Adaptive QoS control of DSRC vehicle networks for collaborative vehicle safety applications.

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Adaptive QoS Control of DSRC Vehicle Networks for Collaborative Vehicle Safety Applications

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Submitted to Swansea University in fulfilment
of the requirements for the Degree of Doctor of Philosophy

2013

Abstract

Road traffic safety has been a subject of worldwide concern. Dedicated short range communications (DSRC) is widely regarded as a promising enabling technology for collaborative safety applications (CSA), which can provide robust communication and affordable performance to build large scale CSA system.

The main focus of this thesis is to develop solutions for DSRC QoS control in order to provide robust QoS support for CSA. The first design objective is to ensure robust and reliable message delivery services for safety applications from the DSRC networks. As the spectrum resources allocated to DSRC network are expected to be shared by both safety and non-safety applications, the second design objective is to make QoS control schemes bandwidth-efficient in order to leave as much as possible bandwidth for non-safety applications.

The first part of the thesis investigates QoS control in infrastructure based DSRC networks, where roadside access points (AP) are available to control QoS control at road intersections. After analyse DSRC network capabilities on QoS provisioning without congestion control, we propose a two-phases adaptive QoS control method for DSRC vehicle networks. In the first phase an offline simulation based approach is used to find out the best possible system configurations (e.g. message rate and transmit power) with given numbers of vehicles and QoS requirements. It is noted that with different utility functions the values of optimal parameters proposed by the two phases centralized QoS control scheme will be different. The conclusions obtained with the proposed scheme are dependent on the chosen utility functions. But the proposed two phases centralized QoS control scheme is general and is applicable to different utility functions. In the second phase, these configurations are used online by roadside AP adaptively according to dynamic traffic loads. The second part of the thesis is focused on distributed QoS control for DSRC networks. A framework of collaborative QoS control is proposed, following which we utilize the local channel busy time as the indicator of network congestion and adaptively adjust safety message rate by a modified additive increase and multiplicative decrease (AIMD) method in a distributed way. Numerical results demonstrate the effectiveness of the proposed QoS control schemes.

Declarations and Statements

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated. Where correction services have been used, the extent and nature of the correction is clearly marked in a footnote(s).
Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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I hereby give consent for the thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

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Acknowledgements

I would like to express my deepest gratitude to my supervisor Dr Jianhua He who has supported me throughout my Ph.D study with his patience and knowledge. The PhD research is not an easy and comfortable journey. I am so grateful for your guidance and the time you worked with me to make this research a success. I have learned a lot of knowledge and useful skills from you which equipped myself to become a better researcher.

My special appreciation goes to my supervisor Dr Xinheng Wang for the academic advices and great support provided to me throughout my research project. Especially in the last year you helped me so much on my thesis writing up, guided me and gave the extra pushes I needed to pass the line of my PhD study.

My sincere appreciation goes to Dr Lin Bai for his kind support and fruitful discussions. I really enjoyed the time of studying both MSc and PhD together with Dr Bai at IAT, Swansea University. I also want to say thanks to all my friends at IAT for making our time here worthwhile. I have learned a lot from all of you, especially Dr Shancang Li and Mr Chao Ma.

My thanks also go to all our lecturers at IAT for their kind help on my MSc study as well as my PhD research, especially to my co-supervisor Prof Tom Chen, and my MSc project supervisor Dr Pavel Loskot.

Last but not least I am indebted to my parents for their constant support and encouragement. You always stood by me and believed me whenever I faced frustration and difficult times. Without your love and support my dream of a PhD degree in telecommunications technology at Swansea University would never have come through.

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List of Abbreviations

CSA	Collaborative Safety Applications
IVC	Inter-Vehicle Communication
GPS	Global Positioning System
DSRC	Dedicate Short Range Communication
QoS	Quality of Service
IEEE	Institute of Electrical and Electronics Engineers
MAC	Media Access Control
AP	Access Point
CCH	Control Channel
AIMD	Additive Increase Multiplicative Decrease
WAVE	Wireless Access for the Vehicular Environment
TCP	Transmission Control Protocol
CVS	Collaborative Vehicle Safety
V2V	Vehicle to Vehicle
V2I	Vehicle to Intrastructure
ITS	Intelligent Transportation Systems
RSU	Road Side Unit
WAN	Wide Area Network
WiMAX	Worldwide Interoperability for Microwave Access
BS	Base Station
UWB	Ultra Wide Broadband
ACC	Adaptive Cruise Control
FCC	Federal Communications Commission
LAN	Local Area Network
MIMO	Multiple-Input and Multiple-Output

V2R	Vehicle to Roadside unit
ASTM	American Society for Testing and Materials
ETSI	European Telecommunications Standards Institute
SCH	Service Channel
OFDM	Orthogonal Frequency-Division Multiplexing
3GPP	3rd Generation Partnership Project
LTE	Long Term Evolution
UMTS	Universal Mobile Telecommunications System
VANET	Vehicular Ad hoc Network
MANET	Mobile Ad hoc Network
RIP	Routing Information Protocol
OSPF	Open Shortest Path First
DSDV	Destination-Sequenced Distance Vector
OLSR	Optimized Link State Routing
AODV	Ad hoc On-demand Distance Vector
DSR	Dynamic Source Routing
ZRP	Zone Routing Protocol
ESA	Emergency Safety Applications
DCF	Distributed Coordination Function
CSMA/CA	Carrier Sense Multiple Accesses with Collision Avoidance
RTS	Ready To Send
CTS	Clear To Send
NAV	Network Allocation Vector
ACK	Acknowledgement
CW	Contention Window
TDM	Time Division Multiplexing
AC	Access Category
SI	Synchronization Interval
EDCA	Enhanced Distributed Coordination Access
TXOPs	Transmission Opportunities
PSA	Periodic Safety Application
TFRC	TCP Friendly Rate Control

BE	Backoff Exponent
ASA	Adaptive Safety Applications
CAA	Cooperation And Adaptation
MMRC	MAC layer Message Rate Control
FCS	Fixed Control Scheme
ARCS	Adaptive Rate Control Scheme
UTRA-TDD	UMTS Terrestrial Radio Access Time Division Duplex

Chapter 1

Introduction

1.1 Research Problems and Motivations

Road traffic safety has been a subject of worldwide concern. The UK Department for Transport reported more than 208,000 casualties of all severities in 2011, in which about 2000 people were killed and 25,000 were seriously injured [1]. The annual worldwide losses due to road accidents are tremendously high.

