersection collision avoidance, and adaptive cruise control are just a few of the potentially lifesaving applications available [21].¹ Advertisement, web surfing, gaming, and video streaming are applications falling into the infotainment category. One should keep in mind that potential benefits of ITS are not limited to these two categories. It is believed that ITS will pave the road to green transportation as well [16, 22].

¹Figure 2.5 depicts some of the applications that are frequently mentioned in ITS standards.



Figure 2.1 First car to go into production with an internal combustion engine [18]

2.1.1 VANETs

VANETs are a form of ad-hoc networks where individual nodes differ from traditional wireless nodes. Unlike traditional mobile devices, there are no power constraint, the nodes are mostly mobile, and the network topology is extremely dynamic. Along with that the existing infrastructure is used in a cooperative manner. As sketched in Figure 2.3, VANETs are studied in two parts: V2V and V2I. The V2V links are established between vehicles, the V2I links are created with infrastructures.

From sparse and fast highways to congested and slow downtown traffic, these network structures are naturally desired to operate in the optimum way. However, the extreme conditions caused by high mobility render VANETs to a short-lived nature. Despite their inherent constraints, VANETs are also a promising heterogeneous network type, since they are planned to consist of contemporary cellular networks, next generation wireless networks along with V2V and V2I link support as well as device-to-device communications options [24].

Car 2 Car - Communication Consortium (C2CCC) is a nonprofit and industry-driven organization formed by various European car manufacturers to standardize the protocols of

Car Crash Statistics

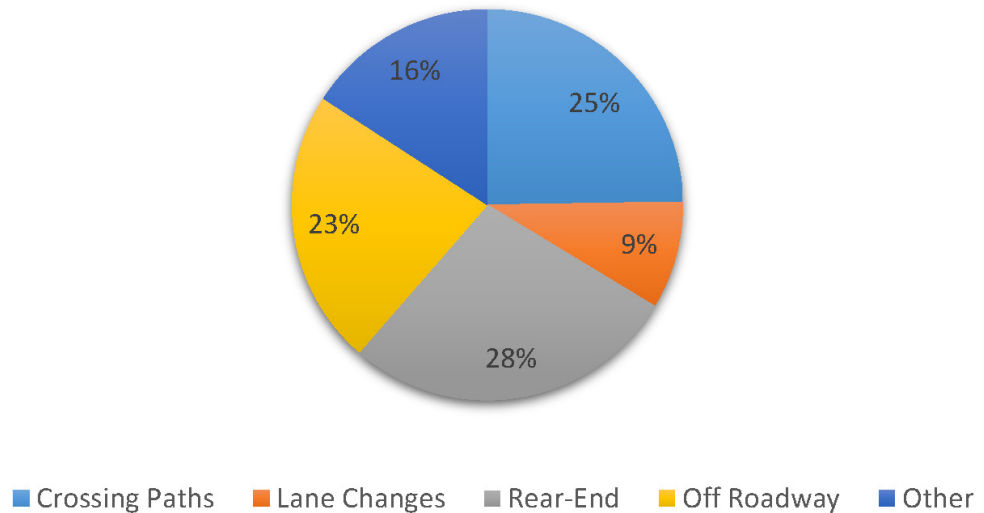


Figure 2.2 Car crash statistics according to GES 2013 [23]

wireless communications between vehicles and infrastructures. Different from Institute of Electrical and Electronics Engineers (IEEE), by using the current and most suitable technologies they define how the equipment suppliers and vehicle manufacturers are to build their products to make sure different manufacturers parts can communicate with others. C2CCC defines vehicular communication architecture as in Figure 2.4. This architecture is designed to use the existing infrastructure along with newly developed V2V systems.

The core of V2V system is IEEE 802.11p, designed for emergency. For high-bandwidth applications C2CCC recommends extensions like 802.11g or Universal Mobile Telecommunications System (UMTS). However they are not suitable and cost effective for high bandwidth V2V communications. The best way to deal with this situation is to use the current 802.11p resource in a more effective way.

2.2 ITS Applications

Although the primary intent for ITS communications systems is safety, like cellular phones and PDAs, entertainment is the main driving force for this kind of communications technology. Infotainment applications make driving more enjoyable and bring new opportunities to the market [25, 26]. With specialized entertainment products to enhance the driver

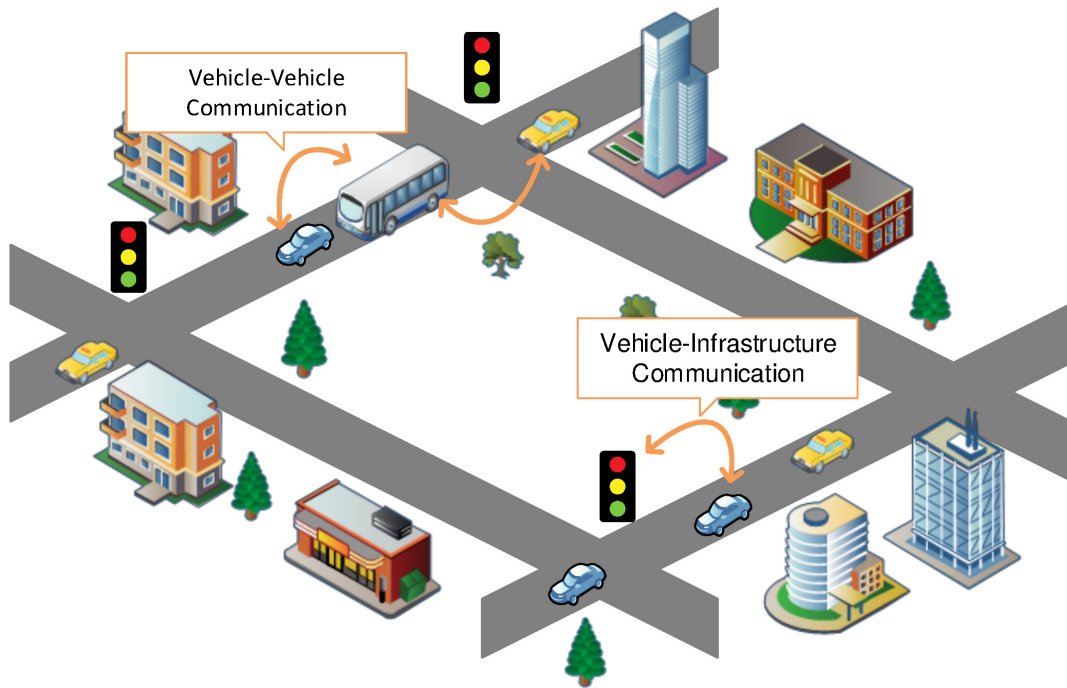


Figure 2.3 Example of a vehicular ad-hoc network

or the passenger experience, these applications such as video streaming and voice over IP (VoIP) require a high bandwidth connection to create a seamless customer experience.

The ITS applications can be categorized in 3 major categories: *safety*, *management* and *infotainment services*.

2.2.1 Safety Applications

Safety of the vehicles and passengers in it is the number one priority for V2V systems. The main use of V2V for safety is to get information of the road ahead as fast as possible. Any crash or road hazard can be reported and the driver can be warned beforehand. Current vehicles solely rely on drivers reflexes. V2V systems will report the anomalies in the traffic flow such as sudden brakes to the driver so he/she can be more cautious.

Also emergency vehicles like ambulances, fire trucks and police cars will communicate with the infrastructure to enable them get their target faster.

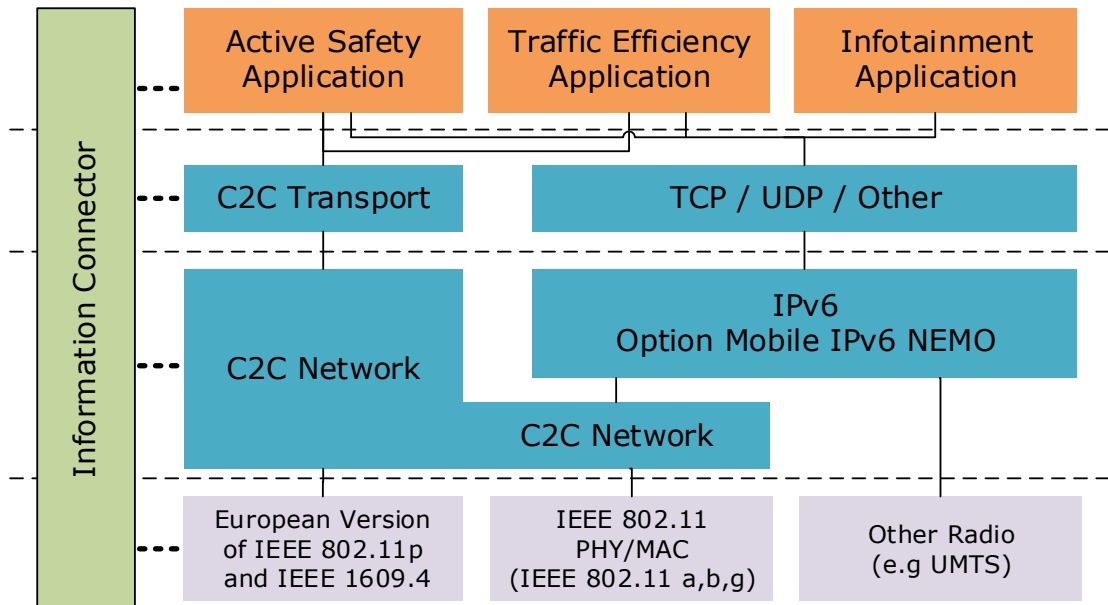


Figure 2.4 C2C-CC architecture Based on ETSI ITS G5 plus GeoNetworking [21].

The most crucial examples of safety applications are given in [27]:

- Stopped or Slow Vehicle Advisor
- V2V Post Crash Notification
- Emergency Electronic Brake Light
- Road Hazard Condition Notification
- Road Feature Notification
- Cooperative Collision Warning
- Cooperative Violation Warning

2.2.2 Management Applications

Managing the traffic is another important issue of the transportation. The traffic flow is governed by the traffic signals, lane markings and traffic lights. However these indicators are mostly static and cannot react to the changing environment. The V2V management applications will help the traffic to be managed easier.

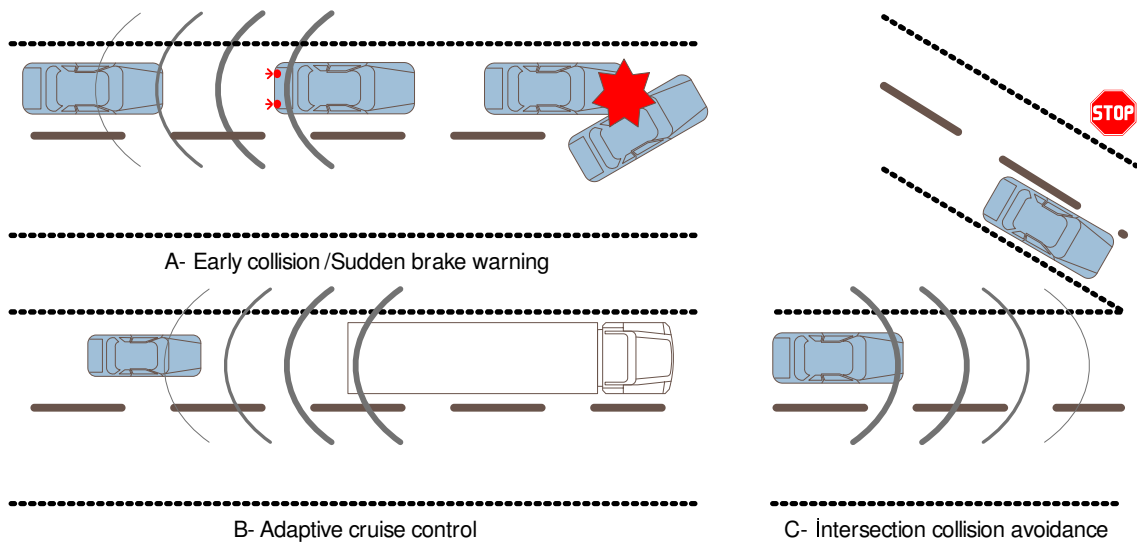


Figure 2.5 Examples of ITS applications

The important management applications can be listed as in [27]:

- Congested Road Notification
- Traffic Probe
- Free Flow Tolling
- Parking Availability Notification
- Parking Spot Locator

2.2.3 Infotainment Applications

Infotainment applications are nonemergency information and entertainment applications. These applications can vary from video broadcasting to map downloading. As they seem to be not so important, they are expected to be the driving force for V2V technology.

Some of the applications given in [27]:

- Remote Vehicle Personalization/Diagnostics
- Service Announcements
- Content, Map or Database Download

- Real-Time Video Relay
- Music Broadcast
- VoIP
- Gaming

2.3 Solutions and Standardization Efforts

In order to encompass all of the aforementioned tasks and constraints, IEEE 802.11p/1609 work group strives to establish a standard known as wireless access in vehicular environments (WAVE) [28] (see Figure 2.6).

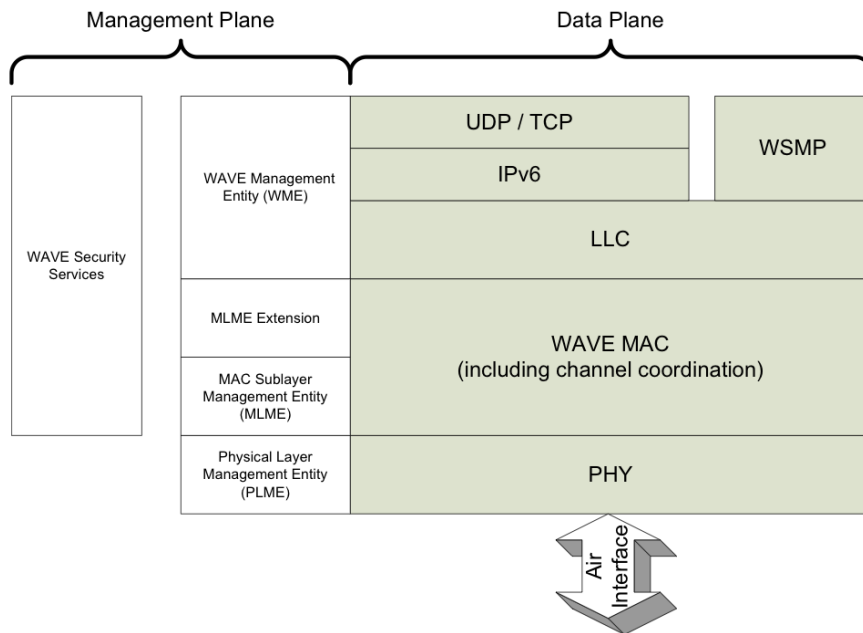


Figure 2.6 WAVE model [29]

The WAVE operates in the 5.9 GHz band of the radio spectrum. The PHY layer of WAVE is a modified version of 802.11a which allows high speed mobility. It works in ad-hoc mode and allows communication outside the context of a basic service set (BSS). This way association between devices are not required. The management operations such as authentication are removed and the data transmission could be done with much smaller delays compared to IEEE 802.11a/b/g. A high level comparison of WAVE with other wireless technologies are given in Table 2.1.

Table 2.1 Comparison of wireless technologies

	DSRC/WAVE	Wi-Fi	Cellular	Mobile WiMAX5
Data rate	3-27 Mbps	6-54 Mbps	< 2 Mbps	1-32 Mbps
Mobility	> 60 mph	< 5 mph	> 60 mph	> 60 mph
Nominal Bandwidth	10 MHz	20 MHz	< 3 MHz	< 10 MHz
Operating Band	5.86-5.92 GHz (ITS-RS)	2.4 GHz, 5.2 GHz (ISM)	800 MHz, 1.9 GHz	2.5 GHz
IEEE std.	802.11p (WAVE)	802.11a/b/g	N/A	802.16e

IEEE 802.11p standard is currently a draft and work on it is still in progress. The WAVE model uses IEEE 1609 standards. These standards are specially created for VANETs and they are also in progress. The 1609 consists of several layers:

- 1609.1: WAVE resource manager
- 1609.2: WAVE security services
- 1609.3: WAVE networking services
- 1609.4: Multichannel operation

IEEE 1609.4 Multi-Channel Operation mechanism is the MAC layer for WAVE architecture. It is an extension to the existing 802.11 MAC. The medium access is managed by this layer. Basic responsibilities of 1609.4 are:

- Managing optional regular switching between control channel and service channel
- Queuing regular time advertisements and/or service advertisements
- Multiplexing/demultiplexing higher layer protocols (IPv6, WSMP)
- Queuing messages for transmission on the correct channels
- Managing transmit message priority

IEEE 1609.4 defines how to access the control/service channel. There are mainly 4 types of access: Continuous access, alternating access, immediate access and extended access(Figure 2.7). The basic safety features of V2V use the continuous access. However, the service channels must be used for the management or the infotainment applications.

The channel operations of WAVE is managed by IEEE 1609.4. However it does not define which channel or which access mode to be used.

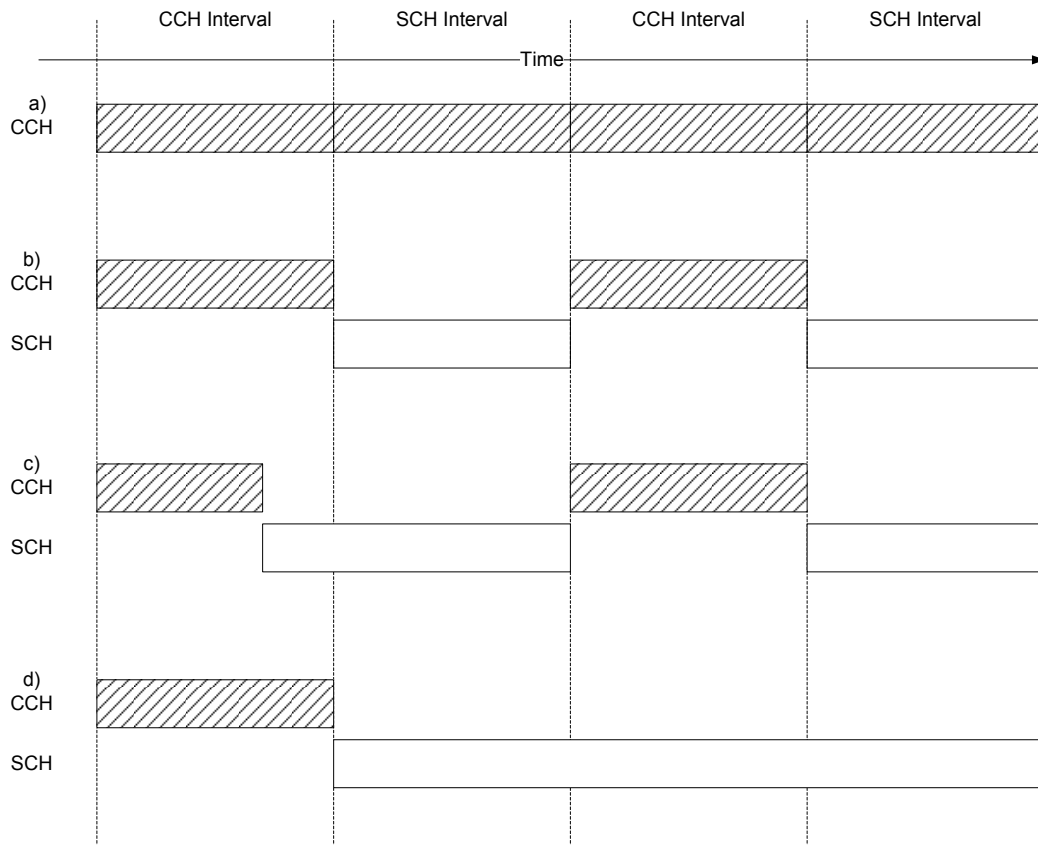


Figure 2.7 WAVE access schemes [29]. Continuous access, Alternating access, Immediate access, Extended access

2.4 Problems of Current Solutions

One should keep in mind that V2V communications take place in the wireless spectrum which is a very valuable, finite, and public resource. This nature of the wireless spectrum brings about multi-access interference (MAI) issues. Interference causes poor signal reception, drastic decrease in system capacity, frequent hand-offs, and service interruptions. Unlike centralized network structures, with ad-hoc vehicle networks there are multiple interference scenarios present simultaneously such as CCI, adjacent channel interference (ACI), narrow-band interference (NBI), wide-band interference (WBI), and so on [30]. In the literature, there are mainly three strategies to combat interference : interference avoidance, mitigation, and cancellation. Of these three strategies, it is obvious that interference avoidance is the simplest and most effective one, since avoidance strategy will pave the path for interference-free communications. However, avoidance relies on identifying unused resources. Thus, any avoidance strategy always includes some sort of identification procedure to sense the use of resources, then decides based on the data

and acts on it accordingly [30]. Note that even such an effort might not be sufficient to prevent MAI problems such as collision. Even though there are numerous collision avoidance strategies in the literature, they are all based on the assumption of having a channel selected already at hand. It is evident that a successful collision avoidance strategy should definitely be preceded by identification of statistically least occupied channel in advance.

In light of the discussion above, Federal Communications Commission (FCC) allocates the 5.850–5.925GHz portion of the radio spectrum as dedicated short range communications (DSRC) for vehicular networks [31]. DSRC standard defines seven 10MHz channels in this range: one control, two reserved, and four non-safety application channels as shown in Figure 2.8. However, a selection mechanism for these channels are not defined explicitly.

	SCH	SCH	SCH	CCH	SCH	SCH	SCH
Frequency GHz	172	174	176	178	180	182	184
	5.86	5.87	5.88	5.89	5.90	5.91	5.92

SCH: Service channel, CCH: Control Channel

Figure 2.8 DSRC channels

It is obvious that selecting a channel randomly at MAC layer is the simplest and widely adopted solution. However, a channel selecting mechanism solely relying on MAC layer functionalities is not sufficient to provide satisfactory performance and needs novel data dissemination strategies benefiting from advanced techniques such as space–time network coding [32]. Therefore, a cross–layer design including both MAC and PHY operations is required. In this regard, from a PHY layer perspective a prediction mechanism is required in order for MAC layer to take appropriate actions in advance. Failure to achieve these cross–layer operations may cause the system to select an interfering or busy channel and drastically lose bandwidth and performance. As once the channel is selected, it will be used until the next cycle and a busy or interfering medium is subject to wait in collision avoidance state. Also note that the collision avoidance mechanism in IEEE 802.11p uses carrier sense multiple access/collision avoidance (CSMA/CA) and can only detect known types of signals [28].

AN ADDENDUM TO OSI: THE ENVIRONMENTAL LAYER

3.1 OSI Model and Cross-Layer Architectures

Sophisticated problems in the field of communications such as networking is traditionally tackled by divide-and-conquer approach. The problem is first reduced down to more tractable sub-problems where each individual problem could be solved independently. The open systems interconnection reference (OSI) is a well established standard for such and approach. The OSI model defines seven functional layers: *Application Layer*, *Presentation Layer*, *Session Layer*, *Transport Layer*, *Network Layer*, *Data link Layer*, *Physical Layer* as seen in Figure 3.1a. Each layer is isolated from other layers and has a well defined task [33]. The data is exchanged between adjacent layers in order to complete the communication process depending on the direction of the flow.