Collaborative Safety Applications (CSA) enabled by vehicular communications is widely regarded as a key to future road safety. By equipping vehicles with Inter-vehicle Communication (IVC) and Global Positioning System (GPS), the driver's horizon of perception can be widened to recognize hazardous events that can not be detected by local sensors or by the driver alone, such as vehicles braking for emergency stops and merging traffic, vehicles in a blind spot, and imminent collisions [2] [3].

Compared to the cellular and satellite communication technologies, DSRC can provide ad hoc and localized communications, with the advantages of high data rate, low message transmission latency, low costs for communication and equipment [4]. DSRC has attracted lots of attention from the automotive industry and wireless network research community. For example, Institute of Electrical and Electronics Engineers (IEEE) developed a Wireless Access in Vehicular Environment (WAVE) to provide seamless, interoperable services to transportation with IVC [5] [6]. Major car manufacturers (e.g., GM, BMW) and research institutes worldwide, most particularly in the US, Germany, Japan and Sweden, are also active in the research and development of DSRC technique [2] [7].

Unlike the non-safety applications, vehicle safety systems have extremely high reliability requirement. Practical and reliable CSA requires robust and reliable message delivery services from the DSRC networks as well [2] [8]. A key to the success of large scale CSA is efficient and robust QoS support from DSRC vehicle networks, which is however very challenging. There are several major obstacles to the provisioning efficient and robust QoS support from DSRC vehicle networks, including:

- Hashing wireless communication channel due to multi-path delay spread and Doppler effect in the outdoor between high-speed vehicles environment [9] [10].

- At MAC layer IEEE 802.11 based random channel access is used in DRSC, which is widely known to be inefficient in providing deterministic QoS guarantee. The channel can be easily congested and results in unacceptable QoS [4] [5] [11] .

- At network layer vehicles are networked in an ad hoc manner with highly dynamic network topology and short-lived connectivity [2] [7] [12].

- At transport layer, as useful safety information is usually limited to the area around a vehicle and broadcast to the neighbour vehicles, congestion control is necessary but very difficult as feedback for broadcast message transmission is very hard, which is different from the well studied end-to-end unicast TCP congestion control protocol [13] [14] [15].

- At application layer, multiple priorities of safety applications and bandwidth demanding non-safety applications are expected to be deployed over DSRC networks , making QoS support problem more complicated and challenging [2] [7] [12].

To the best of our knowledge, robust QoS control of DSRC networks to provide QoS support by utility function for CSA has not been reported in the existing literature. The main motivation of this thesis is to develop and evaluate novel

QoS control schemes for DSRC vehicle networks to provide efficient and robust QoS for CSA.

1.2 Research Objectives

The implications of this research are expected to contribute directly to DSRC network QoS support, which will eventually contribute to realize safe, environment friendly and comfortable driving. With a vision of DSRC network enabled CSA and the importance of QoS support by DSRC networks, this thesis is aimed at systematic design and optimization of QoS control of DSRC network to provide adaptive robust QoS support for CSA, in order to bring CSA closer to practicality. In this thesis the QoS metrics of safety message success probability, message delivery delay and number of messages received per second are considered. The metric of message success probability is defined as the ratio of the number of successful messages (i.e. without collision with any other messages during the entire transmission period) to the overall number of transmitted messages. Message delivery delay is defined as the time elapsed from when a message is generated to the time the message is transmitted. The QoS requirements for the safety messages are assumed to be comparable to those summarized in the Table.1.1 [2].

Table 1.1: Preliminary Application QoS Requirements

	Trans mode	Min Freq	Latency
Emergency brake light	ESA	10	100ms
Pre-crash sensing	ESA	50	20ms
Forward collision warning	PSA	10	100ms
Lane change warning	PSA	10	100ms

The aims of this thesis includes:

- To devise and develop tools for evaluating the efficiency and robustness of QoS support that can be provided by DSRC networks for large scale CSA.
- To design both centralized and distributed QoS control solutions for DSRC networks with the aims of guaranteeing the QoS required by emergency

safety applications and maximizing bandwidth utilization to support non-safety applications for economic concerns.

The main objectives of the thesis are summarized as follows:

- To devise performance evaluation tool (mainly simulation based) for analysing the QoS performance measures in terms of packet loss, delay and transmission range for multiple-class broadcast safety applications over multiple-priority 802.11p MAC with various transmit power, traffic rate and vehicle density.

- To formulate the optimal transmit power and message rate control problem, design and evaluate centralized low-complexity algorithms for the control problem at road intersection scenarios.

- To develop a software package using MATLAB that implements the centralized algorithms, use it to investigate the joint impact of transmit power, message rate, 802.11p MAC and vehicle density on robust QoS support, and identify the dominant components that influence robust QoS support for CSA.

- To devise distributed robust and bandwidth-efficient QoS control schemes which implement the functions of congestion prevention, congestion mitigation and QoS adaptation through power and message rate control.

- To develop a discrete-event driven simulator that implements the distributed QoS control schemes, conduct systematic performance study of the QoS support for CSA, test and demonstrate the viability of the developed robust QoS control schemes in practical network scenarios. For the work presented in this thesis, the main concern is on the investigation of channel access performances of 802.11p networks, which is mainly dependent on the overall number of competing vehicle nodes around one target node (such as the access point in the network). As the overall number of competing nodes does not change much in the scales of message transmission time, we have considered static network scenarios in this thesis. Simulation parameters on

MAC and PHY layer for vehicle network are obtained from IEEE standard 802.11 and 802.11p.

1.3 Structure of Thesis and Main Contributions

Research works has been conducted to successfully achieved the preset research objectives, which are presented in this thesis according to the structure to be introduced.

The first part of the thesis considers the DSRC QoS control in infrastructure based networks, where road side Access Pointers (AP) are available to manage QoS control for single hop DSRC based vehicle networks at road intersections. Under such network scenarios centralized QoS control is possible with the help of APs and beneficial as well. A two-phases adaptive QoS control method is proposed for DSRC vehicle networks, where multiple safety and non-safety applications may coexist. The first phase is to use an offline simulation based approach to find out the best possible system configurations (e.g. Control Channel (CCH) interval length, safety message rate, and channel access parameters) for given numbers of vehicles, under given safety application QoS requirements. The problem to be solved is formulated as a multiple objectives optimization problem. Several utility functions are proposed to take the QoS requirements of safety applications for the coexisting safety and non-safety applications. In the second phase these identified best configurations are used online by roadside AP adaptively according to dynamic traffic loads. Simulation results demonstrated that the adaptive QoS control method can largely outperform the fixed control method under varying number of vehicles.

The second part of the thesis considers the more challenging DSRC QoS control problems in large-scale infrastructureless vehicle ad hoc networks. Under such network scenarios adaptive centralized QoS control is hard to implement as only limited local network knowledge is available. Therefore distributed QoS control schemes for DSRC safety applications are proposed by the adaptive control of channel congestion. Three basic functions (i.e. congestion prevention, congestion mitigation and QoS adaptation) are developed with limited localized knowledge. The main idea for the schemes is to utilize the local channel busy time as the indicator of network congestion and adaptively adjust safety message rate by a modified Additive Increase and Multiplicative Decrease (AIMD) method in a distributed way.

Simulation results demonstrate the effectiveness of the proposed rate control schemes, which have achieved the design goals of improving channel utilization and providing good QoS for high priority safety applications. The proposed adaptive schemes perform much better than fixed rate scheme.

1.4 Publications

Published/Accepted

[1] W. Guan, J. He, C. Ma, Z. Tang, and Y. Li, Adaptive message rate control of infrastructured DSRC vehicle networks for coexisting road safety and non-safety applications, *International Journal of Distributed Sensor Networks, vol. 2012, Article ID 134238, 8 pages, 2012. doi:10.1155/2012/134238*

[2] W. Guan, J. He, L. Bai, Y. Zhou and Y. Li, Adaptive power and rate control for QoS guarantee of DSRC based collaborative road safety applications, *Information Journal, January 2013* (In press)

[3] W. Guan, J. He, L. Bai, and Z. Tang, Adaptive rate control of dedicated short range communications based vehicle networks for road safety applications, *IEEE 73rd Vehicular Technology Conference, pp.1-5, May 15, 2011.*

[4] W. Guan, J. He, L. Bai, and Z. Tang, Adaptive congestion control of DSRC vehicle networks for collaborative road safety applications, *IEEE 36th Conference on Local Computer Networks, pp.913-917, 2011.*

[5] W. Guan, J. He, L. Bai, Z. Tang, Two-phases control of DSRC vehicle networks for road intersection coexisting safety applications, *Communication Technology (ICCT), 2011 IEEE 13th International Conference on, On page(s): 577 - 581*

[6] W. Guan, J. He, L. Bai, Z. Tang, and Y. Zhou, QoS guarantee with adaptive transmit power and message rate control for DSRC vehicle network based road safety applications, *U- and E-Service, Science and Technology - International Conference, vol.264, pp.130-135, 2011.*

[7] J. He, W. Guan, L. Bai, and K. Chen, Theoretic analysis of IEEE 802.11 rate adaptation algorithm SampleRate, *IEEE Communications Letters, vol.15, no.5, pp.524-526, May 2011.*

[8] B. Wu, C. Chen, L. Bai, W. Guan, and H. Xiang, Resource allocation for OFDMA systems with guaranteed outage probabilities, *IEEE 6th International Wireless Communications and Mobile Computing Conference, pp.731-735, 2010.*

[9] L. Bai, W. Guan, C. Chen, J. He, and R. Wang, Modeling high-Speed network traffic with truncated a-Stable processes, *Computation Theory and Information Technology, Macau,China,2011*

[10] D. Wang, L. Bai, X. Zhang, W. Guan, and C. Chen, Collaborative relay beamforming strategies for multiple destinations with guaranteed QoS in wireless machine-to-machine networks, *International Journal of Distributed Sensor Networks, vol. 2012, Article ID 525640, 10 pages, 2012. doi:10.1155/2012/525640*

[11] C. Ma, J. He, Z. Tang, W. Guan, and Y. Li, Investigation of uncoordinated coexisting IEEE 802.15.4 networks with sleep mode for machine-to-machine communications, *International Journal of Distributed Sensor Networks, vol. 2012, Article ID 940302, 11 pages, 2012. doi:10.1155/2012/940302*

[12] L. Bai, C. Chen, W. Guan, Y. Jin, and J Choi, Optimal multiuser beamforming scheme based on the worst SNR in cellular systems," *IEEE 75th Vehicular Technology Conference, pp.1-5, May 6-9, 2012.*

[13] X. Qu, M. Dong, W. Wang, W. Guan, Bit error rate performance bounds of SC-FDE under arbitrary multipath mobile," *International Journal of Computational Intelligence Systems Vol. 4, Iss. 6, 2011*

Chapter 2

Vehicular Communication Networks and Applications

Wireless communication based vehicle networks have been expected to play a vital role in the future vehicle safety systems. It was reported that there were over 40,000 deaths per year for Europe and United States [1]. Worldwide there were 1.2 million people killed in traffic crashes in 2002, contributing to 2.1% of all global deaths. In the UK alone it was reported by the UK Department of Transport that there were a total of 203,950 casualties in all road accidents reported to the police in 2011, among which 1,901 people were killed and 23,122 were seriously injured [1]. These reported road accidents have brought in a huge economic welfare cost, which is estimated to be around 15.6 billion pounds. All these statistics showed how danger everyday driving on the roads can be due to poor road conditions, our own and also other drivers' driving skills and lapses of attention. With increasing drivers and new cars on the roads especially in developing countries such as China and India, there is a strong demand in study of the cause of road accidents and develop effective solutions for prevention of road accidents.