Although, this well-structured design is seems to be suitable for wired-networks to some extend, it causes latency in ITS due to the topology related problems in VANETs and the fragile nature of wireless links. Latency stems from the isolated layers and the algorithmic structure of OSI. Since the ultimate goal of ITS is safety, latency implies property damage and at worst case loss of life.

Most of the time, protocols parameters are set during the design stage with optimal values. However, the highly dynamic environment and topology of VANETs demand on-the-fly parameter changes to adapt surrounding environment in a fast.

The latency and performance issues of layered architectures are commonly overcome by

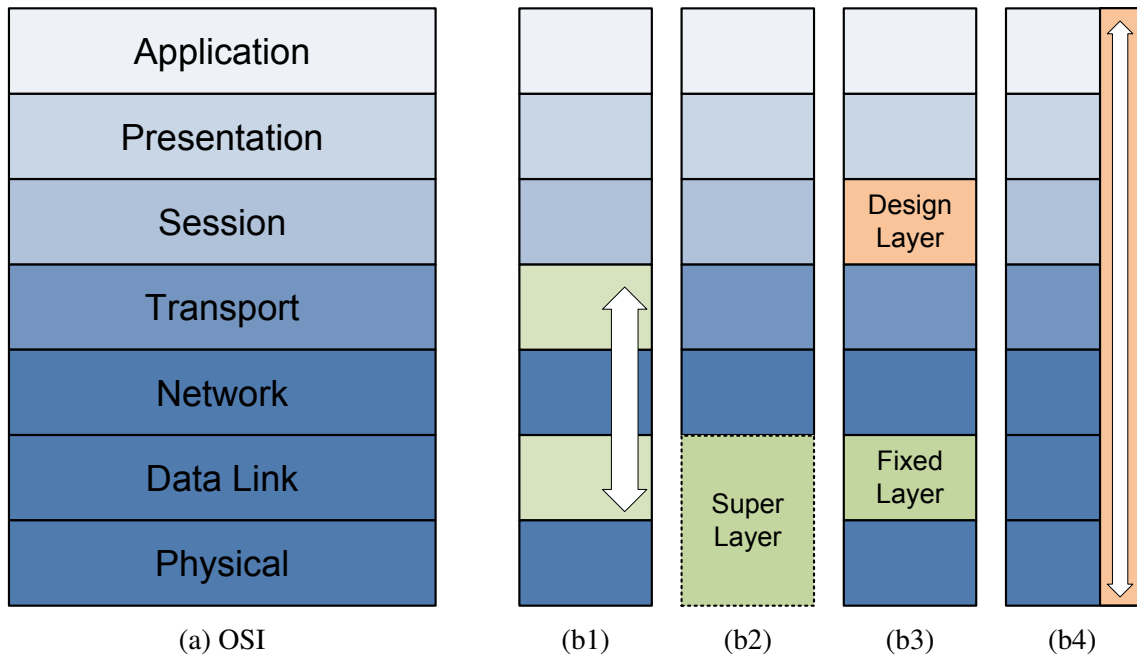


Figure 3.1 (a): Standard OSI reference model, (b): cross-layer approaches, (b1):Creation of new interfaces, (b2):Merging of adjacent layers, (b3): Design coupling without new interfaces, (b4): Vertical calibration across layers

exploiting the layered architecture [34], which is known to be cross-layer design. In the literature, there is no consensus on the definition of cross-layer concept. However, it is believed that this concept definitely includes some sort of a violation in the layered design. In the recent studies, there are four prominent categories cross-layer approaches: *creation of new interfaces*, *merging of adjacent layers*, *design coupling without new interfaces*, *vertical calibration across layers* [35]. Each major category is depicted in Figure 3.1b1- Figure 3.1b4 with the brief explanations as follows:

- Creation of new interfaces (Figure 3.1b1): Defining data exchange interface between any two or more layers at runtime.
- Merging of adjacent layers (Figure 3.1b2): Creating a superlayer by merging two or more adjacent layers.
- Design coupling without new interfaces (Figure 3.1b3): Designing new layers in an interdependent fashion.
- Vertical calibration across layers (Figure 3.1b4): Sharing a database between some or all layers.

In designing a new cross-layer protocol, the violations should be handled carefully. If the original design is modified drastically, fundamental benefits targeted by layered architecture could be lost and the output suffers from maintenance problems [34]. Therefore, it is expected that the modifications should not alter drastically the original design and focus on relatively simpler and tractable adaptations.

VANETs require numerous external sets of information such as speed, road conditions, and vehicle population density and so on. These data are used to optimize parameters in the layered architecture. Overall network performance relies heavily on such parameters which are necessary almost on each and every layer. However, global optimum for overall network is difficult to achieve unless several cross-layer approaches are employed simultaneously.

3.2 Environmental Layer

Before developing any communication mechanism, the underlying environment must be understood in detail. Traffic flow has a unique and stochastic behavior. As it is dependent on weather, rush hours, holidays and even sports games, there is no simple way to model the traffic behavior. There are a few methods used to analyze such flows like point model or diffusion model, but they are not sufficient to solve this problem. As there is no general purpose traffic model to analyze the stochastic nature of the vehicles, a stochastic analysis is the easiest way to understand and create an accurate model for vehicular environments.

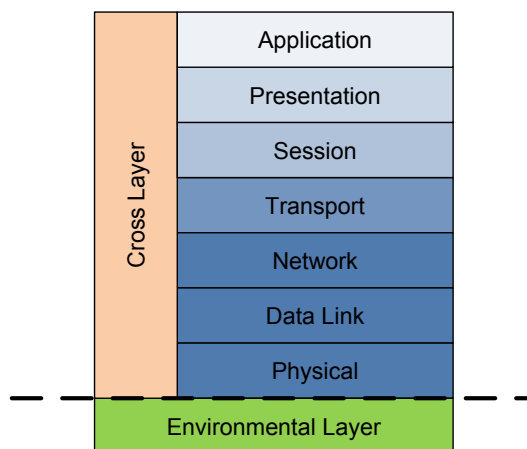


Figure 3.2 Environmental layer with cross-layer for OSI reference model.

The OSI model defines the fundamental internal functional blocks of a communications system. The model consists seven layers from application to physical layer as seen in Figure 3.2. Although this abstract approach is fairly standard in all systems, wireless communications systems do not fit to this abstraction perfectly. As the environmental impacts like fading and shadowing are dependent on the movement of the system or its surroundings, the physical conditions are constantly changing thus effecting the PHY layer drastically. The surrounding environment could be seen as a new abstract layer in addition to the cross-layer which connects all the layers in OSI model.

The environmental layer may include geographic information, stochastic traffic behaviors even weather information to support the overlaying layers to give more accurate decisions.

The cross-layer approach tends break the decoupled structure of the layers, to gain speed and responsiveness. For the life-critical nature of VANETs speed is crucial. As any late message may be responsible of people's lives. Detailed information about underlying technology is given in Chapter 2.

3.3 Real-time Traffic Flow Data Collection and Statistical Analysis

Traffic flow is one of the most unpredictable and stochastic events. As there are no available traffic data other than İBB traffic reports for İstanbul, an image processing based software is developed. This software continuously monitored the E5 highway of İstanbul near İstanbul Ticaret University for several weeks. As it can be seen in Figure 3.3, the visible portion of the road is about 500 meters. The vehicles form both lanes are captured at a rate of 30 frames per second. Every frame is compared with the predecessor frame to catch the motion.

The movement of the cars tracked along the visible portion of the road and from the ratio of $\frac{framesize}{roadsized}$, relative speeds and quantity of the vehicles are calculated.

The behavior of İstanbul traffic is mostly effected by the movements of the working population. As the results concur this prediction, vehicular density is plotted in Figure 3.5. As seen in the figure there is an obvious pattern in the density behavior, however this mere



Figure 3.3 An example frame of traffic capture from İstanbul Ticaret University.

finding is not sufficient to model this sophisticated problem.

Discrepancy between standard well-known and well-established statistical models and the measurement data makes this hard problem even harder. Also there is no comparison data set peculiar to İstanbul and/or Turkey, which creates on other layer of difficulty in validating the limited amount of data collected real-time. This points out that traffic flow data sets for Turkey and especially for Istanbul are required for further investigations and elaborative analysis in this field of research. Comparative analysis therefore should be carried out by using simulation techniques.

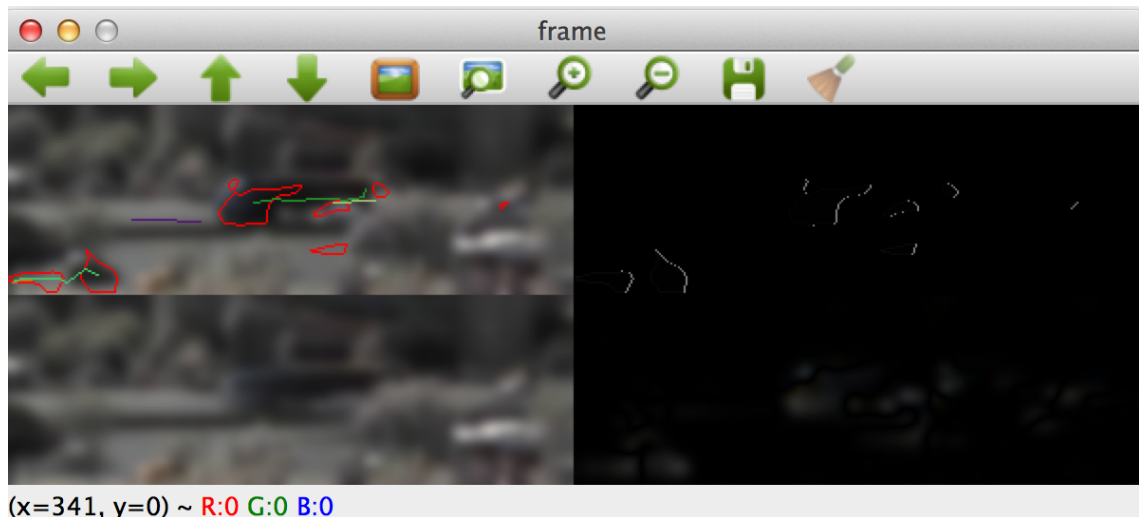


Figure 3.4 An example frame of processed traffic flow.

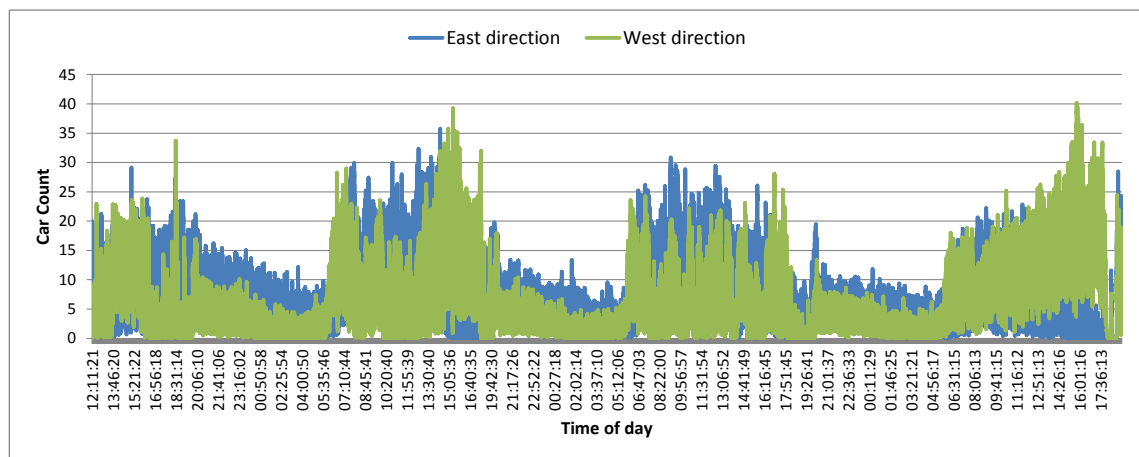


Figure 3.5 Vehicle density near İstanbul Ticaret University on E5 highway in İstanbul.

3.4 Building a Prototype for Measurements

IEEE 802.11p is the study group for V2V communications. This work group has created a draft for V2V communications standards by taking 802.11a as a base [29].

Although 802.11 is a well established standard, the extension 802.11p is currently a draft. As 802.11 is widely adopted wireless standard, vehicular extension of this standard is expected to be the facto standard in vehicular communications. Detailed explanation about this topic is addressed in Chapter 2.

Currently there are no 802.11p off-the-shelf products to create a testing environment. However as 802.11p is build on 802.11a standard, 802.11a devices can be hacked and used

as 802.11p devices. The 802.11 chips are implemented either fully hardware or partially hardware with software management parts. The latter is called a softmac device and can be regarded as SDR. With this kind of technology, a 802.11p prototype is developed to use in PHY layer measurements.

3.4.1 Hardware Details

A V2V communications system prototype is created with of the shelf components. Since the vehicle is mostly mobile, the vibrations and the extreme temperatures generated by the engine or the environment is a big challenge for hardware selection. The onboard unit (OBU) of the any vehicle is considered to be a mobile computing device, however the vehicles has a constant power source while it is on the way. This power source enables the OBU to be more a powerful device.

The prototype is created with an embedded motherboard, a 802.11a radio card and a GPS module. With extension ports on the motherboard, any peripheral is supported by the system.

3.4.1.1 Development Board

To implement the prototype, an x86 based Alix3D2 embedded board whose specifications are given in Table 3.1, is used [36].

Table 3.1 Alix3D2 development board specs.

CPU:	500MHz AMD Geode LX800
DRAM:	256MB DDR DRAM on board
Storage:	CompactFlash socket
Power:	DC jack or passive POE, min. 7V to max. 20V
Expansion:	2 miniPCI slots, LPC bus
Connectivity:	1 Ethernet channel (Via VT6105M 10/100)
I/O:	DB9 serial port, dual USB
Board size:	100mm x 160mm
Firmware:	tinyBIOS

As the development board has a 500MHz CPU and 256MB RAM, it is sufficiently powerful to run an operating system for the proposed prototype. With a strong and durable

casing, the board is protected from the harsh vehicle environment. As an x86 architecture mini-board with two mini-PCI extension slots, two USB ports and a serial port, Alix3D2 is a perfect match for this kind of V2V solution.



Figure 3.6 Prototype with Alix3D2 development board.

3.4.1.2 Radio Card

Radio card is the key component to create a 5.9MHz communications environment. For this task Engenius EMP 8603 [37] mini-PCI wireless adapter is used. The chip of this device is implemented as a softmac device and its drivers are freely available in Linux operating system.

3.4.1.3 GPS Receiver

GPS is a crucial part of the V2V communications environment for locational and timing. Vehicles should to know their position, positions of their neighboring vehicles and the surrounding environment. A simple off-the-shelf USB dongle is sufficient for the prototype.

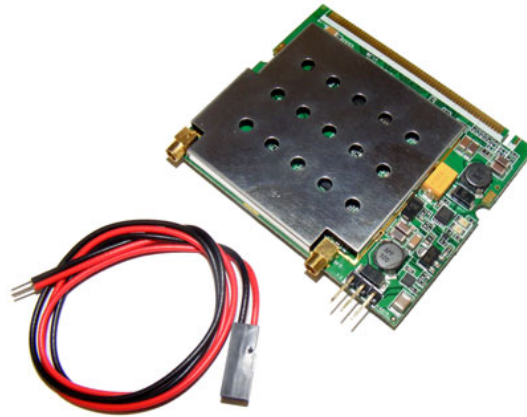


Figure 3.7 Engenius EMP 8603.



Figure 3.8 GPS receiver.

3.5 Software Details

The software of the prototype is based on a modified Linux operating system and the applications on top of it.

3.5.1 Operating System

Linux is an open source and freely available operating system. Linux supports a vast variety of devices and can be modified for special purposes. OpenWRT is a specialized Linux distribution created for embedded network devices. It is a widespread platform generally used in home routers [38].



Figure 3.9 OpenWRT command prompt.

The required drivers, software, and configuration can be set and created via OpenWRT's configuration screen.

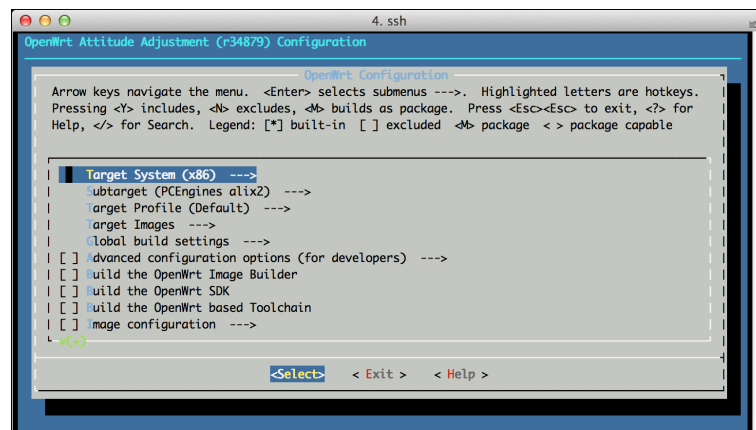


Figure 3.10 OpenWRT configuration screen.

For optimal performance, the system is configured to run on Alix3D2 board and necessary drivers for 802.11p are embedded to operating system kernel.

3.5.2 Application for Prototype

While all the low level handling is done by Linux operating system and related drivers, the control mechanism is built with Python programming language. Python is a high-level scripting language with full Linux support [39].

The implementation is based on traditional socket structures and Linux network daemons. The software operates on a server-client architecture. Each device has a client and server application. From application point of view, the underlying modifications are transparent and the software runs as an old-fashion UNIX application. The architecture of the prototype is given in Figure 3.11.

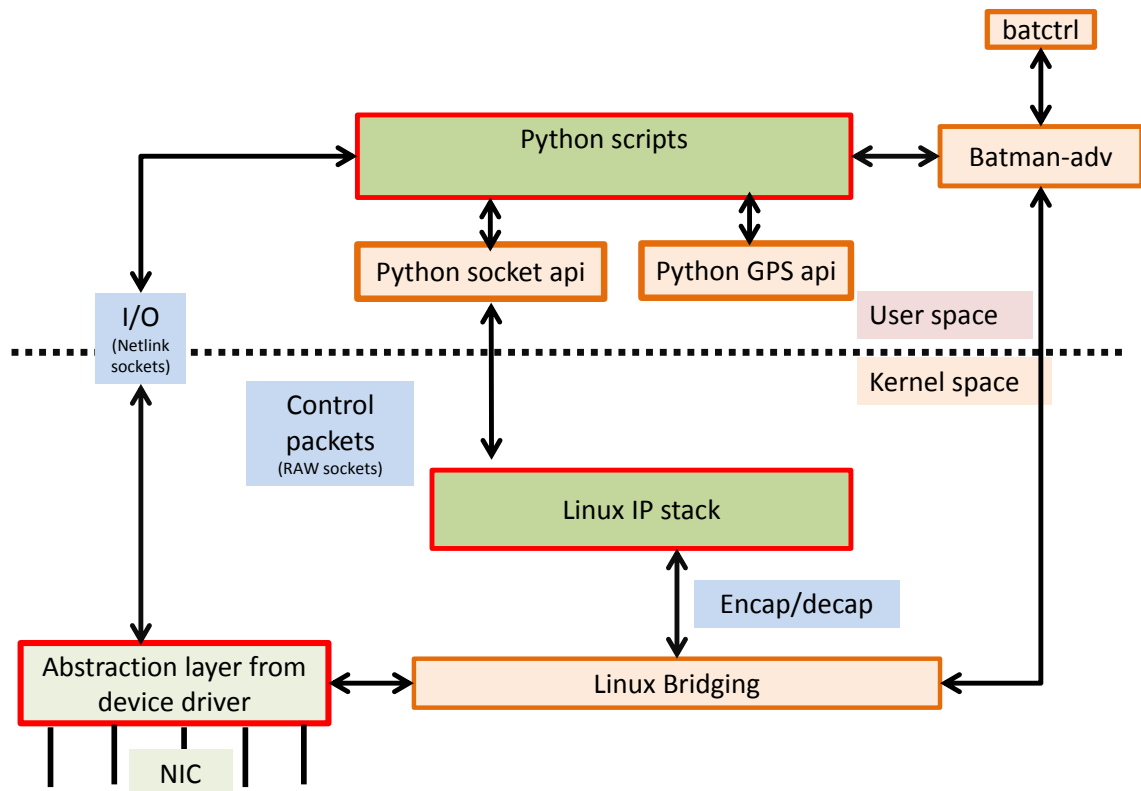


Figure 3.11 General model of the developed system.

After the system powers up, booting sequence starts and the system date is synchronized with GPS. Since time and position are important for the system, the operations are suspended until the time synchronization is complete. Upon synchronization the server application starts to listen broadcast messages and the client starts to broadcast several notifications in plain text format. Note that, the message format of WAVE is not used for the sake of simplicity.

WIRELESS SPECTRUM ANALYSIS FOR V2V

Communications systems use different types of signals to convey bits of information. Acoustic, electromagnetic, and electrical signals are just to name a few. Peculiar to wireless communications, radio frequency (RF) signals are the most dominant type among others due to their amiable propagation characteristics especially in terrestrial domain. However, RF spectrum is a public resource; therefore, it is shared by multiple physically close-by terminals. Publicity gives rise to many issues such as MAI, security, and efficient use of the RF spectrum.

With the ever-increasing demand for wireless services, it is anticipated that the number of devices and technologies operating on RF spectrum will grow further. Although such a growth implies a scarcity in the RF spectrum, measurements reveal that it is underutilized indeed [40]. Both CR and NGWN technologies aim at tackling this inefficiency by steadily checking it whether the specific RF band of interest is occupied or not. This operation is known as “spectrum sensing”. Based on the result of sensing operation, spectral gaps, which are called “white holes”, are then exploited.

It is obvious that a successful spectrum sensing operation depends upon the performance of the methods/techniques employed. Prominent factors in evaluating the performance of these methods are their accuracy, agility, and robustness. From the design perspective, accuracy and agility are contradicting requirements. Therefore, methods present in the literature attempt to find a design which yields a compromise between accuracy and agility [41, 42]. However, radiometer (energy detector) is a very special technique due to the

following reasons: First, radiometer does not necessitate any sort of *a priori* knowledge of the signal to be detected. Therefore, radiometer yields a simplistic design. Second, it is the optimal detector under the absence of *a priori* knowledge of the signal to be detected [43].

As a non-coherent receiver, radiometer collects the energy of the received signal within a specific time interval at a particular frequency band. Putting aside its being the optimal detector in the absence of *a priori* knowledge of the signal to be detected, radiometer has several fundamental shortcomings. For instance, its performance is affected dramatically by the uncertainties in noise variance, low signal-to-noise ratio (SNR) regime, and spread-spectrum signals [44–46]. Beside theoretical studies, it is critical to understand and evaluate the performance of radiometer under practical conditions and applications. Impact of digital modulation, mobility, line-of-sight (LOS)/non-line-of-sight (NLOS), wide- and narrow-band reception are just to name few. However, to the best knowledge of authors, impact of in-phase/quadrature (I/Q) branches on radiometer performance has not been investigated in the literature for different digital modulation schemes. Therefore, in this chapter, impact of I/Q branches is investigated.