According to [16], the number of fatalities fell for bus and coach occupants by 22 percentages, but rose by 6 percentages for car occupants. The most frequently reported contributory factor for the accidents is failed to look properly in driving, which contributes to 42 percent of all reported accidents in the UK in 2011.

From the reported statistics it can be observed road accidents and economic welfare cost could be significantly reduced, if there is a system that can automatically alert the drivers of hazards when they are sleepy and/or lost concentration, or extend the drivers' vision when they are approaching curves or driving in complex traffic situations. Collaborative Vehicle Safety (CVS) system is one of such systems which are driven by advances in wireless communication and vehicular networking technologies. With CVS complex traffic situation information may be acquired through Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communications to support collaborative safe driving [17]. Broadly speaking, CVS system is an important aspect of Intelligent Transport Systems (ITS). ITS has been extensively studied for several decades with the objectives of providing innovative transport and traffic management services and enabling safer and efficient transport [18]. The research carried out in this thesis is mainly focus on the vehicle safety aspect of ITS. However as the vehicle safety applications and non-safety applications are expected to share the frequency spectrum allocated to DSRC applications (which is the subject of this thesis), the QoS control of DSRC networks for support of vehicle safety applications will have large impact on the performances of non-safety applications. In this chapter, the communication technologies which can be used to support communications between vehicle to vehicle and vehicle to infrastructure are reviewed firstly. Then an overview on general vehicular networking research is presented. The vehicular applications and QoS requirements are discussed next. DSRC related standards and representative projects are presented finally.

2.1 Vehicular Communication Technologies

Vehicular communications is the foundation of CVS systems. The communications modes supporting CVS applications can be classified to V2I and V2V.

- V2I communication for vehicle to/from Roadside Unit (RSU): this communication mode requires the use of roadside transceivers. It can support transmission of vehicle safety related data, locally relevant data and/or general Internet access. It is noted that such communication mode can support only a small set of CVS applications, as the communication range of the RSUs is normally limited (e.g. to a few hundreds meters) and it is too expensive to deploy dense RSUs along all the roads. The advantage of such mode on the support of CVS is that centralized network and application control is possible, which can result in simplified network management and effective QoS support for CVS. The investigation of the RSU assisted CVS is presented in the first part of this thesis (Chapter 3 and Chapter 4).

- V2V communication for vehicle to/from vehicle: this communication mode supports vehicle to vehicle communications via direct or indirect connectivity, for example, through broadcast and direct-to-direct wireless technology provided by IEEE 802.11 standards [19]. V2V communication can support communication not only between a vehicle and its neighbouring vehicles, but also a vehicle with others outside of its communication range. Vehicle ad hoc networking (e.g. by IEEE 802.11 and/or cellular networks) could enable the communications for vehicles outside communication ranges. In the cases of without or with only very limited support from RSU, CVS applications will rely mainly on the V2V communications and the network control for effective QoS support can be much more difficult. The second part of this thesis deals with distributed QoS control for V2V enabled CVS.

V2I and V2V communications can be achieved directly by short-range radios (such as 802.11 and Bluetooth) or indirectly through medium to long distance radios (such as satellites or cellular networks). An example vehicle network built on both direct and indirect V2V communications is shown in Fig.2.1, in which direct V2V communications is enabled with 802.11-like short-range radio for vehicles within a local vicinity. Vehicles equipped with short-range radio can also communicate with in-range RSUs. Alternatively, indirect communications can be provided by commercial communication systems, e.g. Wide Area Networks (WANs) using satellite 2G/3G cellular Base Stations (BS), or Metropolitan Area Networks (MANs) such as Worldwide Interoperability for Microwave Access (WiMAX) [20]. Considering that useful safety information is usually limited to the local area around a vehicle and may be exchanged frequently, direct V2V communications is much more cost effective compared to indirect V2V communications for large-scale vehicle safety applications. Messages exchanged by indirect V2V communications encounter unnecessary and potentially excessive delays, which makes indirect V2V communications unsuitable for real-time safety applications. Direct V2V communications will outperform for CSA in terms of both communication performances and cost. Next the capabilities of currently

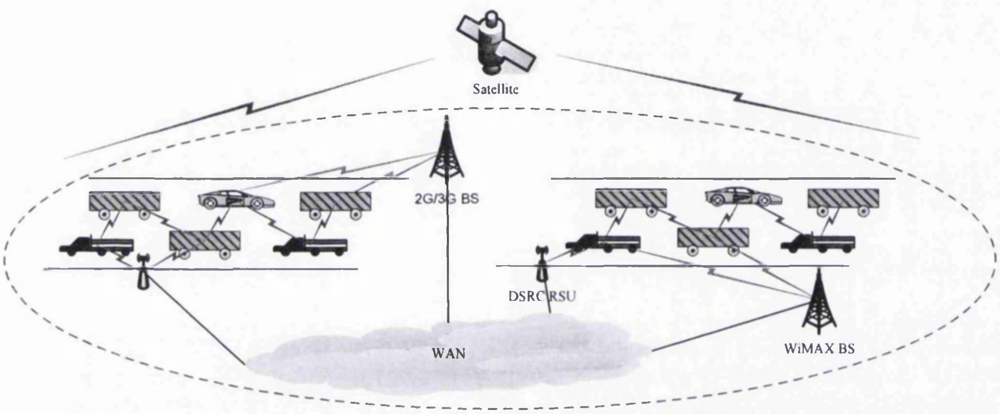

Figure 2.1: An example vehicle networks utilizing hybrid vehicle communication technologies.

available wireless communication technologies that could be applied to support CVS are briefly discussed.