4.1 Statement of the Problem, Signal Model, and Radiometer

Statement of The Problem: Input to radiometer is the received signal at baseband which includes the ambient noise and probably an unknown signal. Radiometer needs to decide whether the unknown signal is present or not in the received signal. Statistically speaking, this is expressed as:

$$r(t) = \begin{cases} n(t), & H_0, \\ x(t) + n(t), & H_1, \end{cases} \quad (4.1)$$

where $n(t)$ is complex additive white Gaussian noise (AWGN) with $\mathcal{CN}(0, \sigma_N^2)$ in the form of $n(t) = n_I(t) + jn_Q(t)$ as both $n_I(t)$ and $n_Q(t)$ being $\mathcal{N}(0, \sigma_N^2/2)$ and $j = \sqrt{-1}$; $x(t)$ is the complex baseband equivalent of the unknown signal; H_0 denotes the hypothesis corresponding to absence of the unknown signal, whereas H_1 is the hypothesis cor-

responding to presence of it. Hence, the statement of the problem can be expressed as deciding whether an unknown signal $x(t)$ is present by examining the statistical characteristics of the received signal $r(t)$ in the presence of noise $n(t)$.

Signal Model: The unknown signal, $x(t)$, can be decomposed into the following form under the narrowband channel assumption [47]:

$$x(t) = m(t)s(t)a(t), \quad (4.2)$$

where $m(t)$, $s(t)$, and $a(t)$ represent complex fading channel process, slow-fading process, and the unknown baseband signal, respectively. In addition, the unknown baseband signal is assumed to be digitally modulated as [48]:

$$a(t) = \sqrt{E_k} e^{j\theta_k} p_k(t), \quad (4.3)$$

where E , θ , $p(\cdot)$ are the energy, phase, and the complex-valued pulse shaping waveform, respectively for the k -th digital symbol with $k = 0, 1, \dots, M$ in an M -ary scheme. Note that all three processes in (6.2) are independent of each other and of $n(t)$.

For modeling the fading processes, physical radio propagation environment should be examined. Transmit signals reach the receiver antenna as multiple rays or paths. Due to constructive and destructive superposition, received signal power level fluctuates drastically leading to the phenomenon known as fading. The resulting signal can be represented with a complex fading channel process as

$$m(t) = h(t)e^{j\phi(t)}, \quad (4.4)$$

where $h(t)$ and $\phi(t)$ refer to the amplitude and phase of the complex channel process, respectively. In case there is sufficiently large number of independent paths superposing at the receiver antenna in the absence of a specular signal such as in LOS environments, $h(t) = |m(t)|$ yields the Rayleigh distribution in accordance with the central limit theorem (CLT). In addition, mobility gives rise to correlation in fading channel process [49].

If the angle-of-arrival (AoA) of the paths at an omni-directional antenna is assumed to be uniformly distributed $[-\pi, \pi)$ on a 2-D plane, then the Jakes' Doppler spectrum occurs as a special case. Correlation in temporal-domain for this special case is given by $R_h(\tau) = J_0(2\pi f_D |\tau|)$, where $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind; f_D is the maximum Doppler frequency with $f_c v/c$, f_c is the operating frequency, v is the mobile speed, and c is the speed of light ($c = 3 \times 10^8$ m/s).

Beside fast-fading process, transmitter-receiver separation and the obstacles present in between affect the received signal power as well. Loss in the received signal power due to the transmitter-receiver separation is known as distance-dependent path loss. It decreases monotonically as a function of the relative distance between transmitter and receiver. Obstacles along the propagation paths between transmitter and receiver cause drastic fluctuations in the power level of the received signal too. This phenomenon is known as shadow fading. Measurement data reveal that the first-order statistics of the slow-fading phenomenon can be approximated by a log-normal distribution. Therefore, the joint effect of path loss and shadow fading could be modeled by a single process of the form given below [47]:

$$s(t) = \exp\left(\frac{1}{2}\mu(t) + \frac{\sigma_G}{2}g(t)\right), \quad (4.5)$$

where $\mu(t)/2$ represents mean, $\sigma_G/2$ is the standard deviation of log-normal fading, and $g(t)$ is a real-valued unit normal process $\mathcal{N}(0, 1)$. It is not difficult to infer from (6.5) that $\mu(t)$ represents the impact of distance-dependent path loss varying over relatively longer periods of time. As in complex fading process, experimental results also report that $g(\cdot)$ exhibits correlation of an exponentially decaying form [50]:

$$R_g(\tau) = E\{g(t)g(t + \tau)\} = \exp\left(-\frac{v|\tau|}{d_\rho}\right), \quad (4.6)$$

where $E\{\cdot\}$ is the statistical expectation and d_ρ refers to the decorrelation distance. Field measurements show that various environments have different decorrelation distances. For example in [50], d_ρ is calculated to be 5.75m and 350m for urban and suburban environmental classes, respectively. It is crucial to state that both (6.5) and (6.6) correspond to

simplified theoretical approximations which are consistent to some extent with experimental results available in the literature. However, there are some other studies available in the literature related to shadowing models such as static and dynamic shadowing [51].

Radiometer: Radiometer strives to collect the energy of the received signal for a specific time interval. Next, the collected energy, which is also known as “decision statistic,” is fed to a decision device. Decision statistic is compared to a pre-determined threshold to come up with a decision regarding the absence/presence of the unknown signal. In discrete domain, the energy detector output can be stated as:

$$d[n] = \sum_{i=0}^{N-1} |r[i]|^2 \quad (4.7)$$

where N is an arbitrary integer number of samples and $r[\cdot]$ represents the discrete counterpart of $r(\cdot)$. For H_0 , AWGN assumption gives rise to a central χ^2 distribution with N degrees of freedom (χ_N^2). On the other hand, for H_1 , (6.7) gives rise to a non-central χ_N^2 distribution with an additional shape parameter. It is also crucial to express in here that in case the number of samples N is sufficiently large, the decision statistics can be considered to be asymptotically normally distributed with certain mean and variance in accordance with the CLT.

4.2 Experimental Setup, Data Collection, and Processing

4.2.1 Experimental Setup, Devices, and Equipment Used

In the experiments, a vector signal generator (VSG) is used for emulating the unknown signal source as transmitter. The transmitter is stationary in all sets of the measurements. The VSG is programmed to send pseudo noise (PN)-23 that is already registered in its memory with a symbol rate of 100kS/s and at a power of -25dBm in all sets of experimental setups. A vector signal analyser (VSA) is used as receiver to capture the measurement data. VSA is capable of exporting baseband I/Q samples to an external device in several forms. The I/Q samples stored in an external media are fed into a computer on which MATLAB software runs. Output of radiometer is obtained via the software. Results are

plotted and evaluated.

It is worth mentioning here that human activities are present during the measurements so that a typical indoor mobile propagation environment is emulated.

4.2.2 Data Collection

Upon fixing the VSG, it is programmed to transmit the PN sequence in binary phase shift keying (BPSK) format for H_1 case. Then, the VSA is fixed where LOS between VSG and VSA is established. Next, the VSA is adjusted in such a way that the transmit signal bandwidth is entirely covered. After completing the LOS measurements in BPSK scheme, VSG is set to send the same PN sequence with a different digital modulation schemes, namely quadrature phase shift keying (QPSK) and 16–quadrature amplitude modulation (QAM) as well. In the sequel, one could wonder why these three modulation schemes are selected specifically in measurements. There are two main reasons for this selection: First, the performance of radiometer under different modulation orders for the same modulation class should be studied. In here, BPSK–QPSK pair corresponds to the scenario where modulation order is investigated. Second, the performance of radiometer under different modulation types should be examined. In here, phase shift keying (PSK) group corresponds to the constant envelope modulation type, whereas QAM itself represents the amplitude modulation (AM) type.

For H_0 scenario, VSG is switched off. Then, it is set to capture the ambient noise within the RF band of interest. Next, the captured data are analyzed whether there is an unknown interfering signal in them. This way the data captured for H_0 is ensured solely to contain the ambient noise.

4.2.3 Data Processing

Collected data includes baseband I/Q samples for each and every set of measurements. Decision statistic for radiometer is obtained via (6.7) through the use of a script written in MATLAB which was fed by the collected I/Q samples.

4.3 Measurement Results

The VSA is set to capture a time period of 100ms for all modulation types. Then, by playing with the variable N in (6.7), different levels of degrees of freedom are obtained. Also, during the whole measurement period, the output power level of VSG is adjusted to be -25dBm in order to better observe the performance of radiometer under low-SNR regime.

First, it is desirable to check with the output of radiometer for each modulation type. Results for BPSK modulation is given in Figure 4.1. It is seen in Figure 4.1 that there is almost no difference between in-phase and quadrature branches. However, decision statistic changes drastically once I/Q branches are taken into account simultaneously.

Results for QPSK modulation is given in Figure 4.2. In contrast to BPSK scenario, in-phase, quadrature, and I/Q branches together exhibit similar behavior for QPSK. This mainly stems from the fact that for QPSK signals, statistically speaking, both in-phase and quadrature branches are visited at the same rate, each of which corresponds to a complex number.

Up until this point, constant envelope modulations have been investigated. In order to check with the behavior of radiometer under inconstant envelope modulation, results for 16-QAM given in Figure 4.3 could be investigated. It is observed in Figure 4.3 that 16-QAM yields a particular behavior which could be classified between behaviors of BPSK and of QPSK. BPSK yields a dramatically different behavior for its I/Q branch as compared to its in-phase and/or quadrature branch, whereas QPSK yields a similar pattern (with a different mean value) for all branches. Nevertheless, 16-QAM, as stated above, exhibits a progressive pattern across in-phase, quadrature, and I/Q branches.

According to (6.1), radiometer is always contaminated with the ambient noise. Therefore, behavior of radiometer under H_0 hypothesis should be investigated separately. Results for the output of radiometer H_0 hypothesis is in Figure 4.4. It is interesting to note that behavior of radiometer follows a similar pattern under H_0 hypothesis and for 16-QAM scenario. However, one should also state that the decision statistics for these cases are

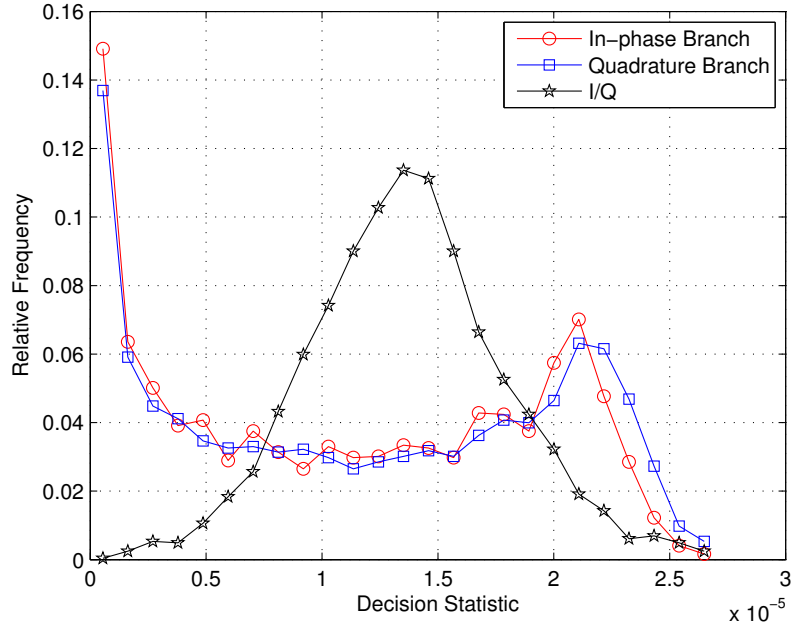


Figure 4.1 Output of radiometer for in-phase-only, quadrature-only, and I/Q input under BPSK modulation.

dramatically different from each other in terms of their amplitudes.

4.4 Concluding Remarks and Future Directions

Radiometer is the optimal spectrum sensing technique when any *a priori* knowledge about the signal to be detected is not present. Beside its optimality, simplistic design, easy implementation, and tractable analysis are key features of radiometer. However, to the best knowledge of authors, all of the studies in the literature focus on the complex domain behavior. In this study, both in-phase and quadrature branches of radiometer are investigated separately under digitally modulated signals. For this purpose, an experimental setup is established and measurements are carried out under stationary LOS conditions. Impact of both constant envelope and AM signals are examined via collected data.

Experimental results reveal that the performance of radiometer varies drastically with the type of digital modulation scheme employed at the unknown signal source. In addition, collected data show that constant envelope modulation behavior is different from AM behavior for radiometer. Furthermore, it is observed that output of radiometer behaves differently for real and complex modulation types within the constant envelope modula-

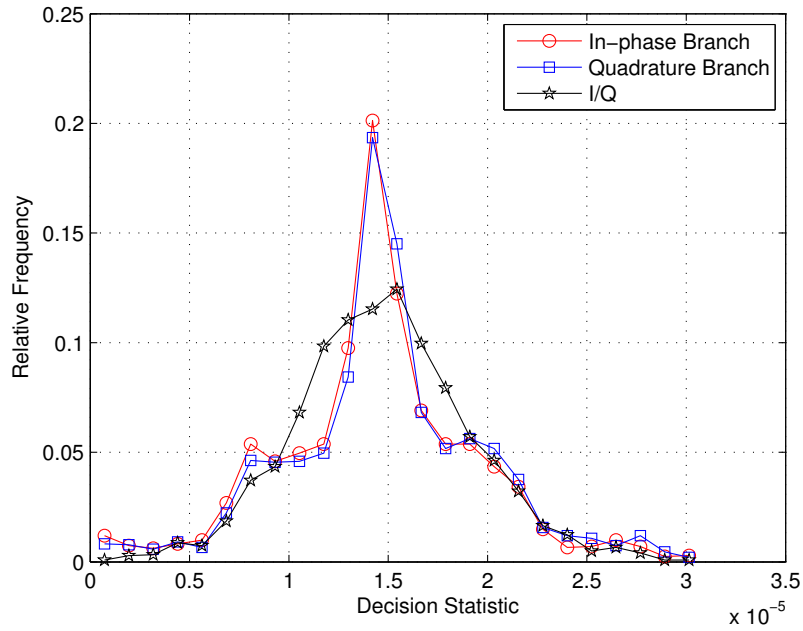


Figure 4.2 Output of radiometer for in-phase-only, quadrature-only, and I/Q input under QPSK modulation.

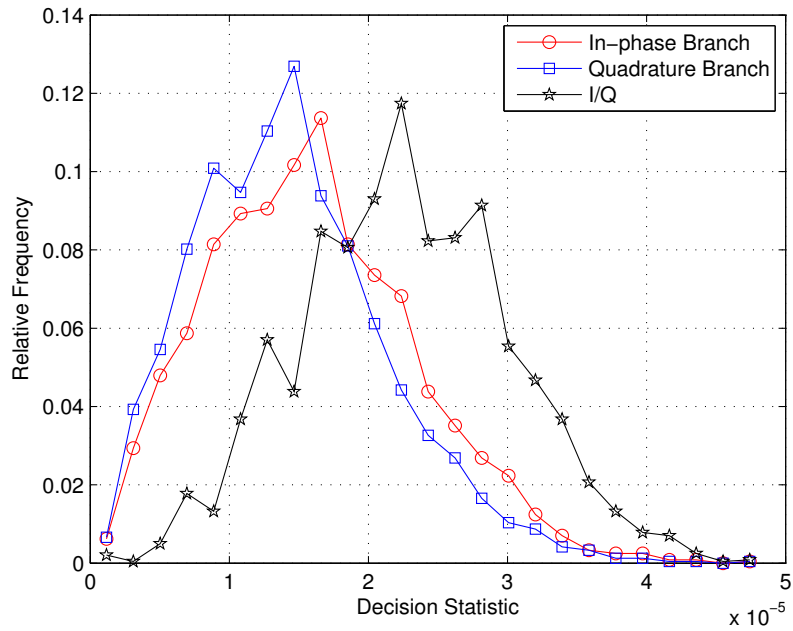


Figure 4.3 Output of radiometer for in-phase-only, quadrature-only, and I/Q input under QAM modulation.

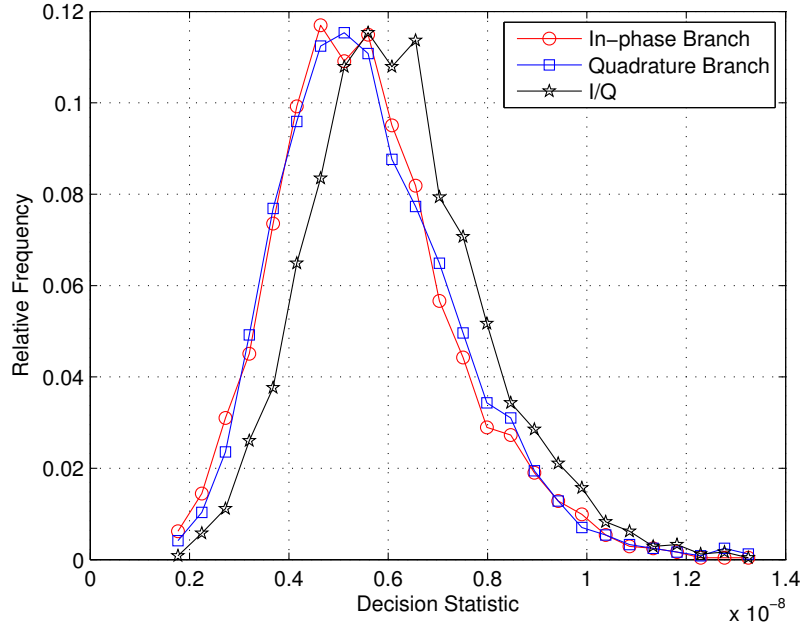


Figure 4.4 Output of radiometer for in-phase-only, quadrature-only, and I/Q input under H_0 hypothesis.

tion class as well.

Based on the experimental results collected, one could also infer that signal classification is possible by simply employing radiometer at the receiver side. As a future work, digital modulation classification with the use of radiometer could be investigated due to mild design requirements of radiometer. Also, impact of NLOS conditions along with mobility needs to be studied as well.

4.5 Defining Optimum Sensing Interval for V2V

4.5.1 I/Q-Level Measurements

As for almost each and every communications technology, one of the most important steps is to study the PHY-layer behaviors in order to be able to develop protocols for V2Vs in different OSI layers. It is known that V2Vs will be based on the protocol suite IEEE802.11, generic PHY-layer behaviors for V2Vs are expected to be inherited as well. Some of the PHY-layer behaviors are broadcast format, fundamental resource allocation mechanisms, cyclic prefix options, and so on.

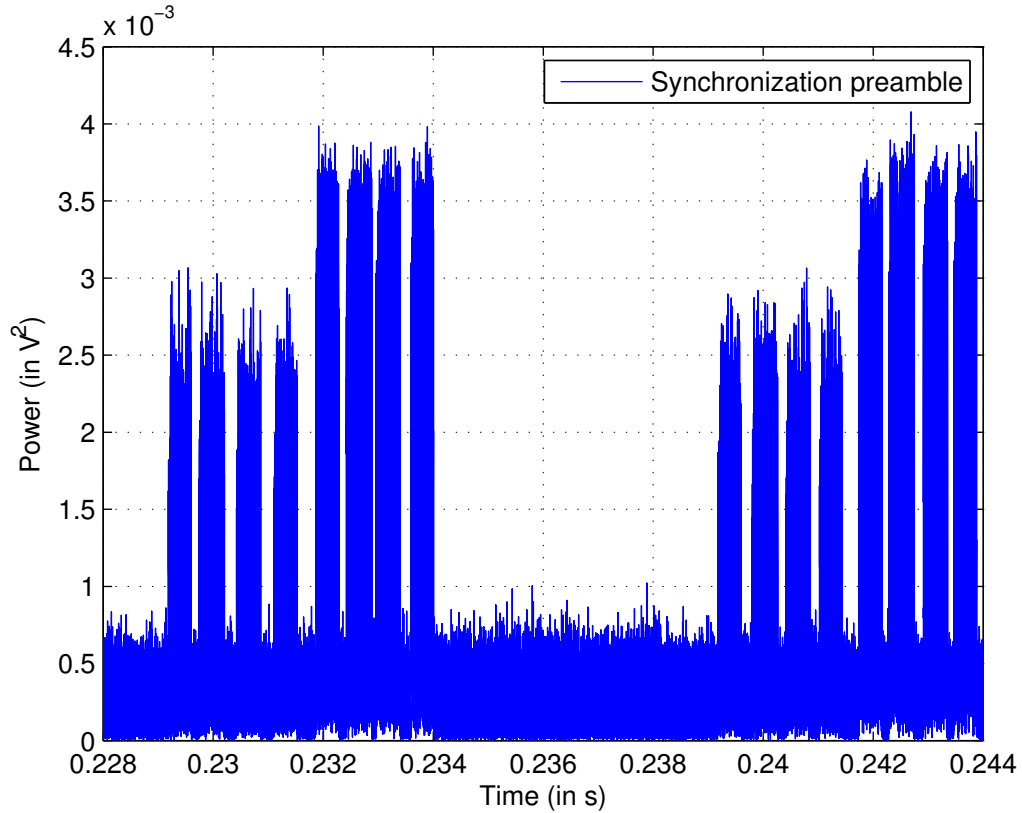


Figure 4.5 Average and standard deviation of the collision rate.

4.5.2 Measurement Results

First of all, two nodes are set in such a way that node in the transmit mode takes a short text message from the application layer and sends it at 5.9GHz. According to the generic IEEE802.11 protocol suite, before the data transmission starts, a synchronization mechanism takes place. With this mechanism, the receiver can handle first coarse and then fine carrier frequency offset estimation and adaptive channel equalization. Synchronization data can be seen in time in Figure 4.5.

Frequency–domain behavior of the PHY data is also very important. Note that specific to generic IEEE802.11 protocol suite, synchronization preamble is also sent on the same band with a relatively narrower bandwidth. Since IEEE802.11 protocol suite employs orthogonal frequency division multiplexing (OFDM) structure, subcarrier formation and its allocation are important. In this regard, a snapshot of the synchronization data is given in Figure 4.6. Note that in Figure 4.6 all subcarriers are deployed around the folding frequency, which represents the direct current (DC) component. In order to better understand

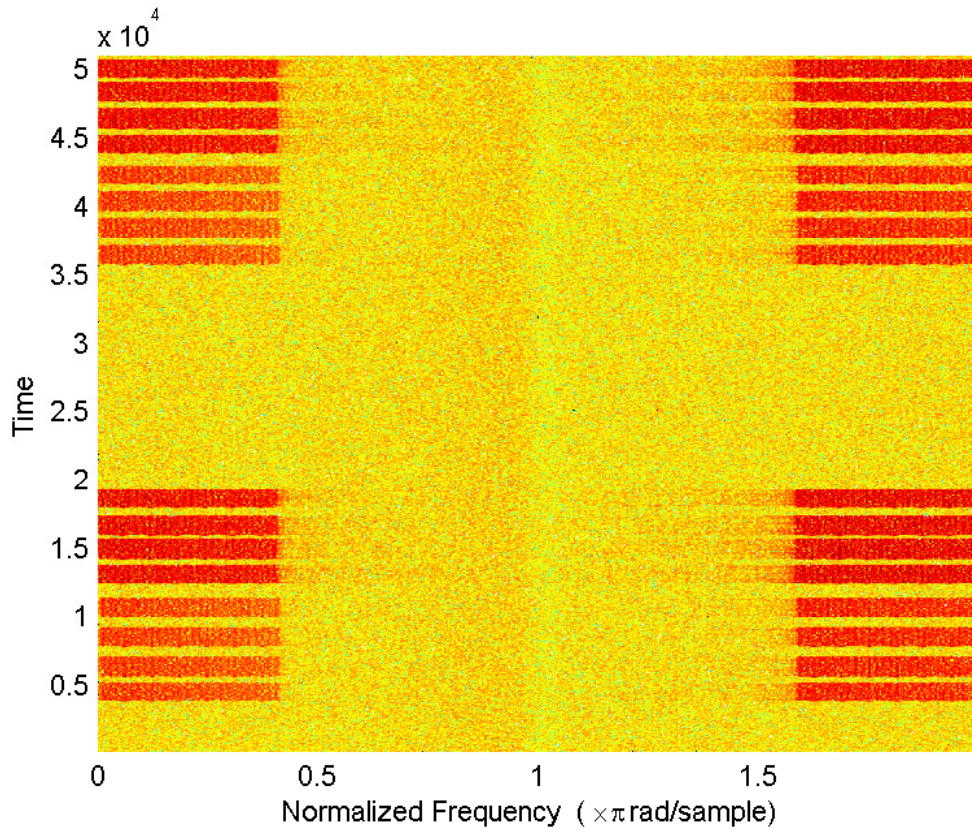


Figure 4.6 Synchronization preamble spectrogram. Note that folding frequency corresponds to the DC component, which is left empty in IEEE802.11 protocol suite.

the subcarrier deployment, Figure 4.7 can be investigated. As can be seen in Figure 4.7, subcarrier deployment manifests itself as uniformly distributed spikes all across the base-band. It is important to keep in mind that Fourier transform establishes some sort of averaging over frequency domain; therefore, spikes are shown in a uniformly distributed manner. Subcarrier layout and allocation might differ for different bursts. However, it is outside the scope of this study.

4.6 Detection of The Bursts in Time

One of the most important aspects of networks adopting IEEE802.11 protocol suite is packet collision. Collision plays a crucial role especially for V2V networks. Hazardous situations and life-threatening conditions might arise in V2V networks since packet collisions cause delay in network entry and successful reception. Therefore, it critical to identify the empty slots for the following two reasons: First of all, identification of empty

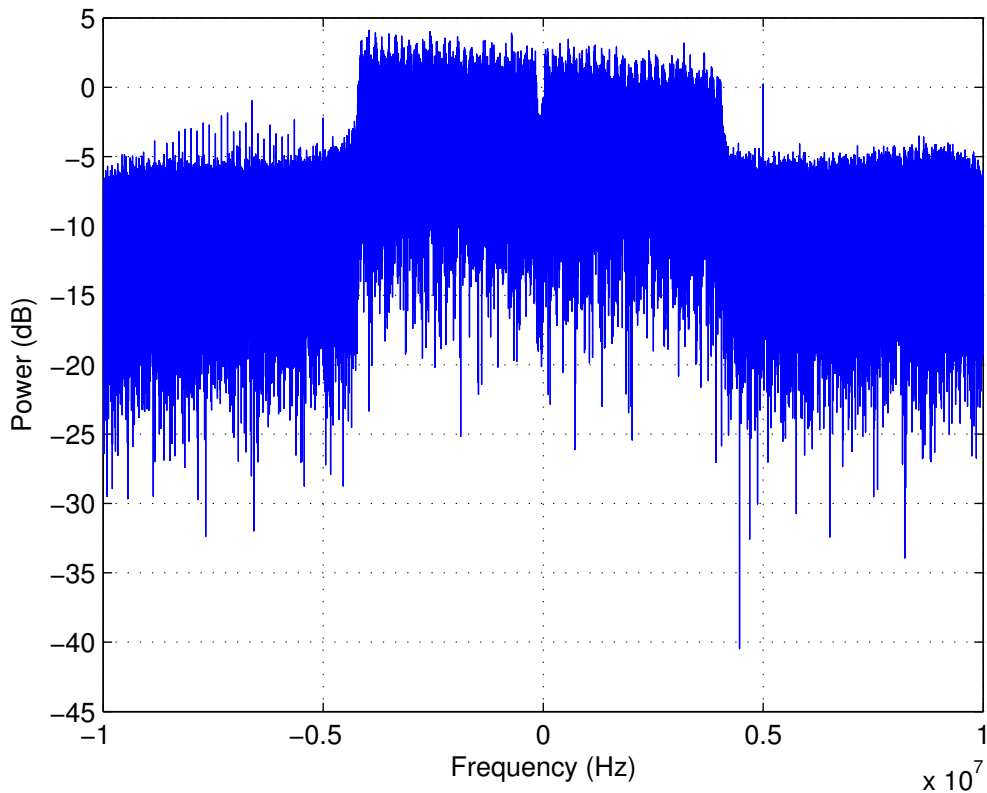


Figure 4.7 Synchronization preamble subcarrier deployment.

slots might increase the probability of success in network entry protocol. Once a successful network entry is achieved, empty slot identification increases the performance.

There are various empty slot identification methods and techniques are present in the literature. Due to strict time and computational complexity constraints, energy detector seems to be a plausible empty slot identification tool for V2V networks. Therefore, in this report, results for energy detection are presented. However, it should be stated that any baseband identification algorithm or method could be employed for this purpose.

4.6.1 Energy Detection

Identification of bursts in time focuses on detecting the presence or absence of a signal, say $x(t)$, by examining the statistical characteristics of the received signal, $r(t)$, including the ambient noise, $n(t)$ [43, 52]. Presence and absence of the such a signal can formally

be stated via the complex baseband equivalent of the received signal as:

$$r(t) = \begin{cases} n(t), & H_0, \\ x(t) + n(t), & H_1, \end{cases} \quad (4.8)$$

where $n(t)$ is complex AWGN with $\mathcal{CN}(0, \sigma_N^2)$ in the form of $n(t) = n_I(t) + jn_Q(t)$ as both $n_I(t)$ and $n_Q(t)$ being $\mathcal{N}(0, \sigma_N^2/2)$ and $j = \sqrt{-1}$. In (6.1), H_0 corresponds to the hypothesis of absence of the unknown signal, whereas H_1 corresponds to the hypothesis of presence of it. Due to the stochastic nature of $r(t)$, performance of spectrum sensing operation relies heavily on the statistical characterizations of both $x(t)$ and $n(t)$.

Energy detector (or radiometer) is a simple, first-order receiver which accumulates the energy of the received signal for a specific time interval. Collected energy, which is called decision statistic, is then sent to a decision device. Decision device compares the instantaneous decision statistic with a pre-defined threshold to come up with a binary conclusion regarding the absence/presence of an unknown signal. In discrete domain, assuming that the detector has a sufficiently high sampling rate, output of the detector is calculated by $d[n] = \sum_{i=0}^{N-1} |r[i]|^2$ where N is an arbitrary number of samples taken into consideration and $r[\cdot]$ denotes the discrete counterpart of the received signal, $r(\cdot)$. For H_0 , AWGN assumption yields a central χ^2 distribution with N degrees of freedom (χ_N^2). For H_1 , $d[n]$ provides a non-central χ_N^2 distribution with an additional shape parameter. If N is selected to be large enough, the decision statistic is assumed to be asymptotically normally distributed with certain mean and variance values in accordance with the central limit theorem. Before proceeding with the performance analysis of radiometer, it is worth mentioning that radiometer is a non-coherent receiver and is known to be the ‘‘optimum’’ detector in the absence of *a priori* knowledge about the received signal [43,52]. Yet, it has very critical drawbacks. First of all, noise-plus-interference uncertainty degrades performance of radiometer drastically [44]. In addition, low SNR regime leads to unsatisfactory results [45]. Combining these two issues, one could easily conclude that radiometer performs poorly in detecting spread-spectrum signals [46]. Furthermore, it is clear that performance of radiometer is heavily dependent on SNR/signal-to-interference-plus-noise ratio (SINR). For the sake of completeness, it is desirable to show how the performance

of radiometer is related to SNR.

As stated earlier, the decision statistic $d[n]$ under the AWGN assumption has a central χ^2 distribution with N degrees of freedom (χ_N^2) for H_0 , whereas it has $\chi_N^2(m)$, where m denotes the shape (non-centrality) parameter [43] for H_1 . Based on these assumptions, one could easily obtain the probability density function (PDF) for H_0 scenario as: $f_{\chi_N^2}(x) = x^{N/2-1} e^{-x/2} / (2^{N/2} \Gamma(N/2))$ where $\Gamma(\cdot)$ denotes the gamma function. Similarly, the PDF for H_1 scenario is given by $f_{\chi_{N,m}^2}(x) = \frac{1}{2} \left(\frac{x}{m}\right)^{N/4-\frac{1}{2}} e^{-\frac{m+x}{2}} J_{N/2-1}(\sqrt{mx})$ where $J_k(\cdot)$ denotes the k -th order modified Bessel function of the first kind. Based on both $f_{\chi_N^2}(x)$ and $f_{\chi_{N,m}^2}(x)$, receiver operating characteristic (ROC) could theoretically be derived by seeking for $\Pr(\chi_N^2 > \lambda | H_1)$ and $\Pr(\chi_{N,m}^2 > \lambda | H_0)$, which correspond to probability of detection and probability of false alarm, respectively. Here, $\Pr(\chi_N^2 > \lambda | H_1)$ is given by $Q_g(\sqrt{2\gamma}, \sqrt{\lambda})$ where λ denotes the decision threshold, $Q_g(\cdot)$ is the generalized Marcum-Q function, γ is the instantaneous SNR. Note that the optimum threshold selection mandates one to have knowledge about the SNR [43, Eq.(35)]. It is not difficult to see that the same conclusion (with more sophisticated calculations) holds also for the SINR in case there are unknown activities within the spectrum of interest apart from that of primary user [53].

4.6.2 Measurement Results

In Figure 4.8, decision statistics, which are the output of energy detector in corresponding time slots, are given for $N = 20$, corresponding to a time frame of $1\mu s$. As can be seen from the figure, a resolution of $N = 20$ yields satisfactory results. However, this requires too frequent detection. Therefore, it might not be desirable either. Hence, it could be optimized by considering the length of a fractional portion of synchronization frame, which could be $1/3$, or $1/4$, depending on the design criterion. It is, of course, critical to state that as $N \rightarrow \infty$, one should wait for the decision statistics to emerge longer. Obviously, a prolonged decision process deteriorates the sensing performance.

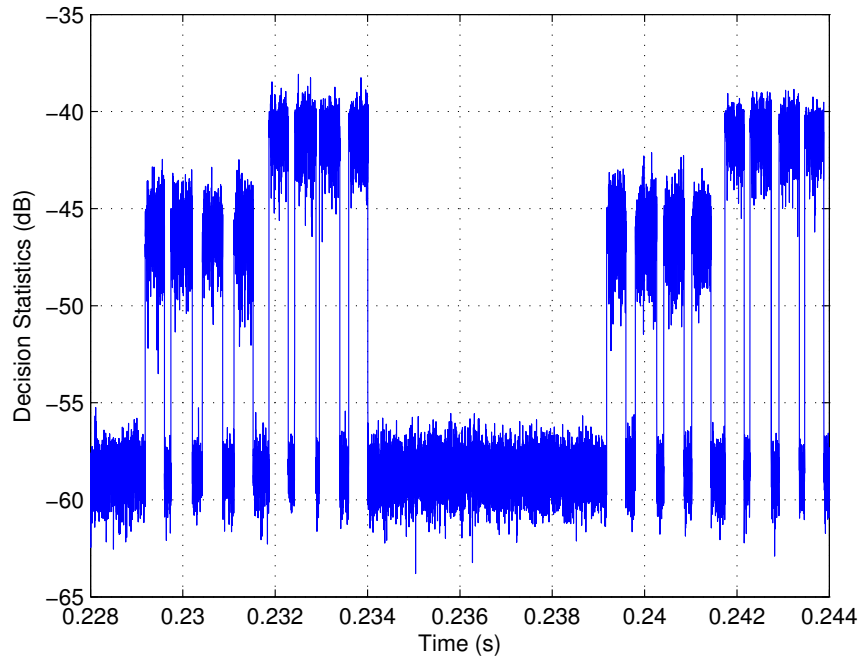


Figure 4.8 Fine detection of occupied slots via energy detection for $N = 20$.

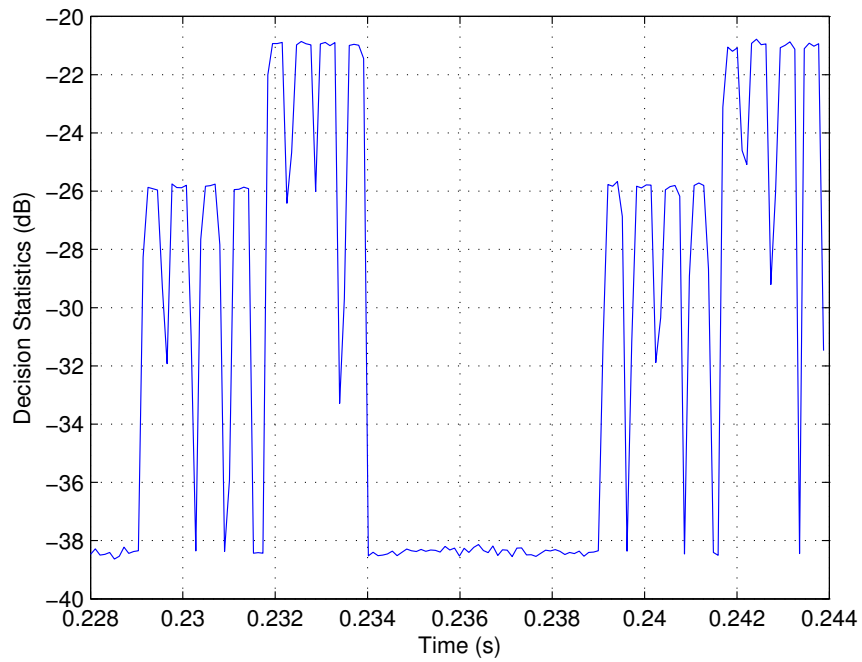


Figure 4.9 An instance of suboptimum detection of occupied slots with $N = 0.25 \times T$, where T denotes the length of a standard synchronization burst.

GREEN AND SECURE VEHICLE-TO-VEHICLE COMMUNICATIONS NETWORK PROTOCOL

5.1 Designing a MAC Layer Protocol for V2V

Contemporary cooperative road / traffic systems are not completely autonomous. Human control still plays a significant role in current designs. However, drivers have various impairments such as slow response time (delays in reactions stemming from multiple reasons like old age, fatigue, driving under influence, distraction [cell phone, entertainment system, etc.]) and impediment in sensory organs which cause accidents leading to serious injuries and deaths. Moreover, being non-responsive to dynamic traffic and weather conditions and lack of knowledge about the capabilities of the vehicle are known to be the two other critical parameters leading to severe traffic accidents. According to the data reported in [2, p. 6], the rate of driver faults in accidents involving death and injury in Turkey was 90.2% in 2011. Ten-year average of the rate of driver faults between 2002 and 2011 is 94.46%. Since similar statistics are obtained throughout the world, as pointed by World Health Organization (WHO) in [1, Ch. I, p. 7], road safety efforts should be increased to reduce traffic accidents. Adopting emerging technologies is an integral part of such efforts. On the market, for instance, there are vehicles that keep track of the road lanes and warn the driver in case an anomaly takes place; keep an eye on the face gestures of drivers to detect whether he/she is sleeping; identify the blind spot; and maintain the following/stopping distance. Such assistive technologies can alleviate problems of each individual driver/vehicle; however, they cannot do anything about the possible problems of other drivers/vehicles. Therefore, such solitary efforts will always stay as a limited

solution unless other drivers/vehicles are taken into account.

In addition to the life-critical issues, fuel consumption is another crucial topic for ITSs as well. With the same reasoning, one could easily claim that in case some diagnostic data could be disseminated among the vehicles that are physically close to each other, a better fuel consumption strategy could be developed for the entire set of vehicles compared to individual fuel consumption optimization strategies. An optimized fuel consumption strategy for a set of vehicles implies that the best overall driving performance could be achieved with less fuel; therefore, with less carbon-based gas emission. Countries such as Japan and The United States, and large-scale organizations such as the European Union (EU) drive ITS especially from this perspective, which is referred to as “green transportation.” Motivated by the green transportation notion, new generation vehicles are engineered to optimize the fuel consumption and reduce carbon-based gas emission under various driving scenarios. However, a comprehensive energy optimization can only be possible with joint optimization of the entire transportation system rather than that of the individuals. For instance, if a driver is told not to speed up in advance due to a hazardous situation already have taken place ahead, then the driver would not accelerate and could save fuel to some extent. Furthermore, if the same driver switches to the defensive driving mode upon the same warning, a possible accident and/or dangerous situation could easily be avoided.

Studies in the literature in the field of vehicle-to-vehicle communications can be classified in different ways. One of these ways is to focus on which aspects of optimization and control towards ITS are investigated. For instance, in [54], a cooperative collision warning protocol is proposed for different scenarios taking into account critical parameters such as transmission delay and human responses. In [55], highway traffic security is tried to be enhanced via wireless communications from the perspective of MAC and upper layer requirements. In [56], physical layer aspect of vehicle-to-vehicle communication is investigated from the green communications point of view focusing on power control. In [20, 57], cooperative forward collision avoidance, intersection safety and vehicle-infrastructure integration are studied and relevant projects are introduced. There are studies contemplating the different topologies for different purposes in vehicular networks [58–61]. It is important to note that recently there has been a great interest

in establishing the security and privacy for vehicle networks as well [62]. For a more comprehensive survey, the readers can refer to [63].

In light of the all aforementioned discussions, one could easily conclude that there are two essential motivations of a cooperative road/traffic system: 1. establishing delay-sensitive, short-range communications and 2. developing an optimum strategy for a specific constraint such as overall fuel consumption. Based on these motivations, the initial part of establishing a Green and Secure Vehicle-to-Vehicle Communications Network (GSV2VCN) is presented in this study. The contributions of this work are three-fold: First, a half-duplex mode transceiver protocol for establishing a vehicle-to-vehicle network is proposed. Being different from IEEE 1609.3, the protocol proposed focuses solely on a universal control channel (CC) to agree on a master of the group of nodes of interest and minimizes the over-the-air signaling considering the delay-sensitive nature of vehicle-to-vehicle networks. Second, master-slave relationship is relaxed in such a way that in case of having the possibility of a hazardous situation, any node could send a pre-determined distress signal over the channel/band that the master broadcasts the beacon. Finally, an object-oriented simulation framework is designed and run to obtain statistics for the protocol proposed. Moreover, the simulation framework is constructed in such a way that it could easily be used to simulate different scenarios, settings for many standards such as IEEE 1609.3 and IEEE 802.11x.

5.2 The Proposed Protocol: An Analogy

In this part, the proposed protocol will be given by an analogy of a nomadic tribe. Once the fundamental concepts and behaviors are defined through the use of this analogy, the protocol will be introduced in a formal manner.

Consider a tribe whose members are individual nomads. The ultimate purpose of the tribe –once it is established– is to warn all of its members in case an anomaly occurs and/or a possibility of hazardous situation arises. The tribe is assumed to be established at least two nearby nomadic individuals talk to and then agree with each other on the master. Each tribe should have a single master. Due to the nomadic behavior, master might change in time. Tribes that consist of only a single nomad is the trivial case, which

will not be examined in here. A tribe is assumed to be of finite and (again, due to the nomadic behavior) a varying population size. Its coverage is, therefore, considered to be limited as well. Scenarios for multiple nearby tribes are outside the scope of this study.

In order for a nomadic individual to talk and/or can be heard, there is a unique and universal channel. Nomadic agree with each other via the same channel. As will be shown subsequently, it suffices to have at least two nomadic individuals to agree with each other via this universal channel to establish a tribe. Nomadic individuals have precise knowledge neither about their own positions nor about those of others. This implies that an individual is only interested in whether there are other individuals nearby. The only way to figure out whether an individual is alone or not is to listen to the universal channel. It is obvious that if there is nobody around and there is an individual far away whose voice is too weak to be heard by others are identical scenarios. In order not to keep the universal channel busy, each individual listens to it most of the times. Listening period of an individual is assumed to be governed by a PDF. In case two (or more) individuals talk on the universal channel exactly at the same time, individuals that are in receive mode experience collision and ignore the ones who talked.

Once the tribe is established (or, equivalently a master is acknowledged), the master sends a special message containing the new channel information. Individuals who acknowledged the master switch over the new channel announced. Only the master is allowed to talk on this new channel by sending a periodic message predetermined. Individuals are not allowed to talk on the new channel unless an emergency occurs. Emergency is announced by the individual who experiences it via sending a predetermined distress signal.

5.3 Analysis and Algorithm of the Proposed Protocol

The algorithmic structure of the proposed protocol consists of negotiation and network establishment. Negotiation is initiated by one of the following two circumstances: Either an individual gets closer to an already-established network without being aware of it, or an individual gets closer to a group of other individuals which have not been able to establish a network yet. Network establishment is initialized after a set of individuals exchange messages via the universal channel. It is important to state here that there will

be collisions during the network establishment stage. Before proceeding further, collision analysis is required for the network establishment stage:

Proposition 1. *Assuming that two nodes transmit the same type of signal/beacon whose width is of T in time within a window T_W satisfying $2T \leq T_W$ in a uniformly distributed manner, the probability of collision is $1 - \left(1 - \frac{(1-\rho)T}{L}\right)^2$, where ρ is the overlapping ratio of the two signals.*

Proof. See Appendix A.1 □

Indeed, Section A.1 provides the generic derivation for a wide variety of distributions of network establishment methods. However, it is crucial to know that whether the strategy adopted for network establishment is convergent or not. Therefore, the following is required:

Corollary 5.3.1. *Proposition 1 is converges for sufficiently large L values.*

Proof. See Appendix A.2 □

Assuming the group of individuals stay physically close to each other for a sufficiently long period of time, network establishment procedure is asymptotically convergent. This way it is guaranteed that network establishment procedure always yields a single master. Considering the dynamic structure of the topology, a new master is forced to be selected based on a timeout mechanism. The main structure of the proposed protocol is given in Algorithm 1.