2.1.1 Short-range Radio Technologies

In this subsection the representative short-range wireless communication technologies Bluetooth, Ultra-wideband (UWB), Adaptive Cruise Control (ACC) radar, 802.11 wireless local network and dedicate short range communication technology are introduced.

2.1.1.1 Bluetooth

Bluetooth has been developed for about two decades with the main aim of replacing the wires used to connect electronic equipments [21] [22]. It has a communication range of 10 meters and up to 100 meters. It may be used for V2I communications for stationary vehicles close to the access points. As the limitation of the communication range and the inherent communication latency with

Bluetooth, it is not capable of support most of the vehicle safety application. But it may find applications for some commercial applications or on-board entertainment applications.

2.1.1.2 Ultra-wideband

Ultra-wideband has been approved by US Federal Communications Commission (FCC) for limited use at very low power outputs and within a limited range of spectrum, such as for low power sensing, communications and positioning applications [23]. It may find a wide range of vehicle safety applications due to its low cost, small size and immunity to multipath interference. However one of the limitation of UWB on vehicle safety applications is its limited communication range with low power transmission mode, which is in the range of tens of meters.

2.1.1.3 Radar Based V2V Communication

ACC radars have been widely used in vehicles for both forward and backward sensing [24] . Radio signals generated for sensing applications by the radars are considered by researchers worldwide for communication purposes as a product. There are ongoing work in Germany, United Kingdom and Japan. Due to the wide bandwidth used by radar systems the available communication data rate is high. However a large limitation of radar based V2V communication is that it can normally support only one way wireless communication. And the communication between vehicles is mainly point-to-point based. Therefore it is unlike to be used by broadcast for vehicle safety applications, which will limit its capabilities to support CVS.

2.1.1.4 IEEE 802.11 Wireless LAN

The 802.11 standards were originally developed for the wireless local area networking, e.g. for Internet access at home, business office and public areas. The recently released standard 802.11n in 2009 is an amendment which improves over previous 802.11 standards [25]. By using Multiple-Input Multiple-Output antennas (MIMO) , 802.11n can provide a maximum data rate from 54 Mbit/s up to 600 Mbits/s [26]. Further development under the IEEE 802.11ac working group is targeting very high throughput in the 5 GHz frequency band [27]. With potential improvements over 802.11n by better modulation scheme and wider channels, 802.11ac is expected to provide a network throughput of at least 1 Gbits/s. On the other hand, the development under the IEEE 802.11ad working group is working to achieve very high throughput at 60 GHz, with a target network maximum throughput of up to 7 Gbits/s [28]. 802.11 systems have the features of low cost, easy of network administration, flexible networking capabilities and high data rate.

Due to the low cost and large availability of 802.11 systems, they have potentials to support vehicle networks applications such as information downloading at 802.11 hot spots.

2.1.1.5 DSRC Technology

DSRC has been widely regarded as a wireless communication technology which is robust and affordable enough to be built into large-scale vehicles. It offers very low latency, a broadcast capability with an operating range of about 1000 meters, which is ideal for general vehicle safety applications [29]. In most conditions the operation range is limited to about 200m at practical level. In the highway, 200m is seen as an appropriate range to ensure effective data exchange. The low latency is one of the most significant advantages in DSRC. The latency of DSRC communication is normally less than 100 milliseconds, for which other competing wireless communications technologies may not be able to achieve. It has attracted significant research and development interests from government, industry and academic institutes. As DSRC is the main technology to be investigated in this thesis, it is introduced with a little bit more details in this subsection. With the realization of the huge potentials of DSRC technology on vehicle safety applications, US FCC has allocated 75MHz of spectrum in the 5.9 GHz band for DSRC [9]. DSRC standards are currently being developed by organizations including the IEEE. IEEE is specifying a wireless access in vehicular environment for DSRC to provide seamless, interoperable V2V and Vehicle to RSU (V2R) communication services for transportation [30]. Despite the great potentials of DSRC technology for safety applications in vehicular network, there are still many challenges faced by the practical deployment of DSRC. One challenge is that vehicle safety applications have stringent requirements for reliable real-time message delivery, as excessive message delays or message loss hinder the effectiveness of safety applications and can even cause unexpected negative consequences. In July 2003 American Society for Testing and Materials (ASTM) and IEEE adopted the Dedicated Short Range Communication (DSRC) standard to meet the needs of the wireless communication demand in vehicles. The aim of this standard is to provide wireless communications capabilities for transportation applications within a 1000m range. It provides seven channels at the 5.9 GHz. In October 1999, the FCC allocated in the USA 75MHz of spectrum in the 5.9GHz band for DSRC to be used by ITS. Also, in Europe in August 2008 the European Telecommunications Standards Institute (ETSI) has allocated 30 MHz of spectrum in the 5.9GHz band for ITS. Technically DSRC operates in the 5.9GHz spectrum which is divided into seven channels. One is the control channel used for exchanging only vehicle safety messages, and the others are Service Channels (SCH). The CCH is used for exchange of management frames and safety related messages; the SCHs are used for application specific information exchanges. The physical layer specification used in DSRC is a variant of 802.11a, which data rate is 54Mbps with the OFDM technology [31]. It contains 52 sub-carriers, and the rate can be selected to 48, 36, 24, 18, 12, 9, 6 Mbps if required. Compared to other wireless protocol, 802.11a allows more client points in the network, which leads to the high reliability of the system. At the same time, it has disadvantage such as smaller cover range and signals are more easily absorbed by wall in that frequency band. But in road environment these disadvantages do not affect too much for vehicle communications [32].