Algorithm 1: Main algorithm

```

Initialization;
Generate unique ID;
while True do
    if isMasterKnown is True and the master is still in charge then
        | Execute protocol;
    else
        | Negotiate;
    end
end

```

Algorithm 2: Negotiation

Listen on CC;

if *Message received* **then**

switch *Message type* **do**

case *Nomination:*

if *isMaster True* **then**

 Broadcast a predetermined channel ID with Declaration message;

else

 Broadcast an acknowledge to the originator with Election message;

 Keep waiting for a random period;

end

endsw

case *Election:*

if *am I acknowledged* **then**

 Set *isMaster* to True;

 Set master dwelling time to 1000;

 Broadcast a random channel ID with Declaration message;

else

 Keep waiting for a random period;

end

endsw

case *Declaration:* Set *isMasterKnown* to True **otherwise** Ignore the message

endsw

else

 Broadcast your name with Nomination message;

end

Algorithm 3: Protocol routine

```
Listen on service channel (SC);
if Message received then
  if Is emergency message then
    | Generate alert;
  end
  | Update statistics;
else
  if Am i master then
    | Broadcast protocol info;
    | Decrease master dwelling time;
    if master dwelling less than 0 then
      | Set isMaster to false;
    end
  end
end
```

There are three types of messages in the protocol proposed: Type I. nomination, Type II. election, and Type III. declaration. Type I messages consist only of the ID of the broadcasting individual itself. These messages will be broadcast at the following three points in time: (i) initial network setup; (ii) when master timeout mechanism initializes; and (iii) when a new member wants to join the group. Election messages are referred to as Type II and they will be sent when a new master is being selected. It consists of both the ID of the individual itself and that of the nominee. If an individual hears/receives its own ID within a Type II message, then it will become the master and broadcast this info with a Type III message including the new service channel. Note that once a Type III message is broadcast, none of the individuals but the master keeps listening to the universal channel.

Upon a Type III message broadcast, the SC determined will only be used by the master. However, situations such as a sudden change in the flow, drastic deceleration in the group or an abnormal stoppages are exceptions to this rule. In such cases the individual who experiences the anomaly is allowed to send a distress/emergency signal on the SC by breaking the standard message pattern of the master.

5.4 Simulation of the Protocol

The simulation setup considers a rectangular region consisting of a four-lane road whose length is 300m. The region can have a maximum of 264 uniformly distributed vehicles of a single-type (*e.g.*, mid-size) in total assuming every vehicle is of 4.5m long. At each simulation run, a uniformly distributed random integer is selected within the range [2, 264] to populate vehicles across the rectangular region. The positions of the vehicles within this region is uniformly distributed as well. The general parameters and corresponding values used in simulation setup is given in Table 5.1. It is noteworthy to state that the upper-bound of the uniformly distributed random wait period in Table 5.1 is selected to be a number which is slightly above twice as the maximum number of vehicles that can fit in the rectangular region of interest. Note also that, such a duration corresponds to a maximum displacement of 2.5m for a vehicle speed of 15kmph.

Table 5.1 General parameters and values used in simulations

Random wait period:	$U.D.$ [1ms, 600ms)
Processing delay:	1ms
Propagation delay:	ignored due to being < 1ms
Average vehicle speed:	ITU-R Vehicular A

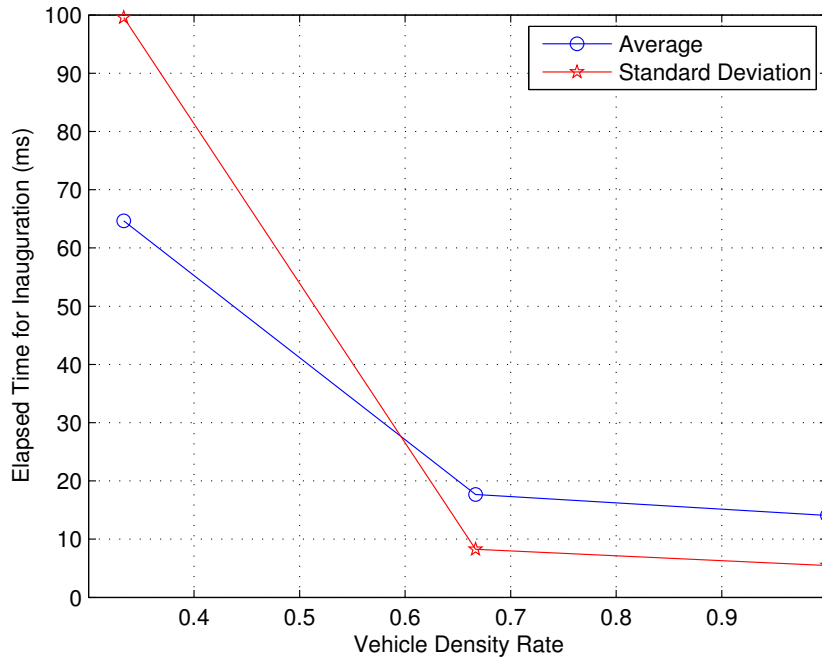


Figure 5.1 Elapsed time for recognition of the master.

At each simulation cycle, a vehicle can be in either receive or transmit mode. The vehicles

in transmit mode cannot receive any message during their transmission periods. The vehicles in receive mode can receive only a single message at each cycle, otherwise the messages are assumed to collide with each other and ignored by the receiver of interest. Each simulation cycle ends when each and every vehicle is aware of the master.

Based on the simulation setup given above, three traffic density rates are defined. One-third of the rectangular region occupied in a uniformly distributed manner corresponds to 33% (low) density, whereas two-third occupancy equals 66% density. In light of these, Figure 5.1 shows mean and standard deviation of the time elapsed for recognition of the master. As can be seen from the figure, both mean and standard deviation of the statistics exhibit an exponentially decaying behavior as the traffic density increases. Such a behavior stems from the fact that waiting period for each individual vehicle is modeled with a random variable that is uniformly distributed between 1ms and 600ms. This implies that for low-density traffic, it takes more time for an individual to transmit and/or acknowledge a message. However, for high-density traffic scenarios, there are more vehicles to take turn to transmit and/or acknowledge a message leading to a smaller average time period as compared to that of low-density scenarios.

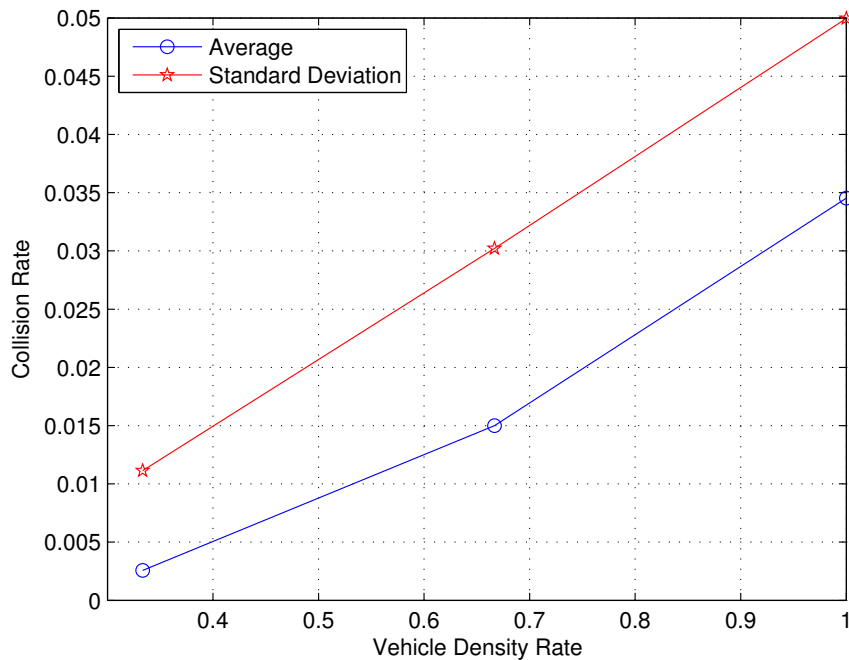


Figure 5.2 Average and standard deviation of the collision rate.

Collision rate statistics are important to evaluate the protocol proposed as well. In simulations, a single collision is assumed to occur in case minimum of three vehicles transmit

simultaneously no matter how many packets actually collide over-the-air. Figure 5.2 represents the collision rate statistics. As can be seen from the figure, when the traffic density increases, the collision rate exhibits a linear trend. Another important observation in Figure 5.2 is the average collision rate. It stays always below 3.5% for each traffic density scenario with the settings adopted implying a considerably (statistically insignificant) low rate.

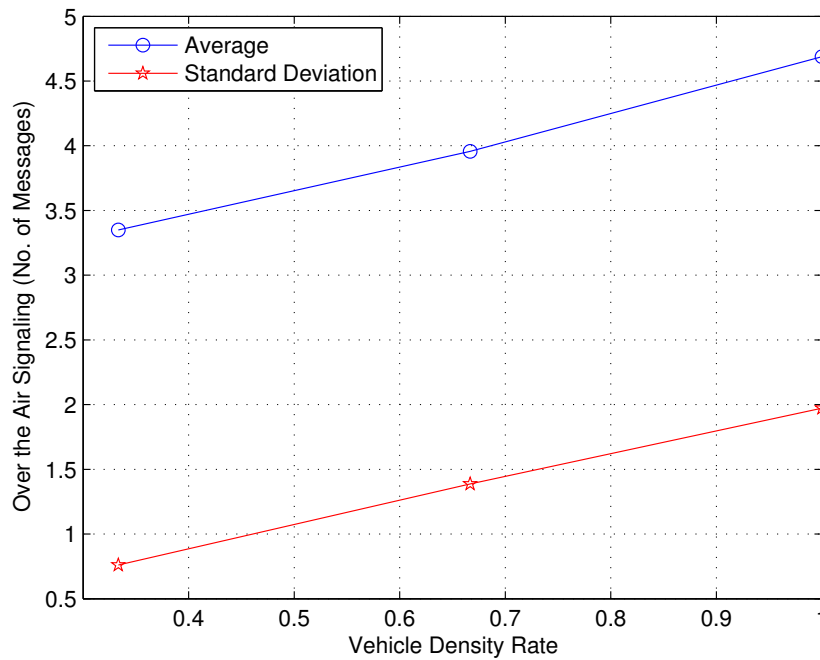


Figure 5.3 Average and standard deviation of the over-the-air signaling obtained for the entire set of simulations.

Over-the-air signaling (signaling overhead) of the proposed protocol is given in Figure 5.3. In parallel to the results given in Figure 5.2, over-the-air signaling increases linearly. It is critical to note that the proposed protocol requires at least three messages (Type I, Type II, and Type III) to be transmitted before the network is established; therefore, the average statistics should always stay above three independent of the traffic density.

5.5 Conclusion and Future Work

There has been a great effort to bring intelligence into the transportation systems in order to enhance safety of the vehicle drivers and reduce the environmental pollution especially caused by carbon-based emission. With such motivations, in this study, initial part of establishing a GSV2VCN is proposed. It is shown that the proposed protocol could be

used as an alternative to IEEE 1609.3 standard.

There are highly challenging and still open problems in the field of vehicle-to-vehicle communications. First, there is an inherent trade-off between security/privacy/authorization of the data to be exchanged and processing delay. Therefore, if possible, an optimal solution to this trade-off issue should be investigated. Second, the proposed protocol should be modified in such a way that it functions for multiple adjacent networks rather than for a single network. In addition to this, the analysis should be generalized and extended to cover some other practical scenarios such as multiple speed classes rather than uniformly distributed vehicle speed values for individuals.

A CROSS-LAYER ADAPTIVE CHANNEL SELECTION MECHANISM FOR IEEE 802.11P SUITE

In this chapter, a cross-layer adaptive channel selection mechanism is proposed for IEEE 802.11p suite. Therefore, it is first desirable to discuss a complete characterization of the proposed system in conjunction with layered structure.

6.1 Channel Selection Mechanism

Channel selection mechanism in V2V networks relies on IEEE 802.11 suite including both PHY and MAC layers [64, 65]. PHY layer is responsible for various air interface functionalities such as synchronization, channel estimation, and equalization. MAC layer takes care of channel access and scheduling operations. Note that IEEE 802.11p and IEEE 1609.x are jointly known as WAVE and specifically IEEE 1609.4 part extends MAC to multichannel-operations-enable mode. Peculiar to V2V networks, WAVE multichannel operations are carried out over two types of channels, namely control channel and service channel. It is important to keep in mind that there is a single control channel, whereas there are multiple service channels in WAVE. Because the safety and control signals/messages are sent over control channel and other types of application signals/messages are transmitted over service channels, a coordination mechanism is necessary. It is obvious that a successful coordination mechanism relies on the joint performance of both PHY and MAC layers, which directly points out a cross-layer design.

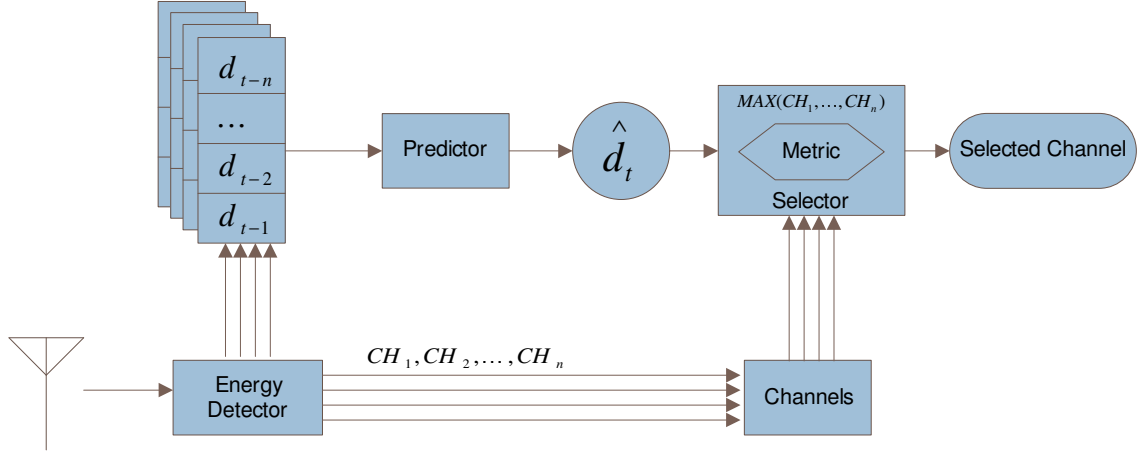


Figure 6.1 Proposed channel selection mechanism

6.1.1 System and Signal Model

The received signal at baseband which includes the ambient noise and probably an unknown signal is given input to radiometer. The radiometer needs to decide whether the unknown signal is present or not in the received signal, which is expressed as:

$$r(t) = \begin{cases} n(t), & H_0, \\ x(t) + n(t), & H_1, \end{cases} \quad (6.1)$$

where $n(t)$ is complex AWGN with $\mathcal{CN}(0, \sigma_N^2)$ in the form of $n(t) = n_I(t) + jn_Q(t)$ as both $n_I(t)$ and $n_Q(t)$ being $\mathcal{N}(0, \sigma_N^2/2)$ and $j = \sqrt{-1}$; $x(t)$ is the complex baseband equivalent of the unknown signal; H_0 denotes the hypothesis corresponding to absence of the unknown signal, whereas H_1 is the hypothesis corresponding to presence of it. Hence, the statement of the problem can be expressed as deciding whether an unknown signal $x(t)$ is present by examining the statistical characteristics of the received signal $r(t)$ in the presence of noise $n(t)$.

The unknown signal, $x(t)$, can be decomposed into the following form under the narrow-band channel assumption [47]:

$$x(t) = m(t)s(t)a(t), \quad (6.2)$$

where $m(t)$, $s(t)$, and $a(t)$ represent complex fading channel process, slow-fading process, and the unknown baseband signal, respectively. In addition, the unknown baseband signal is assumed to be digitally modulated as [48]:

$$a(t) = \sqrt{E_k} e^{j\theta_k} p_k(t), \quad (6.3)$$

where $E, \theta, p(\cdot)$ are the energy, phase, and the complex-valued pulse shaping waveform, respectively for the k -th digital symbol with $k = 0, 1, \dots, M - 1$ in an M -ary scheme. Note that all three processes in (6.2) are independent of each other and of $n(t)$.

For modeling the fading processes, physical radio propagation environment should be examined. Transmit signals reach the receiver antenna as multiple rays or paths. Due to constructive and destructive superposition, received signal power level fluctuates drastically leading to the phenomenon known as fading. The resulting signal can be represented with a complex fading channel process as

$$m(t) = h(t) e^{j\phi(t)}, \quad (6.4)$$

where $h(t)$ and $\phi(t)$ refer to the amplitude and phase of the complex channel process, respectively. In case there is sufficiently large number of independent paths superposing at the receiver antenna in the absence of a specular signal such as in LOS environments, $h(t) = |m(t)|$ yields the Rayleigh distribution in accordance with the CLT. In addition, mobility gives rise to correlation in fading channel process [49]. If the AoA of the paths at an omni-directional antenna is assumed to be uniformly distributed $[-\pi, \pi)$ on a 2-D plane, then the Jakes' Doppler spectrum occurs as a special case. Correlation in temporal-domain for this special case is given by $R_h(\tau) = J_0(2\pi f_D |\tau|)$, where $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind; f_D is the maximum Doppler frequency with $f_c v/c$, f_c is the operating frequency, v is the mobile speed, and c is the speed of light ($c = 3 \times 10^8$ m/s). Note that there are five major mobility classes adopted widely in the literature including: stationary, pedestrian(3 Km/h), low-speed vehicular(60 Km/h), medium-speed vehicular(120 Km/h) and high-speed vehicular(250+ Km/h). Note also that the first four categories are adopted from [66]. The high speed category should be considered to be an

extension to the older standards with updated requirements.

Beside fast-fading process, transmitter-receiver separation and the obstacles present in between affect the received signal power as well. Loss in the received signal power due to the transmitter-receiver separation is known as distance-dependent path loss. It decreases monotonically as a function of the relative distance between transmitter and receiver. Obstacles along the propagation paths between transmitter and receiver cause drastic fluctuations in the power level of the received signal too. This phenomenon is known as shadow fading. Measurement data reveal that the first-order statistics of the slow-fading phenomenon can be approximated by a log-normal distribution. Therefore, the joint effect of path loss and shadow fading could be modeled by a single process of the form given below [47]:

$$s(t) = \exp\left(\frac{1}{2}\mu(t) + \frac{\sigma_G}{2}g(t)\right), \quad (6.5)$$

where $\mu(t)/2$ represents mean, $\sigma_G/2$ is the standard deviation of log-normal fading, and $g(t)$ is a real-valued unit normal process $\mathcal{N}(0, 1)$. It is not difficult to infer from (6.5) that $\mu(t)$ represents the impact of distance-dependent path loss varying over relatively longer periods of time. As in complex fading process, experimental results also report that $g(\cdot)$ exhibits correlation of an exponentially decaying form [50]:

$$R_g(\tau) = E\{g(t)g(t + \tau)\} = \exp\left(-\frac{v|\tau|}{d_\rho}\right), \quad (6.6)$$

where $E\{\cdot\}$ is the statistical expectation and d_ρ refers to the decorrelation distance. Field measurements show that various environments have different decorrelation distances. For example in [50], d_ρ is calculated to be 5.75m and 350m for urban and suburban environmental classes, respectively. It is crucial to state that both (6.5) and (6.6) correspond to simplified theoretical approximations which are consistent to some extent with experimental results available in the literature. However, there are some other studies available in the literature related to shadowing models such as static and dynamic shadowing [51].

6.1.2 Energy Detection

Energy detector (or radiometer) is a simple, first-order receiver which accumulates the energy of the received signal for a specific time interval. Collected energy, which is called decision statistic, is then sent to a decision device. Decision device compares the instantaneous decision statistic with a pre-defined threshold to come up with a binary conclusion regarding the absence/presence of an unknown signal. In discrete domain, assuming that the detector has a sufficiently high sampling rate, output of the detector is calculated by

$$d[n] = \sum_{i=0}^{N-1} |r[i]|^2 \quad (6.7)$$

where N is an arbitrary number of samples taken into consideration and $r[\cdot]$ denotes the discrete counterpart of the received signal, $r(\cdot)$. For H_0 , AWGN assumption yields a central χ^2 distribution with N degrees of freedom (χ_N^2). For H_1 , $d[n]$ provides a non-central χ_N^2 distribution with an additional shape parameter. If N is selected to be large enough, the decision statistic is assumed to be asymptotically normally distributed with certain mean and variance values in accordance with the CLT. Before proceeding with the performance analysis of radiometer, it is worth mentioning that radiometer is a non-coherent receiver and is known to be the “optimum” detector in the absence of *a priori* knowledge about the received signal [43, 52]. Yet, it has very critical drawbacks. First of all, noise-plus-interference uncertainty degrades performance of radiometer drastically [44]. In addition, low SNR regime leads to unsatisfactory results [45]. Combining these two issues, one could easily conclude that radiometer performs poorly in detecting spread-spectrum signals [46]. Furthermore, it is clear that the performance of radiometer is heavily dependent on SNR/SINR. For the sake of completeness, it is desirable to show how the performance of radiometer is related to SNR.

As stated earlier, the decision statistic $d[n]$ under the AWGN assumption has a central χ^2 distribution with N degrees of freedom (χ_N^2) for H_0 , whereas it has $\chi_N^2(m)$, where m

denotes the shape (non–centrality) parameter [43] for H_1 . Based on these assumptions, one could easily obtain the PDF for H_0 scenario as:

$$f_{\chi_N^2}(x) = x^{N/2-1} e^{-\frac{x}{2}} / (2^{N/2} \Gamma(N/2)) \quad (6.8)$$

where $\Gamma(\cdot)$ denotes the gamma function. Similarly, the PDF for H_1 scenario is given by

$$f_{\chi_{N,m}^2}(x) = \frac{1}{2} \left(\frac{x}{m} \right)^{N/4-\frac{1}{2}} e^{-\frac{m+x}{2}} J_{N/2-1}(\sqrt{mx}) \quad (6.9)$$

where $J_k(\cdot)$ denotes the k –th order modified Bessel function of the first kind. Based on both $f_{\chi_N^2}(x)$ and $f_{\chi_{N,m}^2}(x)$, ROC could theoretically be derived by seeking for $\Pr(\chi_N^2 > \lambda | H_1)$ and $\Pr(\chi_{N,m}^2 > \lambda | H_0)$, which correspond to probability of detection and probability of false alarm, respectively. Here, $\Pr(\chi_N^2 > \lambda | H_1)$ is given by $Q_g(\sqrt{2\gamma}, \sqrt{\lambda})$ where λ denotes the decision threshold, $Q_g(\cdot)$ is the generalized Marcum–Q function, γ is the instantaneous SNR. Note that the optimum threshold selection mandates one to have knowledge about the SNR [43, Eq.(35)]. It is not difficult to see that the same conclusion (with more sophisticated calculations) holds also for the SINR in case there are unknown activities within the spectrum of interest apart from that of primary user [53].

6.2 Channel Selection

Cross–layer channel selection mechanism relies on both PHY and MAC operations as outlined in Figure 6.2. In order for MAC layer to select a specific channel, a short–term history of the time–domain statistics of candidate channels are stored. Next, a short–term/next step prediction is evaluated based on the collected data. Evaluation is followed by selection step where the node chooses the channel that has the maximum value of a pre–defined metric.