2.1.2 Terrestrial Long Range Radio Technologies

2.1.2.1 Digital Cellular Networks

The number of mobile subscribers has increased tremendously in the last decade with more than one million new subscribers every day. Mobile phone penetration worldwide is approaching 60% and mobile is the preferred method for voice communication. Meanwhile mobile data usage has also grown fast in the digital cellular networks. Nowadays the mobile users expect similar data communication performances to the those experienced with wired networks. Therefore mobile network operators are requesting high data capacity with low cost of data delivery. 3GPP (3rd Generation Partnership Project) Long Term Evolution (LTE) and LTE-Advanced are designed to meet those targets. The peak data rate requirements for LTE downlink and uplink were set to 100 Mbps and 50 Mbps, respectively [33] [34]. For LTE-Advanced the peak data rate was set to 100 Mbps for high mobility environment and 1 Gbps for low mobility environment [35]. The increasing network capacity of the cellular networks makes it possible to develop and support new applications, such as the vehicle safety applications. With the packet data capabilities there is no need to set up connections for the vehicle safety applications, therefore avoid the large connection setup delay.

In addition the ubiquitous coverage and large mobile phone penetration mean there will be very high service availability for vehicle safety applications and extra infrastructure and equipment costs to run the vehicle safety applications. However, supporting vehicle safety applications over cellular networks is by no means trivial. First of all, even without the need of connection setup for data traffic there is still a large latency for packet data delivery in LTE networks. The radio round trip time for LTE can be up to 10 ms and access delay can be up to 300 ms. As there are possible delays incurred inside the networks for packet processing and/or buffering, the end-to-end packet delivery latency is still very high. Such high packet delivery latency may not meet the stringent delay requirements of vehicle safety applications. Secondly, majority of the vehicle safety applications is likely to be periodically broadcast safety messages, for example to establish mutual awareness of the neighbour vehicles. Such traffic pattern are not going to be cost-effectively and efficiently supported by the present in cellular networks. Thirdly, due to the large size of vehicle networks and heavy traffic to be generated from the vehicles, introducing the vehicle safety application traffic to the cellular networks will inevitably affect the QoS of normal mobile subscribers. In view of the challenges faced by the infrastructure based networking in the cellular networks, there are interesting attempts by the CarTALK and FleetNet projects in Europe to explore the potential of ad hoc communication networking in cellular networks for vehicle safety applications [36]. By ad hoc communication networking mobile users could communicate to their neighbours directly like what happens for 802.11 ad hoc networking. The data packets are not going through the base stations and mobile switching infrastructure. Therefore such ad hoc communication networking service can be free or at very low cost, which is desirable for vehicle safety applications. Both projects exploited the properties of UMTS Terrestrial Radio Access Time Division Duplex (UTRA-TDD), which is regarded as a promising candidate for vehicle ad hoc communications. However, the ad hoc communication networking service is far from practical deployment. There are still modifications required to be made on many aspects, such as synchronization for ad hoc operation, power control and prioritized channel access for vehicle safety applications.

2.1.2.2 WiMAX

Worldwide Interoperability for Microwave Access (WiMAX) is a standards-based technology, which enables the delivery of last mile wireless broadband access as an alternative to cable and Digital Subscriber Line (DSL) [37]. It is based on IEEE standard 802.16e, which is approved in 2005. WiMAX is designed to provide 30 to 40 Mbps data rates. With the recent development, 802.16m-2011 standard based WiMAX can provide both 120 Mbps downlink and 60 Mbps uplink. The service areas of WiMAX networks are normally limited to cities. With the relatively low costs associated with the deployment of a WiMAX network, it is also economical viable to provide last mile broadband Internet access in remote locations. Compared to Wi-Fi technology, WiMAX is a long range system with service coverage of many kilometres. WiMAX specified rich QoS mechanisms and connection oriented MAC, which is different from the widely used random channel access protocol CSMA/CA for Wi-Fi.

With the high network capacity and excellent QoS mechanisms specified by WiMAX, WiMAX can be a good communication technology to support vehicle safety applications. However, WiMAX networks do not provide ubiquitous coverage as with cellular networks. The services may be only available to metropolitan areas, while limits the support to vehicle safety applications. WiMAX networks also have a similar problem in supporting vehicle safety applications as that faced by cellular networks, which is the inefficiency on the support of localized message broadcast. Although WiMAX defines peer to peer and ad hoc communication modes, by which an end user may communicate to other users, these users need to be in the range of a base station and serviced by the same base station. The support on localized ad hoc broadcast for vehicle safety applications is still a big challenge for WiMAX networks. Due to the connection based communication specified in WiMAX, it is also a big doubt on the capability of WiMAX networks supporting communication for a large size of vehicle networks.

2.1.3 Non-terrestrial Long Range Radio Technologies

2.1.3.1 Satellite Communications

Satellite systems have a ubiquitous communication coverage, which can find specific applications to vehicle safety issues, especially when the coverage is a big problem and other communication technologies are not available for some areas. However, two-way satellite services are still very expensive and the data capacity is very limited [38]. Therefore satellite communications is not a strong candidate for general vehicle safety applications. In addition, the communications through satellite systems will incur large delay (e.g. hundreds of milliseconds or even several seconds), which could not satisfy the stringent QoS delay (delay in particular) poised by critical vehicle safety applications.

2.1.3.2 Global Positioning System (GPS)

GPS is unlikely to be used for direct communication between vehicles [39]. However GPS can provide location estimates of the vehicles, which is critical for the majority of vehicle safety applications. With increasing positioning accuracy GPS can be used together with other vehicle communication technology to improve the performance of vehicle safety applications. Additionally onboard digital maps and GPS can be combined to support navigation as well as active safety systems, for example curve speed warning, vision enhancement, speed limit assistant and collision warning/avoidance.