The proposed channel selection metric is defined to be the first–order difference of vari-

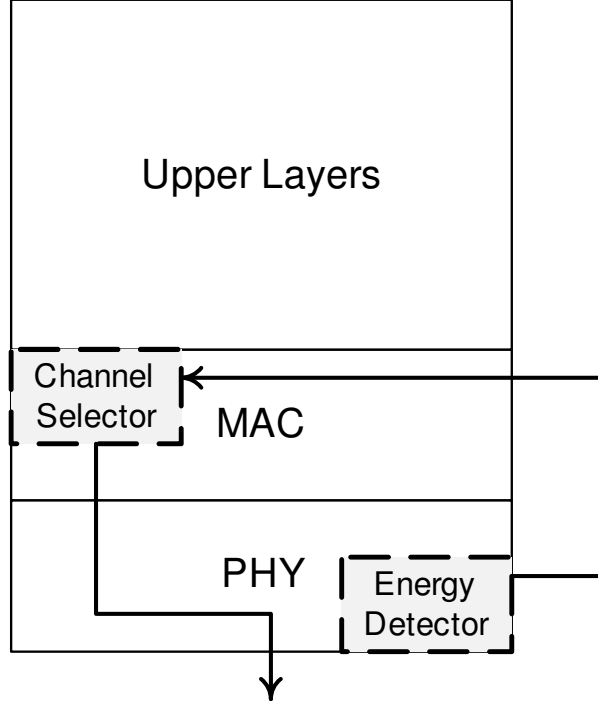


Figure 6.2 Proposed cross-layer architecture

ance estimates of the predicted value of the energy detection operation output. As will be shown subsequently, variance estimates are scaled appropriately in order not to violate the Kolmogorov's assumptions for the probability metric. Before proceeding further, prediction of the energy detector output should be given. Assuming that the predicted value of the energy detection operation, namely $\hat{\mathbf{X}}_{n+1}^k$, is a wide-sense stationary (WSS) process, then:

$$\hat{\mathbf{X}}_{n+1}^k = \sum_{i=0}^{L-1} \alpha_i \mathbf{X}_{n-i}^k + \mu_{\mathbf{X}^k} \quad (6.10)$$

expresses the weighted moving average prediction where $\hat{\mathbf{X}}_{n+1}^k$ denotes the predicted value for the $n + 1$ -th step based on past L historical data of k -th channel; α_i s denote the weighting coefficients; and $\mu_{\mathbf{X}^k}$ represents the intercept of the prediction.

Once L past energy detector observations are at hand, the channel selection mechanism then proceeds with calculating the variance of the past observations as:

$$\sigma_{\mathbf{X}^k}^2[n] = \sum_{i=0}^{L-1} E \left\{ (\mathbf{X}_{n-i}^k)^2 \right\} - (E \{ \mathbf{X}_{n-i}^k \})^2 \quad (6.11)$$

where $E \{ \mathbf{X}_{n-i}^k \}$ denotes the sample mean of the past L observations. In order for the channel selection mechanism to quantify whether a state transition takes place at the prediction stage/step, (6.11) needs to be scaled so that as mentioned above, Kolmogorov's assumptions for the probability metric are not violated:

$$\psi_X[n] = \varrho^k \sigma_{\mathbf{X}^k}^2[n] \quad (6.12)$$

where ϱ^k is a constant for the k -th channel which satisfies $0 < \psi_{\mathbf{X}^k}[n] \leq 1$.¹ Finally, the channel selection mechanism applies the first-order difference operator to (6.12) and reaches the channel selection metric as:

$$\Theta_n^k = D^{-1}(\psi_{\mathbf{X}^k}[n]) \quad (6.13)$$

where $D^{-1}(\cdot)$ denotes the first-order difference operator being applied to its input. Now, the channel selection mechanism is ready to provide the hard-decision based on (6.13) as follows:

$$\hat{d}_n^k = \begin{cases} 1, & \gamma < \Theta_n^k, \\ 0, & \gamma \geq \Theta_n^k, \end{cases} \quad (6.14)$$

where \hat{d}_n^k denotes the predicted binary state of the k -th channel at the n -th step for the next $n+1$ -th step and γ is an adaptive threshold below which is predicted to be occupied.

There are some critical points in establishing the steps (6.10) through (6.14). First and foremost, the depth of the history, L should be specified. Consequently, weighting coefficients α_i s in (6.10) need to be determined in an effective way as well. Second, ϱ^k in (6.12) should be decided. Because (6.10) is a linear model in essence, any minimization approach based on 2-norm ($\|\cdot\|_2$) such as mean-squared-error (MSE) could be adopted in determining the weighting coefficients as shown subsequently. On the other hand, determining the depth of the history, L , is actually nothing but deciding the order of the

¹Note that in (6.12) the case where $\psi_X[n] = 0$ is excluded since it implies $\sigma_{\mathbf{X}^k}^2[n] = 0$ pointing out absolute certainty.

linear model adopted in (6.10) based on a specific set of criteria. Mean magnitude residual statistics, sum of squares of Pearson residuals, and Akaike information criteria (AIC) are prominent model–order selection strategies present in the literature [67]. However, model–order selection is outside the scope of this study.

In what follows, it will be shown that the proposed channel selection mechanism has a prediction error which cannot be reduced further and the aforementioned issues will all be clarified.

Proposition 2 (Irreducible prediction error). *The proposed channel selection mechanism has an irreducible prediction error variance, σ_e^2 , which cannot be reduced further and is a function of the threshold that is used by the energy detector at the decision stage.*

Proof. see Appendix A.3. □

Based on the analysis carried out in Appendix A.3, it is seen that the channel selection mechanism relies heavily on the threshold for the decision device operating on energy detector. There are several implications of Proposition 2. First of all, it states that prediction error variance reaches its lower bound with the first threshold when there are multiple thresholds. For instance in [67], two–level threshold strategy is applied where the first stage is clipping the original time series and the other is used at the prediction stage. Similar multi–stage scenarios take place in decision fusion schemes as well [68]. Hence, with the aid of Proposition 2, it is known in advance that the lower bound for the prediction error variance could only be achieved in case decision is obtained directly from the original time series. Second, due to the positive semi–definite structure of error variance, multiple threshold strategies cannot outperform single–threshold strategies in terms of prediction error variance given that both single– and multiple–threshold strategies are of the same mathematical structure such as both being linear or non–linear and so on. Performance results and irreducible prediction error will be investigated in the subsequent sections. A sketch of the proposed channel selection mechanism is given in Figure 6.1.

6.3 Numerical Results

Performance of the proposed method is investigated in various traffic conditions and scenarios. Also a performance comparison is established between the method proposed and Markovian-based prediction scheme. In the sequel, one might be interested in why specifically Markovian-based scheme is selected for comparison purposes. The reason is three-fold: (i) Peculiar to the spectrum sensing problem, spectrum occupancy could best be represented with a Bernoulli process, which is a special case of Markov chain. Therefore, Markovian-based structures provide a very high-level flexibility in both modeling and analyzing the spectrum sensing problem (ii) Markovian-based schemes are vastly employed prediction strategies present in the literature. This stems from the fact that it has a simplistic design and tractable statistical analysis. Furthermore, depending on the problem formulation several adaptations and extensions such as multi-layer Markovian or hidden Markov model (HMM)-based approaches could easily be obtained with minor modifications in the original model organization. (iii) Finally, Markovian-based models are so versatile that they could be exploited to tackle spectrum sensing problems in different parts of OSI. For instance, it could be used both in PHY and MAC layers to shed light on different aspects of spectrum sensing problem.

Simulation setup considers several levels of traffic load ranging from light occupancy to densely occupied scenario based on the parameters reported in [69]. At this point, it is worth mentioning why parameter selection is based on the findings reported in [69]. (I) First and foremost, the proposed method requires both theoretical and empirical analyses. Therefore, studies which focus on both theoretical and empirical findings should be evaluated. From this perspective [69], is a prominent work in the literature. (II) Also, as proposed, channel selecting mechanism could be shared by both PHY and MAC layers in the sense of cross-layer approach. In [69], the same strategy is followed and both PHY and MAC layers are binded. (III) Finally, as discussed above, a generic Markovian-based structure for industrial, scientific, and medical (ISM) band depending on several important occupancy parameters is provided in [69] such that it could be used for comparing other findings with each other.

In simulating channel access, both busy and idle channel statistics are taken into account.

According to the empirical observation–based model given in [69], busy and idle channel state transitions can be well approximated by the exponential distribution with a factor that changes with the traffic load. For the proposed method, first energy detector is used to obtain the decision statistics. Next, decision statistics are fed to the prediction stage. Prediction is yielded by equal gain combining ($\alpha_i = \alpha_j = \frac{1}{L}, \forall i, j$). Along with the past measurement results, prediction is quantified with the metric defined in Section 6.2. Finally, a binary decision is reached so that MSE is obtained for the performance evaluations. It should be stated at this point that equal gain combining might not be the optimal prediction strategy for many scenarios. However, it establishes simplicity in implementation from the practical point of view because it skips the stage at which the weighting coefficients are estimated. Therefore, equal gain combining is adopted in the numerical results.

For Markovian–based prediction scheme, first output of a Bernoulli stochastic variable is used in order to determine the initial state of the channel. Next, simulated channel statistics are compared with a threshold whose value can be adjusted according to several levels of traffic load. Once busy/idle periods are shaped, prediction stage is initiated. For the Markovian–based scheme, a specific portion of the simulated data is fed to the predictor in order to estimate the transition probability matrix. Then, predictions are calculated based on the initial state (last training data sample) and the transition probability matrix estimate. Finally, MSE values are obtained for performance evaluations and comparisons. General parameters used in the simulations are given in Table 6.1.

Performance results for Markovian–based scheme are plotted in Figure 6.3. It is seen in Figure 6.3 that performance of the Markovian–based prediction method improves with the increasing traffic load. This mainly stems from the fact that underlying stochastic channel access becomes denser with the increased traffic load; therefore, number of transitions between busy and idle states becomes less frequent. Since it is known that steady–state behavior always converges a biased binary estimation given that the transition probability matrix is not symmetric, prediction step always yields a biased output in favor of the busy state. Another important observation in Figure 6.3 is that the performance of the Markovian–based prediction scheme cannot be improved any further by increasing the amount of history at the training stage. As can be verified from Figure 6.3, 10% of the

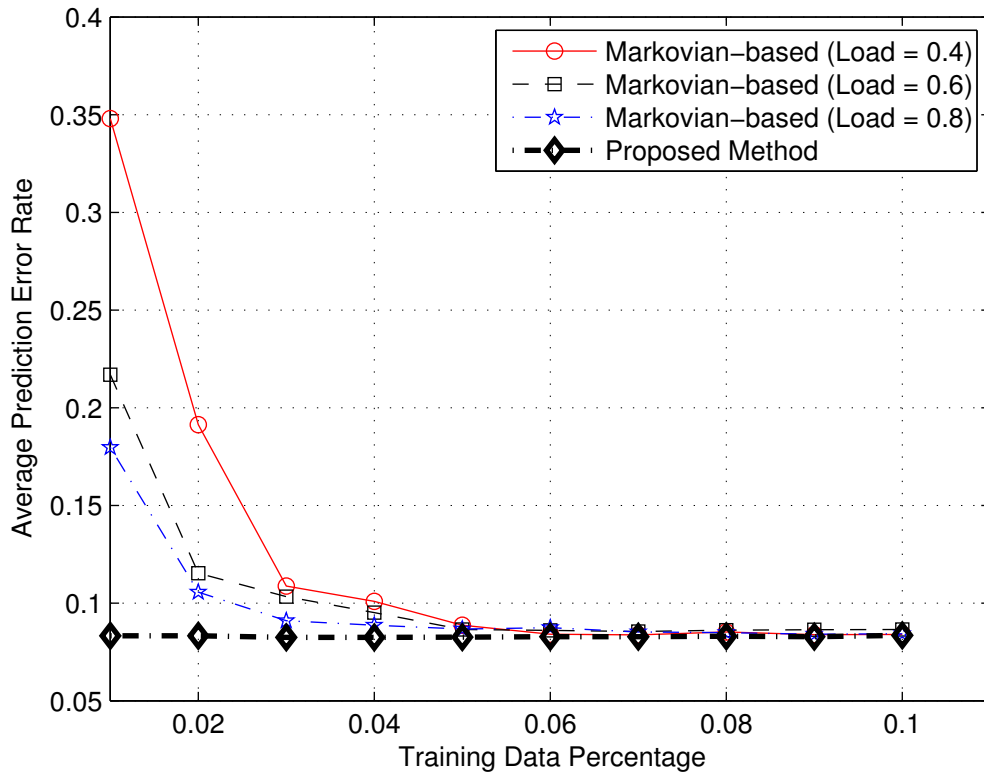


Figure 6.3 Markovian-based prediction results along with the proposed method performance

entire data set is sufficient under each level of traffic load to reach the same performance level in training the Markovian-based scheme.

Performance of the proposed method for $L = 2$ can be seen in Figure 6.3 as well under a generic scenario for comparison purposes. Here, $L = 2$ is adopted, since in conjunction with equal gain combining strategy it provides some sort of a lower bound for the performance of the proposed predictor, as discussed above. This way, a fair comparison platform between the proposed method and the Markovian-based structures could be established. First and foremost, the proposed method yields a stationary MSE in contrast to Markovian-based scheme. This is caused by the combined impact of both energy detector and the equal gain combining. Recall that the channel selection mechanism first collects the energy of the received signal at a sufficiently high sampling rate (generally satisfying the Nyquist criterion) for a very short period of time. This implies that especially switching from idle state to busy state can be captured in a few consecutive decision statistics produced by the energy detector. Once consecutive, high-resolution, and very

low-latency decision statistics are fed to the prediction procedure, dramatic power fluctuations in the decision statistics due to fading are smoothed out to some extent since equal gain combining is nothing but applying a low-pass filtering operation to its input. This way, the proposed method firstly can capture the transitions very effectively and secondly, false-alarms due to drastic power fluctuations caused by fading are eliminated automatically. Hence a stationary output for the proposed method is established as observed in Figure 6.3.

Table 6.1 Common parameters used in the simulation setup

Parameters	Values
Occupied state parameter λ^{-1}	15.9, 9.10, 4.48, 2.90, 1.98, 1.39, 1.01, 0.74, 0.55, 0.36, 0.21ms (based on [69, §V.A, Table I, p. 103])
Idle state parameter μ^{-1}	1.11, 1.08, 1.05, 1.03, 1.02, 1.03, 1.03, 1.02, 1.03, 1.03, 1.03ms (based on [69, §V.A, Table I, p. 103])
Sampling interval	200ns
Low-pass filter duration (T_A)	Between 0ms and 85ms (based on [70, §V.C, p. 444])
Number of samples for energy detection (N)	20
Major propagation channel characteristics	Rayleigh fading with Jakes' spectrum
Average SNR under H_1 scenario	10dB

The discussion above could be investigated in a better way by examining Figure 6.4. In Figure 6.4, a single snapshot of the prediction stage is plotted for ≈ 20 ms. As can be seen from the figure, there are two plots corresponding to the output of both the energy detector (decision statistic) and the predictor. Based on the values given in Table 6.1, several bursts are generated and passed through the energy detector. The decision statistics, output of the energy detector, are stored. Next, a specific portion of the data stored (10% as discussed above) is used for estimating the weighting coefficients of the predictor for $L = 2$. Then, the predictor runs. Note that the prediction lags one sample behind its input as expected. Nevertheless, one could conclude that by looking at the time scale of the bursts, prediction reacts very rapidly. Yet, it is observed in Figure 6.4 also that the predictor fails to track the actual observations when dramatic fluctuations occur in the received signal power. This is not surprising since prediction could only take into account a temporal window whose duration is $L \times T_A$. Therefore, any burst whose duration, say T_B , satisfying $T_B < L \times T_A$ will yield a dramatic fluctuation in the decision statistic. Thus, prediction will not be able to keep track of these sudden changes in the received signal power.

It is desirable also to see the impact of traffic load on the performance of the proposed method. Average error rate performances for the proposed method under various levels of

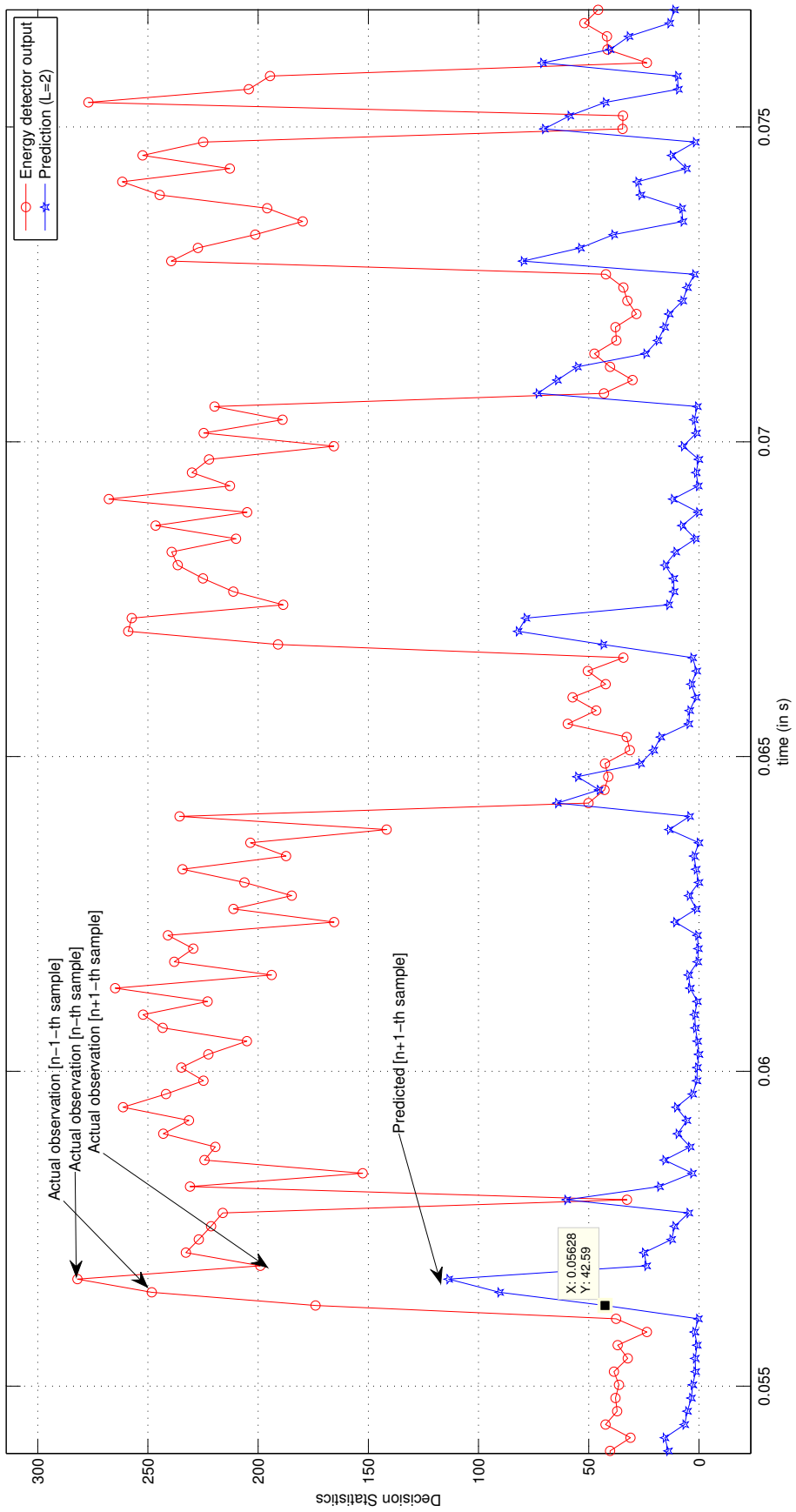


Figure 6.4 A single snapshot of the prediction stage for $\approx 20\text{ms}$

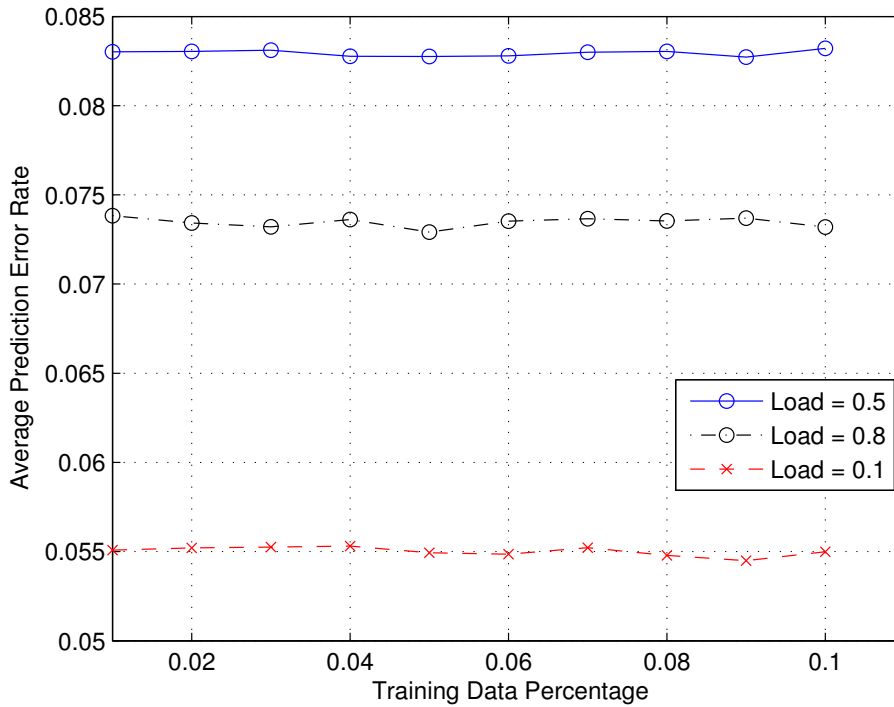


Figure 6.5 The proposed method average error rate performance under various levels of traffic load

traffic load are given in Figure 6.5. Note that the traffic load does not change the average error rate performance drastically. However, it is observed from Figure 6.5 that the traffic load might influence the performance of the proposed method around 2% on average between the best- and the worst-case scenarios. Moreover, it is seen that the proposed method exhibits its worst performance under the average traffic load scenario. This is not surprising since the entropy of the channel occupancy statistics reaches its maximum when the load is 0.5 [71].