2.1.4 Comparison of Wireless Technologies

In a comparison of available and planned wireless technologies, as shown in Table.2.1 [2], DSRC appears to uniquely meet the basic communications require-

Table 2.1: Comparison of Wireless Technologies

	DSRC	Cellular	Satellite	Wi-Fi	Bluetooth
Latency	200ms	15-35 sec	60+ sec	3-4	NA
Frequency	5.9GHz	Depending	Depending	2.4/5 GHz	2.4GHZ
Range	1000m	20-30km	NA	1000m	10m
Rate	27Mbps	60K-2Mbps	54Mbps	1Mbps	1.1875kbit/s
Coverage	Nominal	High	High	Nominal	Low
Two-way communication	Y	Y	N	Y	Y
Point-to-Point/Point-to-multipoint	Y	Y	Y	Y	Y

ments for most of the vehicle safety applications identified earlier in this chapter. These requirements, which are potentially supported by DSRC, include:
- range of less than 1000 meters, which is supported by DSRC;
- one-way and two-way directionality, both to and from the vehicle;
- both point-to-point and point-to-multipoint communications;
- and most compellingly, latency less than 100 milliseconds (the potential DSRC latency is three orders of magnitude lower than other existing wireless technologies).

2.2 Vehicle ad hoc Networks (VANET)

Based on the aforementioned wireless communication technologies moving vehicles can form self-configuring vehicle ad hoc networks, in which each vehicle can act as a mobile wireless router. VANET can be viewed as a special type of mobile ad hoc networks, which is also a self-configuring network of mobile devices connected by wireless communication technologies, especially 802.11 wireless technology. Next research work on MANET is highlighted, which is then followed by discussion on VANET research work.

2.2.1 Mobile ad hoc Networks (MANET)

The research on MANET dates back to the mid of 1990s when laptops and 802.11 technology started to become popular. It can find many applications, such as setting up ad hoc networks in battlefields for military uses, search and rescue in emergences, intelligent transportation, ad hoc networking of personal electronic equipments such as laptops for entertainment and business work. In MANET each mobile device may move independently and freely in any direction, therefore the links to other devices may change dynamically and unpredictably. In order for two mobile devices to communicate, if they are within each other's transmission range they can communication directly; otherwise they need to find some other mobile devices to forward their data packets. In turn they are encouraged to act as mobile routers to forward data packets on the behalf of other mobile devices. Therefore mobile routing is a primary issue in the MANET, with the basic tasks of maintaining network topology and effective delivery of data traffic over such dynamic network topology. Since the advent of MANET there have been extensive research efforts contributed to MANET routing. Unlike the traditional routing protocols (such as Routing Information Protocol (RIP) and Open Shortest Path First (OSPF)) designed for wired networks, MANET routing protocols need to face the challenges which may not be present for wired networks, for example:

- Due to the participation of major mobile devices on packet forwarding as wireless routers there can be much more available routes for MANET than those in wired networks. Therefore the complexity of discovering the available routes and determining an efficient one can be much higher;

- Due to the dynamic link changes the network topology is dynamic as well. Therefore MANET routes may have very short lifetime and resilience of the routing protocols for MANET to route failures has to be much higher than that for wired networks.

- Due to the dynamic network topology in MANET routing protocols will consume considerable bandwidth and power, which actually are other major concerns for MANET, as MANET has been characterized as capacity limited.

- The mobility of the mobile devices and longer communication delay in MANET make the convergence of routing process much slower than that for wired networks.

In MANET mobile devices have to discover the network topology and routes to forward packets. The basic idea of MANET routing is that a mobile device may announce its presence and wait for announcements from neighbours, by which each device can learn about the nearby neighbours and determine routes to reach them. The MANET routing proposed in the literature can be classified into three major types:

- Proactive routing: For this type of routing each mobile device maintains the lists of destinations and routes to reach them by periodical distribution of routing tables throughout the network. An advantage of such routing protocols is that the source devices have full information about the network topology and can identify routes to destination with routing metrics tailored to the need of source devices. For example, one source device may prefer to shortest routes, while another source device may choose routes consuming the least energy for packet delivery. However, due to the change/failure of links the network topologies maintained by the devices may be outdated and the reaction to the link failures can be quite slow. Representative proactive MANET routing protocols include Destination-Sequenced Distance Vector routing protocol (DSDV) and Optimized Link State Routing Protocol (OLSR) [40] [41].

- On-demand routing (or reactive routing): Due to the above mentioned issues of proactive routing such as need of updating global topology information which consumes much network bandwidth, reactive routing protocols have been proposed to keep the routing control overhead to the minimum.

The basic idea is that only when a device has packets to transmitted or forward, a route is discovered. In general a reactive routing protocol has two steps: 1) route discovery by broadcasting routing request packets towards a destination. Intermediate nodes along the path forward the route request packet; 2) route maintenance after a route is established by sending packets to check if the route is working. The representative reactive routing protocols are ad hoc On-demand Distance Vector (AODV) and Dynamic Source Routing (DSR) [42] [43]. One drawback of on-demand routing is the extra delay to discover new routes at the beginning of sessions or recover broken routes, which may be much longer compared to proactive routing. Another drawback of on-demand routing is the cost of flooding route request packets.

- Hybrid routing: Hybrid routing protocols are proposed to combine the advantages of both proactive and reactive MANET routing protocols. A representative hybrid routing protocol is Zone Routing Protocol (ZRP). In ZRP the neighbours of a node are classified to be in either intrazone or interzone. For the intrazone neighbours proactive routing protocols can be used to maintain the local topology, while for the interzone neighbour discovery reactive routing protocols can be used on-demand [44].

It is noted that although the main work of this thesis is focused on the road safety applications based on the single hop broadcast mechanism, the work can be simply extended to applications with multiple hop unicast and/or broadcast based mechanisms, which is left for the future work.