In conjunction with the aforementioned discussion, it is important to check the collision rate performance of the proposed channel selection mechanism. In order to evaluate this, a single-channel access scheme is assumed. As in the previous cases, channel access is shaped by the parameters reported in [69] with a traffic load ranging from light occupancy to densely occupied scenario. Based on the predictor output, it is decided whether the channel is accessed or not. Cases where “no access” takes place are omitted since no access strategy will never yield a collision for any single-channel access scheme. Hence, collision rate is calculated for the predictor output when channel access is allowed. The results are plotted in Figure 6.6 under various traffic loads. In parallel with the results

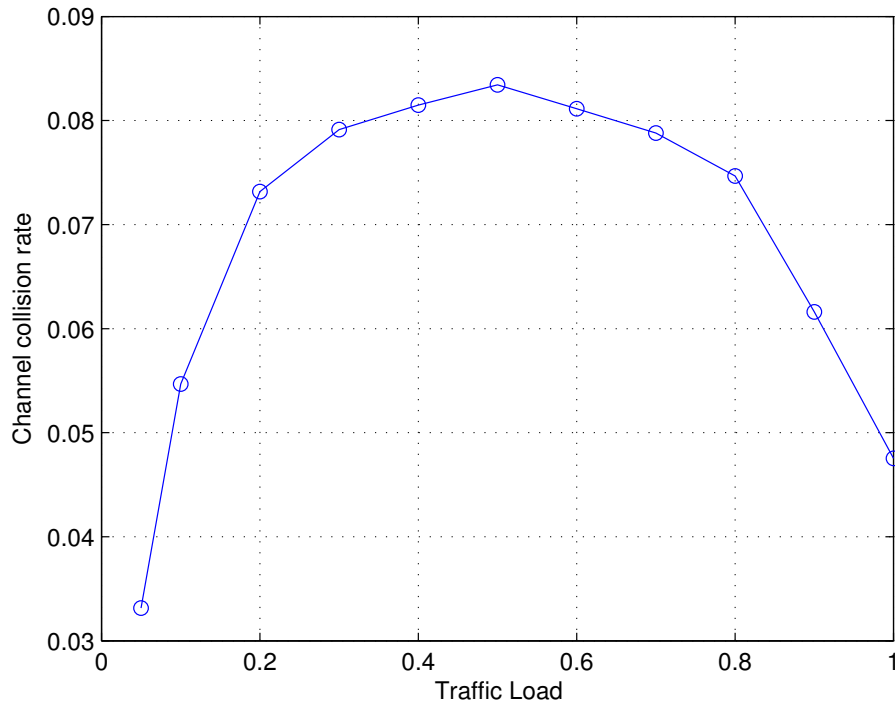


Figure 6.6 Collision rate for the proposed channel selection mechanism

given in Figure 6.5, collision rate reaches its maximum when the traffic load is 0.5.

In the sequel, it is important to investigate how the proposed mechanism behaves under various threshold values. Recall that the proposed channel selection mechanism relies heavily on selecting an optimal threshold value, γ , in (6.14). Three different threshold values and corresponding collision rates are given in Figure 6.7. To better understand how the proposed mechanism behaves under various threshold values, Figure 6.7 could be examined in conjunction with Figure 6.6, since Figure 6.6 shows the results regarding optimal threshold selection. As can be seen from both Figure 6.6 and Figure 6.7, the proposed mechanism performs poorly in case random threshold selection strategy is employed. On the contrary, Figure 6.6 implies that optimum threshold gives rise to the minimum collision rate for all traffic load rates. From the practical point of view, obtaining the optimum threshold value might be difficult; therefore, cases where optimum threshold is not available should be examined as well. In Figure 6.7, two different suboptimal threshold values and corresponding collision rates are given. As can be seen from the figure, depending on the traffic load, one of the thresholds slightly outperforms the other in one part; whereas the situation is reversed in the other part, as expected.

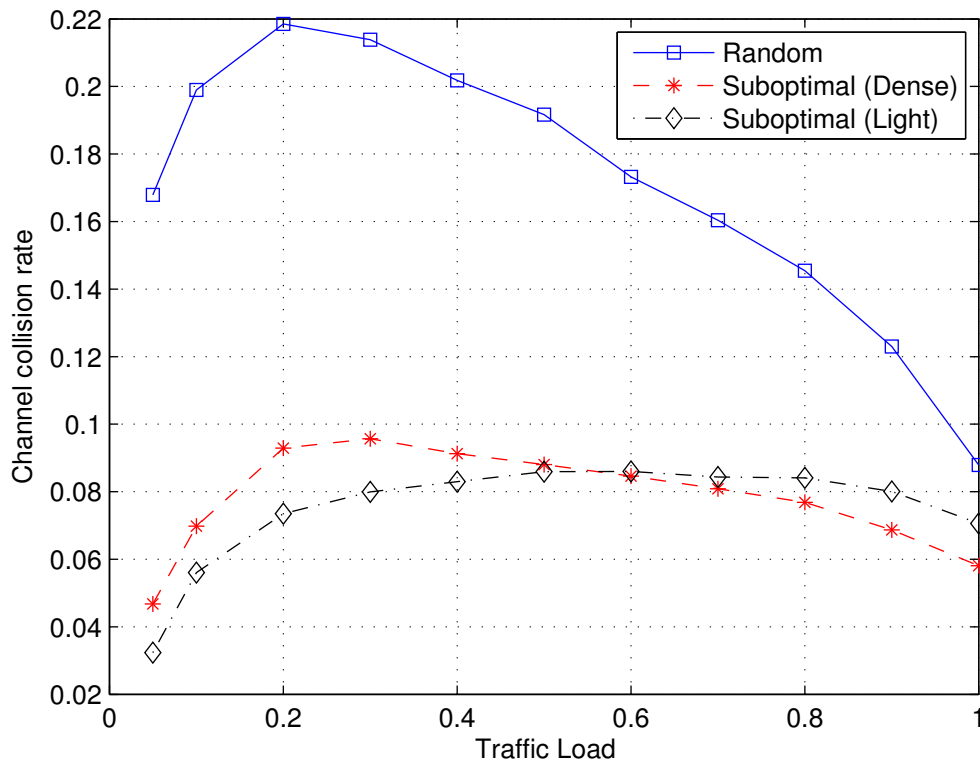


Figure 6.7 Performance of the proposed mechanism under various threshold values in terms of collision rates. Note that one of the threshold values yields better performance under dense traffic load, whereas the other performs better in light traffic load. However, random threshold selection strategy leads to dramatic collision rates.

It is worth mentioning that whether the theoretical lower bound mentioned in Appendix A.3 given with (A.23) exists. As Proposition 2 implies, lower bound could be reached in case the behavior of the decision device could be characterized statistically, since (A.23) is a function of the decision threshold, γ . For the energy detector, it is known that optimal decision threshold theoretically exists as expressed in [72, §III.B].

Before concluding this part, one might want to contemplate the worst-case scenario regarding the prediction error variance. Selecting the weighting coefficients α_i in (6.10) plays an important role on the error variance behavior. In this regard, any approach ignoring the actual observations, \mathbf{X}_{n-i}^k , in (6.10) would lead to no-information case; therefore, yield the maximum entropy. It automatically implies that maximum entropy could only be reached by setting $\alpha_i = 0, \forall i$. In (6.10), such a setting gives rise to a prediction, $\hat{\mathbf{X}}_{n+1}^k$, which is equal to AWGN due to the autoregressive (AR) structure with a certain mean and variance pair. Theoretically speaking, AWGN could take any real value; therefore, prediction error variance diverges for the worst-case scenario.

RESULTS AND DISCUSSION

In this dissertation, a cross-layer predictive channel selection mechanism is proposed to increase utilization and performance of V2V networks which are based on WAVE multi-channel architecture. With the proposed scheme, channel history is used to predict the next state of the wireless channel from the MAC layer perspective with the aid of PHY layer input. By taking advantage of the cross-layer design, MAC layer is fed with energy detector output statistics provided by the PHY layer to make the best decision in order to find the most appropriate non-emergency/service channel. The proposed method implies a channel access protocol which improves the effectiveness of the collision avoidance procedure. Furthermore, the proposed architecture could be adapted to various scenarios and conditions by appropriately selecting the model parameters. Analysis along with the results shows that the proposed method outperforms the widely deployed Markovian-based prediction method in the following two perspectives. First, it is obtained that the average prediction error rate of the proposed method is always below those of Markovian based schemes. It is worth mentioning here that Markovian based schemes are selected for performance comparison purposes since Markovian assumption provides an excellent fit with empirical data concerning with idle and busy periods from the MAC layer perspective along with its utmost implementation flexibility. In the best case scenario average prediction error rate is improved by approximately 25% under each and every traffic load (light/mild/dense) environments with the proposed method. Second, the proposed method provides always a stable average prediction error rate with respect to the amount of training data used. Markovian based schemes can only converge the performance of the proposed method after training data percentage is increased to 10% of the

total history available. Note also that Markovian based schemes exhibit various average prediction error rates under different traffic loads with minimum (less than 2% of the historical data) amount of training data used. In contrast to Markovian based schemes, the proposed method still stays below 10% of average prediction error rate within the same region. These numerical findings show that the proposed method is a promising candidate which could be deployed in the WAVE standard.

One of the critical observations regarding the performance of the proposed method is obtained when the threshold selection mechanism is investigated. Stochastic analysis shows that the performance of the proposed method is bottlenecked by the optimal threshold value used in the detection device (*e.g.* energy detector or higher-order detector). Numerical studies show that unless optimal threshold is selected the performance of the proposed method cannot be considered to be optimal. The most important performance metric for this case is the collision rate on the channel dictated by the proposed channel selection mechanism. Numerical results yield that suboptimal threshold selection under both light and dense traffics help the proposed method achieve less than 10% of collision rate. Recall that optimal threshold selection could help the proposed method achieve less than 4% channel collision rate under light traffic scenarios.

Cross-layer architecture allows the proposed method to be extended further in various ways. For instance, both traffic and geographical information could be incorporated into the architecture as a pseudo-layer appended into both PHY, MAC, and network layers. Moreover, predictive strategy could be enhanced further by taking into account network traffic type statistics such as web access, VoIP, video streaming, and gaming. Considering the fact that different network traffic types exhibit distinct statistical behaviors, enhanced predictive strategies could be devised based on these statistical models and parameters reflecting the stochastic nature of each traffic type.

Even though the traffic type is one of the most important parameters in mobile networks, cross-layer design itself should be investigated as a separate paradigm. Currently there are several other approaches in cross-layer architecture designs for VANETs. Considering the vast variety of traffic types, topology structures, and QoS requirements of VANETs, it is difficult to point out a single cross-layer design as an optimal one. Therefore, a

comprehensive comparative analysis should be carried out including the proposed scheme along with other methods present in the literature.

Since the ideal cross-layer design should take into consideration all layers present in OSI, studies should be extended in such a way that upper layer issues such as routing and forwarding are also evaluated. This implies that the incorporation of the network layer to the proposed protocol is the next logical step to reach the ideal cross-layer design.

Apart from the cross-layer design perspective, other aspects of V2V should be studied as well. For instance, security and privacy issues are two of the prominent concepts which fall into this category. Note that the interconnected devices create a security and privacy risks for users that are not explicitly mentioned in already-developing standards. One of the risks is the vulnerability of remote access to vehicles with malicious intent. Such an attack might lead to traffic accidents. Another risk includes the identification of the message source; non-authorized access and tracking. This risk leads to monitoring individuals without their consent and/or permissions. In order to avoid such risks and problems, static addresses like MAC address should be changed randomly to ensure the anonymity of the message source. Certificate authorities should be added to the proposed scheme as well in order to validate users and create a secure connection between vehicles.

Once the security and privacy concerns are handled, a more extended view of ITS in the presence of other networks could be established by incorporating collaborative, cooperative, and coordinated access schemes into the model proposed. This way, relays, horizontal and vertical handover algorithms, and V2I link support can be optimized since VANETs are considered to be an integral part of NGWNS. This kind of an approach can reduce the time spent inside the vehicles and lower the carbon emission rates to reduce the cost of transportation.

Finally along with the theoretical studies, practical implementations and field tests should be carried out extensively to ensure the validity of model proposed. However, it is seen that diversity of the platforms available in the literature is not sufficient to encompass all possible scenarios under each and every possible network environments. This points out an important gap in the literature from the perspective of simulation/development platforms and environments. Recently there is a strong tenancy in developing such frame-

works. However, it is believed that these efforts are not considered to be sufficient unless they are published and made accessible to all researchers working on this field.

BIBLIOGRAPHY

- [1] Peden, M., Scurfield, R., Sleet, D., Mohan, D., Hyder, A. A., Jarawan, E., and Mathers, C., (2004). World report on road traffic injury prevention, Technical report, , World Health Organization, Geneva.
- [2] General Directorate of Public Security and Turkish Statistical Institute, (2012). Traffic Accident Statistics – Road, Technical Report, MTB 2012-504-110, Ankara.
- [3] Campolo, C., Cortese, A., and Molinaro, A., (2009). “Crasch: A cooperative scheme for service channel reservation in 802.11p/wave vehicular ad hoc networks”, International Conference on Ultra Modern Telecommunications Workshops (ICUMT), 12–14 October 2009, St. Petersburg, Russia.
- [4] Roche, S., Chen, S., Vuyyuru, R., Altintas, O., and Wyglinski, A., (2012). “Knowledge-based dynamic channel selection in vehicular networks (poster)”, IEEE Vehicular Networking Conference (VNC), 14–16 November 2012, Seoul, South Korea.
- [5] Inage, K., Lee, S., Fujii, T., and Altintas, O., (2011). “White space vectors for channel selection in vehicular cognitive networks”, IEEE Vehicular Networking Conference (VNC), 14–16 November 2011, Amsterdam, Netherlands.
- [6] Chen, S. and Vuyyuru, R., (2013). “Dynamic channel selection for wireless mobile ad hoc networks: Adaptation and learning”, IEEE 9th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 7–9 October 2013, Lyon, France.
- [7] Chen, S., Vuyyuru, R., Altintas, O., and Wyglinski, A. M., (2011). “On optimizing vehicular dynamic spectrum access networks: Automation and learning in mobile wireless environments”, IEEE Vehicular Networking Conference (VNC), 14–16 November 2011, Amsterdam, Netherlands.
- [8] Heinzelman, W., Chandrakasan, A., and Balakrishnan, H., (2000). “Energy-efficient communication protocol for wireless microsensor networks”, 33rd Annual Hawaii International Conference on System Sciences, 4-7 January 2000, Hawaii, USA.
- [9] Wang, K., Wang, T., and Tseng, C., (2013). “A fair scheme for multi-channel selection in vehicular wireless networks”, Wireless Personal Communications, 73(3):1049–1065.
- [10] Mapar, F. M. and Chowdhury, K., (2014). “Predictive decision-making for vehicular cognitive radio networks through Hidden Markov models”, IEEE International Conference on Communications (ICC-2014), 10–14 June 2014, Sydney, Australia.

- [11] Brahmi, I. H., Djahel, S., and Ghamri-Doudane, Y., (2012). “A Hidden Markov Model based scheme for efficient and fast dissemination of safety messages in VANETs”, IEEE Global Communications Conference (GLOBECOM 2012), 3-7 December 2012, Anaheim, CA, USA.
- [12] Li, H. and Irick, D., (2010). “Collaborative spectrum sensing in cognitive radio vehicular ad hoc networks: Belief propagation on highway”, IEEE 71st Vehicular Technology Conference (VTC 2010-Spring), 16–19 May 2010, Taipei, Taiwan.
- [13] Di Felice, M., Chowdhury, K., and Bononi, L., (2010). “Analyzing the potential of cooperative cognitive radio technology on inter-vehicle communication”, Wireless Days (WD), 2010 IFIP, 20–22 October 2010, Venice, Italy.
- [14] Ghandour, A. J., Fawaz, K., and Artail, H., (2011). “Data delivery guarantees in congested vehicular ad hoc networks using cognitive networks”, 7th International Wireless Communications and Mobile Computing Conference (IWCMC–2011), 4–8 July 2011, Istanbul, Turkey.
- [15] Boyaci, A., Yarkan, S., and Zaim, A., (2013). “Identification of shadowed fast fading interference in cellular mobile radio systems”, 21st Signal Processing and Communications Applications Conference (SIU), 24–26 April 2013, Haspolat, Northern Cyprus.
- [16] Boyaci, A., Ozturk, E., Yarkan, S., and Zaim, A., (2013). “Towards green and secure vehicle-to-vehicle communications: A protocol for establishing the network”, 7th International Conference on Application of Information and Communication Technologies (AICT), 23–25 October 2013, Baku, Azerbaijan.
- [17] Boyaci, A., Zaim, H., and Sönmez, C., (2015). “A cross-layer adaptive channel selection mechanism for IEEE 802.11 p suite”, EURASIP Journal on Wireless Communications and Networking, 2015(1):1–13.
- [18] Daimler, The birth of the automobile, <http://www.daimler.com>, 05 April 2015.
- [19] Hasan, S. F., Siddique, N., and Chakraborty, S., (2012). Intelligent Transport Systems: 802.11-based Roadside-to-Vehicle Communications, 1st edition, Springer, New York.
- [20] ElBatt, T., Goel, S. K., Holland, G., Krishnan, H., and Parikh, J., (2006). “Cooperative collision warning using dedicated short range wireless communications”, 3rd International Workshop on Vehicular Ad-hoc Networks, 24–26 September 2006, Los Angeles, California, United States.
- [21] CAR 2 CAR Communication Consortium, (2007). CAR 2 CAR Communication Consortium Manifesto, Technical report, , Braunschweig.
- [22] Alsabaan, M., Alasmay, W., Albasir, A., and Naik, K., (2013). “Vehicular networks for a greener environment: A survey”, Communications Surveys Tutorials, IEEE, 15(3):1372–1388.
- [23] U.S. Department of Transportation, Traffic Safety Facts 2013, <http://www-nrd.nhtsa.dot.gov/Pubs/812139.pdf>, 15 August 2015.

- [24] Cheng, X., Yang, L., and Shen, X., (2015). “D2D for intelligent transportation systems: A feasibility study”, *IEEE Transactions on Intelligent Transportation Systems*, 16:1–10.
- [25] Schneiderman, R., (2013). “Car makers see opportunities in infotainment, driver-assistance systems [special reports]”, *Signal Processing Magazine, IEEE*, 30(1):11–15.
- [26] Jang, E.-J., Woo, R., and Han, D. S., (2013). “Improvement of connectivity between infrastructure and consumer devices for infotainment services”, *Consumer Electronics, IEEE Transactions on*, 59(2):329–334.
- [27] Emmelmann, M., Bochow, B., and Kellum, C., (2010). *Vehicular Networking: Automotive Applications and Beyond*, 1st edition, Wiley.
- [28] IEEE, (2010). “Ieee standard for information technology– local and metropolitan area networks– specific requirements– part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications amendment 6: Wireless access in vehicular environments”, *IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009)*, pages 1–51.
- [29] Armstrong, L., Status of Project IEEE 802.11 Task Group P, http://grouper.ieee.org/groups/802/11/Reports/tgp_update.htm, 13 December 2014.
- [30] Arslan, H., Yarkan, S., Sahin, M. E., and Gezici, S., (2011). Interference mitigation and awareness for improved reliability, *Reliable Communications for Short-range Wireless Systems*, pages 190–233, Cambridge University Press, Cambridge UK.
- [31] ASTM, (2010). “Standard specification for telecommunications and information exchange between roadside and vehicle systems — 5 ghz band dedicated short range communications (dsrc) medium access control (mac) and physical layer (phy) specifications”.
- [32] Shen, X., Cheng, X., Yang, L., Zhang, R., and Jiao, B., (2014). “Data Dissemination in VANETs: A Scheduling Approach”, *IEEE Transactions on Intelligent Transportation Systems*, 15(5):2213–2223.
- [33] Day, J. D. and Zimmermann, H., (1983). “The osi reference model”, *Proceedings of the IEEE*, 71(12):1334–1340.
- [34] Srivastava, V. and Motani, M., (2005). “Cross-layer design: a survey and the road ahead”, *IEEE Communications Magazine*, 43(12):112–119.
- [35] Jarupan, B. and Ekici, E., (2011). “A survey of cross-layer design for vanets”, *Ad Hoc Netw.*, 9(5):966–983.
- [36] PC Engines, Alix3D2 Development Board, <http://www.pceingines.ch/alix3d2.htm>, 03 November 2014.
- [37] EnGenius Technologies, EMP-8603 S/PREMIUM, <http://www.engeniustech.com.sg/node/48>, 03 November 2014.

- [38] OpenWRT, Wireless Freedom, <http://openwrt.org/>, 15 August 2015.
- [39] Python Software Foundation, Python Programming Language, <http://www.python.org/>, 15 August 2015.
- [40] Spectrum Occupancy Measurements Location 4 of 6: Republican National Convention, New York City, New York August 30, 2004–September 3, 2004, aug 15 2005, www.sharedspectrum.com/wp-content/uploads/4_NSF_NYC_Report.pdf, 18 June 2015.
- [41] Hur, Y., Park, J., Woo, W., Lee, J. S., Lim, K., Lee, C.-H., Kim, H. S., and Laskar, J., (2006). “A Cognitive Radio (CR) System Employing A Dual-Stage Spectrum Sensing Technique : A Multi-Resolution Spectrum Sensing (MRSS) and A Temporal Signature Detection (TSD) Technique”, IEEE Global Telecommunications Conference (GLOBECOM '06), 27 November– 1 December 2006, San Francisco, California, USA.
- [42] Lee, W.-Y. and Akyildiz, I. F., (2008). “Optimal spectrum sensing framework for cognitive radio networks”, IEEE Transactions on Wireless Communications, 7(10):3845–3857.
- [43] Urkowitz, H., (1967). “Energy detection of unknown deterministic signals”, Proceedings of the IEEE, 55(4):523–531.
- [44] Sonnenschein, A. and Fishman, P. M., (1992). “Radiometric detection of spread-spectrum signals in noise of uncertain power”, IEEE Transactions on Aerospace and Electronic Systems, 28(3):654–660.
- [45] Tang, H., (2005). “Some physical layer issues of wide-band cognitive radio systems”, First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 8–11 November 2005, Baltimore, Maryland, USA.
- [46] Dillard, R. A., (1979). “Detectability of spread-spectrum signals”, IEEE Transactions on Aerospace and Electronic Systems, AES-15(4):526 –537.
- [47] Qaraqe, K. A. and Yarkan, S., (2010). “A second-order statistical method for spectrum sensing in correlated shadowing and fading environments”, 21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2010), 26–29 September 2010, Istanbul, Türkiye.
- [48] Proakis, J. G., (2001). Digital Communications, McGraw-Hill.
- [49] Stüber, G. L., (2001). Principles of Mobile Communications, 2nd edition, Kluwer Academic Publishers, Norwell, MA, USA.
- [50] Gudmundson, M., (1991). “Correlation Model for Shadow Fading in Mobile Radio Systems”, Electronics Letters, 27(23):2145–2146.
- [51] Oestges, C., Czink, N., Bandemer, B., Castiglione, P., Kaltenberger, F., and Paulraj, A. J., (2010). “Experimental characterization and modeling of outdoor-to-indoor and indoor-to-indoor distributed channels”, IEEE Transactions on Vehicular Technology, 59(5):2253–2265.

- [52] Kostylev, V. I., (2002). “Energy detection of a signal with random amplitude”, IEEE International Conference on Communications (ICC), 28 April–2 May 2002, New York, New York, USA.
- [53] Zeng, Y., Liang, Y.-C., Hoang, A. T., and Peh, E., (2009). “Reliability of spectrum sensing under noise and interference uncertainty”, IEEE International Conference on Communications Workshops, 14–18 June 2009, Dresden, Germany.
- [54] Yang, X., Liu, J., Vaidya, N. F., and Zhao, F., (2004). “A vehicle-to-vehicle communication protocol for cooperative collision warning”, First Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services, MOBIQUITOUS 2004, 22–26 August 2004, Boston, MA, USA.
- [55] Biswas, S., Tatchikou, R., and Dion, F., (2006). “Vehicle-to-vehicle wireless communication protocols for enhancing highway traffic safety”, IEEE Communications Magazine, 44(1):74–82.
- [56] Torrent-Moreno, M., Mittag, J., Santi, P., and Hartenstein, H., (2009). “Vehicle-to-vehicle communication: fair transmit power control for safety-critical information”, IEEE Transactions on Vehicular Technology, 58(7):3684–3703.
- [57] Misener, J. A. and Shladover, S. E., (2006). “Path investigations in vehicle-roadside cooperation and safety: A foundation for safety and vehicle-infrastructure integration research”, IEEE Intelligent Transportation Systems Conference (ITSC’06), 17–20 September 2006, Toronto, Canada.
- [58] Wisitpongphan, N., Bai, F., Mudalige, P., Sadekar, V., and Tonguz, O., (2007). “Routing in sparse vehicular ad hoc wireless networks”, IEEE Journal on Selected Areas in Communications, 25(8):1538–1556.
- [59] Abdrabou, A. and Zhuang, W., (2011). “Probabilistic delay control and road side unit placement for vehicular ad hoc networks with disrupted connectivity”, IEEE Journal on Selected Areas in Communications, 29(1):129–139.
- [60] Tonguz, O. K. and Boban, M., (2010). “Multiplayer games over Vehicular Ad Hoc Networks: A new application”, Ad Hoc Networks, 8(5):531–543.
- [61] Malandrino, F., Casetti, C., Chiasserini, C.-F., and Fiore, M., (2013). “Optimal content downloading in vehicular networks”, IEEE Transactions on Mobile Computing, 12(7):1377–1391.
- [62] Li, Z., Liu, C., and Chigan, C., (2013). “On secure VANET-based ad dissemination with pragmatic cost and effect control”, IEEE Transactions on Intelligent Transportation Systems, 14(1):124–135.
- [63] Luo, J. and Hubaux, J.-P., (2006). A Survey of Research in Inter-Vehicle Communications, Embedded Security in Cars, pages 111–122, Springer, Berlin.
- [64] Yoo, H. and Kim, D., (2013). “Dynamic Channel Coordination Schemes for IEEE 802.11p/1609 Vehicular Networks: A Survey”, IET Communications, 2013:1–8. Article ID: 827317.

- [65] Lin, C.-S. and Lin, J.-C., (2013). “Physical-layer transceiving techniques on data-aided orthogonal frequency-division multiplexing towards seamless service on vehicular communications”, *IET Communications*, 7(8):721–730.
- [66] International Telecommunication Union (ITU), Rec. ITU-R M.1225, GUIDELINES FOR EVALUATION OF RADIO TRANSMISSION TECHNOLOGIES FOR IMT-2000, <http://www.itu.int/rec/T-REC-X/en>, 15 August 2015.
- [67] Yarkan, S. and Arslan, H., (2007). “Binary Time Series Approach to Spectrum Prediction for Cognitive Radio”, 66th IEEE Vehicular Technology Conference, [VTC 2007–Fall], 30 September–3 October 2007, Baltimore, Maryland, USA.
- [68] Yarkan, S., Toreyin, B. U., and Cetin, K. A. Q. A. E., (2012). “An online adaptive cooperation scheme for spectrum sensing based on a second-order statistical method”, *IEEE Transactions on Vehicular Technology*, 61(2):675–686.
- [69] Geirhofer, S., Tong, L., and Sadler, B. M., (2008). “Cognitive Medium Access: Constraining Interference Based on Experimental Models”, *IEEE Journal on Selected Areas in Communications*, 26(1):95–105.
- [70] Goldsmith, A. J., Greenstein, L. J., and Foschini, G. J., (1994). “Error Statistics of Real-time Power Measurements in Cellular Channels with Multipath and Shadowing”, *IEEE Transactions on Vehicular Technology*, 43(3.P.I):439–446.
- [71] Shannon, C. E., (1948). “The Mathematical Theory of Communication”, *The Bell System Technical Journal*, 27:379–423; 623–656.
- [72] Zhang, W., Mallik, R., and Letaief, K. B., (2009). “Optimization of cooperative spectrum sensing with energy detection in cognitive radio networks”, *IEEE Transactions on Wireless Communications*, 8(12):5761–5766.

PROOFS

A.1 Proof of Proposition 1

First of all, it should be stated that width of the window within which T is located is selected to be T_W satisfying $NT \leq T_W$, where N is the number of distinct nodes that could transmit their signals simultaneously. It is evident that $2 \leq N$ is required in order for collisions to occur. Also, even though $2T \leq T_W$ is not mandatory; it is desired that the analysis could support a collision-free scenario as well. From this perspective, the analysis carried out here does not distinguish between two-node and three- or more-node collision scenarios. In other words, a single-collision and multiple-collisions scenarios are regarded the same. Therefore, for the sake of having an easier analysis $N = 2$ is assumed.

Let a pulse of width of T be placed somewhere across T_W with a PDF, say $f_{t_k}(t)$, for the k -th node with $k = 1, 2, \dots, N$. Therefore, t_k is a random variable whose PDF, $f_{t_k}(t)$, is defined within $[0, L]$ where $L = T_W - T$. It is evident that

$$|t_k - t_l| < T \tag{A.1}$$

suffices in order for a single collision to take place with $k \neq l = 1, 2, \dots, N$. As stated above, since there is no difference from the perspective of collision, $N = 2$ yields $|t_2 - t_1| < T$. Note that $|t_2 - t_1| < T$ implies a strict regime because an infinitesimal overlap of signals is regarded as a collision. For practical reasons, it would be desirable

to have tolerance of overlapping temporal region. Therefore,

$$|t_2 - t_1| < (1 - \rho) T \quad (\text{A.2})$$

could be written, where ρ denotes the width of the temporal region in which signals of both nodes overlap each other with $0 \leq \rho < 1$. As can be seen from (A.2), ρ could be chosen arbitrarily in such a way that strict (*i. e.*, $\rho = 0$) and maximum tolerance regime (*i. e.*, $\rho < 1$) can both be covered.

Let first $\Delta t = t_2 - t_1$. Since $f_{t_1}(t) = f_{t_2}(t)$, then:

$$f_{\Delta t}(t) = \int_{-\infty}^{\infty} f_{t_1}(\tau) f_{t_2}(t - \tau) d\tau \quad (\text{A.3})$$

$$f_{\Delta t}(t) = \underbrace{\int_0^{t+L} \left(\frac{1}{L}\right)^2 d\tau}_{-L < t \leq 0} + \underbrace{\int_t^L \left(\frac{1}{L}\right)^2 d\tau}_{0 < t \leq L} \quad (\text{A.4})$$

Note that running integrals on the right hand side of (A.4) have different upper- and lower-bound pairs with the convolution intervals given under the integral. Therefore, calculations should be carried out regarding the convolution interval yields a piece-wise PDF as follows:

$$f_{\Delta t}(t) = \begin{cases} \frac{1}{L^2} (L + t) & , \quad -L \leq t \leq 0 \\ \frac{1}{L^2} (L - t) & , \quad 0 < t \leq L \\ 0 & , \quad \text{otherwise} \end{cases} \quad (\text{A.5})$$

It is critical to remember that collision analysis requires one-sided PDF due to $|\cdot|$ in (A.2). Also, (A.5) is perfectly symmetric around $t = 0$. Hence, one-sided version of PDF should transfer the piece defined within $-L < t \leq 0$ onto $0 < t \leq L$. This conversion is obtained via time-reversal of the relevant piece $\frac{1}{L^2} (L + t)$. Time-reversal is obtained by

applying change of variable as $t \rightarrow -t$ yielding $\frac{1}{L^2} (L + (-t))$. Thus, the final output for the $f_{|\Delta t|}(t)$ becomes:

$$f_{|\Delta t|}(t) = \begin{cases} \frac{2}{L^2} (L - t) & , \quad 0 \leq t \leq L \\ 0 & , \quad \text{otherwise} \end{cases} \quad (\text{A.6})$$

Now one is ready to measure the probability of having a collision. Since collision occurs when $0 \leq |\Delta t| \leq (1 - \rho) T$, then the probability of having a collision corresponds to:

$$\begin{aligned} \Pr(0 \leq |\Delta t| \leq (1 - \rho) T) &= \int_0^{(1-\rho)T} f_{|\Delta t|}(t) dt \\ &= \frac{2}{L^2} \int_0^{(1-\rho)T} (L - t) dt \\ &= 1 - \left(1 - \frac{(1 - \rho) T}{L}\right)^2 \end{aligned} \quad (\text{A.7})$$

which completes the proof.

A.2 Proof of Corollary 5.3.1

With the aid of results obtained in Section A.1, one could check easily whether (A.7) is convergent by investigating the limiting conditions. Recall first that $2T \leq T_W$. In order for a strategy to be convergent, one should check both $N \rightarrow \infty$ and $T_W \rightarrow \infty$. First, $N \rightarrow \infty$ will be investigated.

It is clear that (A.6) is valid $\forall m, n, m \neq n, |\Delta t|_{mn} = |\Delta t|_{nm} = |t_n - t_m|, m, n \in \{1, 2, \dots, N\}$ since $|\Delta t|_{mn}$ are independent and identically distributed (i.i.d.). In order to check if (at least) a collision occurs, $\min\{|\Delta t|_{mn}\}$ should be investigated from the perspective of the collision condition given in Section A.1. However, first PDF of $\min\{|\Delta t|_{mn}\}$ should be evaluated. For the sake of brevity, let $\mathbf{X} = \min\{|\Delta t|_{mn}\}$. It is evident that $\mathbf{X} = \min\{|\Delta t|_{12}, |\Delta t|_{23}, |\Delta t|_{31}\}$ for $N = 3$. Since what is sought for is PDF of \mathbf{X} , then $\forall x, \Pr(\mathbf{X} \leq x)$ should be examined. However, due to the very nature of $\min(\cdot)$ operator, the event $\{\mathbf{X} \leq x\}$ is ambiguous. To see this, assume that

$\{\mathbf{X} \leq x_c\} = |\Delta t|_{12}$ where $x_c \in (0, L)$. Obtaining $\{\mathbf{X} \leq x_c\} = |\Delta t|_{12}$ implies all $|\Delta t|_{12} < |\Delta t|_{23}$, $|\Delta t|_{12} < |\Delta t|_{31}$, and $|\Delta t|_{12} < x_c$; but yields no piece of information regarding $|\Delta t|_{23} \lesseqgtr x_c$ or $|\Delta t|_{31} \lesseqgtr x_c$. In other words, $\{\mathbf{X} \leq x\}$ can only have a meaning when $x = L$ in parallel with (A.6) which is valid under every scenario for each and every sort of σ -algebra representing the certainty. In contrast, $\{x_c < \mathbf{X}\} = |\Delta t|_{12}$ yields a conclusive result, since it is valid when all $|\Delta t|_{12} < |\Delta t|_{23}$, $|\Delta t|_{12} < |\Delta t|_{31}$, $x_c < |\Delta t|_{12}$, and $x_c < |\Delta t|_{23}$ are held si. Note that $\{x_c < \min\{|\Delta t|_{12}, |\Delta t|_{23}, |\Delta t|_{31}\}\} = |\Delta t|_{12}$ is sufficient to analyze the event in terms of $\forall m, n, m \neq n, |\Delta t|_{mn}$ and of $\forall x_c \in (0, L)$.

The event $\{x < \mathbf{X}\}$ can be decomposed in the following way:

$$\{x < \mathbf{X}\} = \bigcap_{\substack{d \in m \times n \\ m \neq n}}^D \{x < |\Delta t|_d\} \quad (\text{A.8})$$

where $\cdot \times \cdot$ denotes the Cartesian product and $D = \frac{N(N-1)}{2}$. If the probability measure is applied to both side of (A.8), then:

$$\Pr(\{x < \mathbf{X}\}) = \Pr\left(\bigcap_{\substack{d \in m \times n \\ m \neq n}}^D \{x < |\Delta t|_d\}\right) \quad (\text{A.9})$$

is obtained. Since what is sought for is $\forall x \in [0, L], \Pr(\mathbf{X} \leq x)$ and $\{x < \mathbf{X}\}^c = \{\mathbf{X} \leq x\}$, $(\cdot)^c$ being the complement of its input, (A.9) could be written as follows with the aid of Kolmogorov axioms:

$$\begin{aligned} \Pr(\{\mathbf{X} \leq x\}) &= 1 - \left(\prod_{\substack{d \in m \times n \\ m \neq n}}^D \Pr(\{x < |\Delta t|_d\})\right) \\ &= 1 - \left(\prod_{\substack{d \in m \times n \\ m \neq n}}^D \Pr(\{x < |\Delta t|_d\})\right) \\ &= 1 - \left(\prod_{\substack{d \in m \times n \\ m \neq n}}^D (1 - \Pr(\{|\Delta t|_d \leq x\}))\right) \end{aligned} \quad (\text{A.10})$$

Note that $F_{|\Delta t|_d}(x) = \Pr(\{|\Delta t|_d \leq x\})$, where $F_{\mathbf{Z}}(\cdot)$ is the cumulative distribution function (CDF) of the random variable \mathbf{Z} . In addition, all $|\Delta t|_d$ are assumed to be i.i.d. as stated before. Thus, (A.10) translates into:

$$\Pr(\{\mathbf{X} \leq x\}) = 1 - \left(\prod_{\substack{d \in m \times n \\ m \neq n}}^D 1 - F_{|\Delta t|_d}(x) \right) \quad (\text{A.11})$$

$$\Pr(\{\mathbf{X} \leq x\}) = 1 - (1 - F_{|\Delta t|_d}(x))^D$$

Finally, the PDF is calculated by taking the derivative:

$$\frac{d}{dx} \Pr(\{\mathbf{X} \leq x\}) = \frac{d}{dx} \left(1 - (1 - F_{|\Delta t|_d}(x))^D \right) \quad (\text{A.12})$$

$$f_{\mathbf{x}}(x) = D f_{|\Delta t|_d}(x) (1 - F_{|\Delta t|_d}(x))^{D-1}$$

where $f_{|\Delta t|_d}(x)$ is given in (A.6) along with the fact that $0 \leq x \leq 1$. Recall that $N \rightarrow \infty$ implies $D \rightarrow \infty$. However, for $0 \leq x \leq 1$, the behavior of (A.12) becomes asymptotically convergent yielding $f_{\mathbf{x}}(x) \rightarrow 0$. By the very definition of PDF, one could conclude that:

$$\lim_{N \rightarrow \infty} f_{\mathbf{x}}(x) = \delta(x) \quad (\text{A.13})$$

After investigating $N \rightarrow \infty$, one is ready to contemplate $T_W \rightarrow \infty$. Assuming that T is fixed, it is obvious that $T_W \rightarrow \infty$ implies $L \rightarrow \infty$. Therefore, both (A.6) and (A.12) converges due to the term L^2 in the denominator. Hence:

$$\lim_{T_W \rightarrow \infty} f_{\mathbf{x}}(x) = 0 \quad (\text{A.14})$$

which completes the proof.

A.3 Proof of Proposition 2

Proof. In order to prove Proposition 2, let $L = 1$ since the analysis is more tractable and valid for any channel. Therefore, the indices k and i will be dropped. However, one should keep in mind that proof holds for $1 < L$ since (6.10) satisfies the linearity conditions.

Mean-squared prediction error is given by:

$$\sigma_e^2 = E \left\{ \left(\hat{\mathbf{X}}_{n+1} - (\alpha \mathbf{X}_n + \mu_{\mathbf{X}}) \right)^2 \right\} = \overbrace{\sigma_{\hat{\mathbf{X}}_{n+1}}^2 + \alpha^2 \sigma_{\mathbf{X}_n}^2 - 2\alpha E \left\{ \hat{\mathbf{X}}_{n+1} \mathbf{X}_n \right\}}^{\varphi(\alpha)} + \underbrace{\mu_{\mathbf{X}}^2 + 2\mu_{\mathbf{X}} \left(\alpha E \left\{ \mathbf{X}_n \right\} - E \left\{ \hat{\mathbf{X}}_{n+1} \right\} \right)}_{h(\mu_{\mathbf{X}})} \quad (\text{A.15})$$

where $h(\mu_{\mathbf{X}})$ in (A.15) is the final term which should be minimized. Because the condition that is sought for is $\frac{d}{d\mu_{\mathbf{X}}} h(\mu_{\mathbf{X}}) = 0$, it is clear that:

$$\mu_{\mathbf{X}} = \mu_{\hat{\mathbf{X}}_{n+1}} - \alpha \mu_{\mathbf{X}_n} \quad (\text{A.16})$$

is obtained where $\mu_{\mathbf{Z}} = E \{ \mathbf{Z} \}$ for any stationary stochastic process \mathbf{Z} . Note that $\varphi_{\hat{\mathbf{X}}_{n+1} \mathbf{X}_n}$ in (A.15) can be rewritten as:

$$\varphi(\alpha) = \text{Var} \left(\hat{\mathbf{X}}_{n+1} - \alpha \mathbf{X}_n \right) \quad (\text{A.17})$$

where $\text{Cov} \left(\hat{\mathbf{X}}_{n+1} \mathbf{X}_n \right)$ denotes the covariance $E \left\{ \hat{\mathbf{X}}_{n+1} \mathbf{X}_n \right\}$. In this regard, following the same reasoning as that for $h(\mu_{\mathbf{X}})$, minimization of $\varphi(\alpha)$ in (A.15) seeks a solution for

$$\frac{d}{d\alpha}\varphi(\alpha) = 0:$$

$$\alpha = \rho_{\hat{\mathbf{X}}_{n+1}\mathbf{X}_n} \frac{\sigma_{\hat{\mathbf{X}}_{n+1}}}{\sigma_{\mathbf{X}_n}} \quad (\text{A.18})$$

where $\rho_{\hat{\mathbf{X}}_{n+1}\mathbf{X}_n} \in [-1, 1]$ denotes the cross-correlation coefficient estimates bearing in mind that:

$$\rho_{\hat{\mathbf{X}}_{n+1}\mathbf{X}_n} = \frac{\text{Cov}\left(\hat{\mathbf{X}}_{n+1}\mathbf{X}_n\right)}{\sigma_{\hat{\mathbf{X}}_{n+1}}\sigma_{\mathbf{X}_n}} \quad (\text{A.19})$$

Next, α in (A.18) can be plugged into $\varphi(\alpha)$ in (A.15) and after some mathematical manipulations the following:

$$\text{Var}\left(\hat{\mathbf{X}}_{n+1} - \alpha\mathbf{X}_n\right) = \sigma_{\hat{\mathbf{X}}_{n+1}}^2 \left(1 - \rho_{\hat{\mathbf{X}}_{n+1}\mathbf{X}_n}^2\right) \quad (\text{A.20})$$

is obtained. Recall that $\rho_{\hat{\mathbf{X}}_{n+1}\mathbf{X}_n} \in [-1, 1]$; therefore, $\rho_{\hat{\mathbf{X}}_{n+1}\mathbf{X}_n}^2 \in [0, 1]$.

Once the prediction is established, one might want to quantify the probability that the predicted value of the energy detector is above a threshold so that the channel selection mechanism could act on it accordingly. In this regard, the channel selection mechanism investigates $\Pr\left(\left(\hat{\mathbf{X}}_{n+1} - \mu_{\hat{\mathbf{X}}_{n+1}}\right) < \gamma\right)$. Considering the fact that energy detector yields always nonnegative output as declared in (6.7), $\hat{\mathbf{X}}_{n+1}$ is actually a nonnegative stochastic process. Therefore, $\Pr\left(\left(\hat{\mathbf{X}}_{n+1} - \mu_{\hat{\mathbf{X}}_{n+1}}\right)^2 < \gamma^2\right)$ is read. Applying Chebyshev's inequality:

$$\gamma^2 \left(1 - \Pr\left(\left(\hat{\mathbf{X}}_{n+1} - \mu_{\hat{\mathbf{X}}_{n+1}}\right)^2 \geq \gamma^2\right)\right) \leq \sigma_{\hat{\mathbf{X}}_{n+1}}^2 \quad (\text{A.21})$$

is yielded. Then, combining both (A.20) and (A.21):

$$\underbrace{\gamma^2 \left(1 - \rho_{\hat{\mathbf{X}}_{n+1}\mathbf{X}_n}^2\right)}_{\xi} \underbrace{\left(1 - \Pr\left(\left(\hat{\mathbf{X}}_{n+1} - \mu_{\hat{\mathbf{X}}_{n+1}}\right)^2 \geq \gamma^2\right)\right)}_{\kappa} \leq \text{Var}\left(\hat{\mathbf{X}}_{n+1} - \alpha\mathbf{X}_n\right) \quad (\text{A.22})$$

is held. Note that all γ^2 , ξ , and κ are nonzero. Furthermore, both $\xi, \kappa \in [0, 1]$. This implies that:

$$0 < \gamma^2 \xi \kappa \leq \text{Var} \left(\hat{\mathbf{X}}_{n+1} - \alpha \mathbf{X}_n \right) \quad (\text{A.23})$$

revealing that prediction has an irreducible lower bound of error and the lower bound is a function of the threshold γ used by the energy detector. This completes the proof. \square

APPENDIX B

CURRICULUM VITAE

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EDUCATION

Degree	Department	University	Date of Graduation
Master	Computer Eng.	İstanbul University	2010
Undergraduate	Computer Eng.	İstanbul University	2007
High School	Fen	Tavşanlı İMKB Anadolu Öğr. Lis.	2003

WORK EXPERIENCE

Year	Corporation/Institute	Enrollment
2007	Netaş	Software Engineer
2010	Huawei	Software Engineer
2012	İstanbul Ticaret Üniversitesi	Research Assistant

PUBLICATIONS

Papers

1. Boyaci, A., Zaim, H., and Sönmez, C., (2015). "A cross-layer adaptive channel selection mechanism for IEEE 802.11 p suite", *EURASIP Journal on Wireless Communications and Networking*, 2015(1):1–13, doi:10.1186/s13638-015-0441-z.

Conference Papers

1. Boyaci, A., Yarkan, S., and Zaim, A., (2013). "Identification of shadowed fast fading interference in cellular mobile radio systems", 21st Signal Processing and Communications Applications Conference (SIU), 24–26 April 2013, Haspolat, Northern Cyprus.
2. Boyaci, A., Ozturk, E., Yarkan, S., and Zaim, A., (2013). "Towards green and secure vehicle-to-vehicle communications: A protocol for establishing the network", 7th International Conference on Application of Information and Communication Technologies (AICT), 23–25 October 2013, Baku, Azerbaijan.
3. Boyaci, A., Yarkan, S., Sönmez A.C., (2015). "I/Q Kolları Ayrımına Dayalı, Kesirli-oranlı Radyometrik Spektrum Sezme", Signal Processing and Communications Applications Conference (SIU), 16-19 May 2015, Malatya, Türkiye.
4. Boyaci, A., AKI F.N., Yarkan, (2015). "On Error Variance for Autoregressive-Process-Based Spectrum Occupancy Prediction with Energy Detector for Cognitive Networks", The International Wireless Communications & Mobile Computing Conference (IWCMC 2015), 24-28 Aug 2015, Dubrovnik, Croatia.