2.2.2 VANET

VANET can be viewed as a specific class of MANET in which each node can have high mobility therefore network topology may change very fast [2]. Similar to MANET, VANET is operated in a distributed manner with self-configuration, self-organization and self-healing capabilities. There is no or limited availability of central management entity. VANET can be used for communication and driving cooperation for vehicles to support vehicle safety applications, locality based applications and comfortable applications [45] [46].

Most concerns for MANET can be applied to VANETs, such as routing, data dissemination, congestion control, MAC, privacy and security issues. However, VANET has several distinct features if compared to MANET, which has large influence on the protocol design for VANET. These features and possible impact on protocol design are briefly discussed as follows.

- Due to the high mobility of VANET, protocols designed for MANET may not be directly applicable to VANET. For example, routing protocols for VANET are required to adapt to network topology changes more quickly.
- On the other hand, some of the MANET protocols may be optimized for VANET as vehicles movements are constrained by the roads layouts and their locations are more predictable. For example, predictable location information can be utilized by routing and data dissemination to achieve improved performances.
- Power constraint in general MANET is not a concern for VANET as it is easy to recharge battery in vehicles. Nonetheless transmit power is still to be control for the purposes of maintaining a certain communication range while reducing interference.
- Vehicle safety applications are the utmost important for VANET, which have very high QoS requirements compared to the general applications studied for MANET. The protocols designed for VANET need to take into account these requirements, which usually results in more challenges.
- Vehicle networks are usually open and there can be much more mobile devices in VANET than in MANET. Therefore protocols designed for VANET have to scale well, for example, up to thousands of mobile devices in VANET. Additionally, as vehicles in VANET have to keep a certain distance for safety concern, a large scale VANET can have low vehicle density, which means it is more likely for the links between vehicles to be lost and networks to be partitioned. Therefore routing and data dissemination are more difficult in VANET.

Due to the specific features of VANET, extensive research works have been done on protocol design to deal with the challenges associated with VANET. Especially there are a plethora of routing protocols proposed for VANET, with primary objective of improving vehicle safety applications as well as objectives of supporting traffic management and onboard entertainments. The VANET protocols can be broadly classified as topology-based and geographic (position-based) routing [47]. For topology-based routing information about available links in the network is utilized to determine a route for packet forwarding. On the other hand one-hop neighbour position and destination position information are utilized to make packet forwarding decision for geographic routing.

As network link information may dynamically change topology-based routing, routes chosen by topology-based routing protocols are likely to be broken and the convergence of routing table can be very slow. Geographic routing works only with the assumption that positions of neighbour vehicles are available which may be obtained from GPS navigation system, which may not always be true in reality. An advantage of geographic routing over topology-based routing is that geographic routing protocols do not maintain established routes, as they are more robust to the dynamic network environment in VANETs.

2.3 Vehicular Safety Applications and Requirements

Vehicular communication networks can provide variety of applications with different requirements. Currently, vehicular networks are still under development, several safety related applications have been determined and will be implemented in the future. Due to the limitation of current technologies, some applications are not available now, but they will be supported finally.

Some research institutes and vehicle corporations have proposed their list of applications, but classifications of vehicular applications have not been finalized by any standard. Therefore, these applications are classified into different categories from their reports.

Generally, these proposed applications can be divide into two major categories:

safety applications and non-safety applications. Next the safety applications will be introduced.

2.3.1 Safety Applications

The primary function of vehicular communication networks is to provide safety information and assist drivers to avoid potential dangers. Electronic sensors equipped on each vehicle can detect speed, acceleration or deceleration or any other changes and send appropriate messages to neighbours. Drivers in the neighbour vehicles can take the proper actions with those notification messages.

2.3.1.1 Emergency Safety Applications

Emergency Safety Applications (ESA) is designed to be used for emergency scenarios. It generates emergency messages to broadcast if accidents happen or are emerging [48] [49]. ESA messages have high priority and timely and supply robust communication services. Position information obtained by GPS is normally included in the ESA messages to inform or make a caution to the neighbour vehicles.

ESA messages will be generated in the following scenarios:

Chain collision warning: Vehicles moving on the highway are at the speed of 80 kmh or higher, that means there is less than 1 second reaction time for drivers when the gap is about 20 meters between two vehicles. Collision warning application warns drivers with sound or vision alerts in the following vehicles to avoid chain collision. Occasionally, drivers can not see what happened ahead, e.g. several vehicles or large vehicles block their vision or the poor weather condition etc., with the help of this application, drivers can change to next lane or slow the speed to avoid any further accidents when crash occurs ahead . If necessary, road side unit will join to give a notice within a large area.

Intersection collision warning: The intersection collision warning application warns drivers when a probable collision at an intersection. Inter-vehicle device determines to give a caution based on vehicles' velocity, acceleration, position and turning status that are obtained from neighbours.

Crash warning: When vehicles stuck on the road after a crash, crash warning application keeps broadcasting vehicle crash messages in a longer period until danger is clear. According to the damage level and other conditions, lower priority level messages will be generated to replace ESA messages. Vehicle to vehicle messages warns the approaching vehicles with location information included. Vehicle to road side units messages warns vehicles with map position, heading and status.

Blind merge warning: The blind merge warning application warns driver if a vehicle is attempting to merge from a limited visibility location with another vehicle is approaching. Roadside unit send control signal to vehicles based on velocity, acceleration, heading and location. A safe to go message sent from roadside unit when there is no approaching vehicle.

2.3.1.2 Periodic Safety Applications

PSA is designed for announcing existence of a vehicle by non-emergent messages. PSA messages are periodically generated and broadcast to build mutual awareness, for example, the basic information can be carried by PSA messages, such as velocity, acceleration or deceleration [50].

2.3.2 Non-Safety Applications

In [2], it concludes non-safety applications that may applied in the future.
Traffic management It is assumed that the infrastructure will make periodic broadcasts requesting the information from nearby vehicles. Vehicles send a message regarding their position, heading, and speed to the traffic signal infrastructure, which processes the information from each direction and determines the optimal signal phasing based on the real-time information.

Information from other vehicles Instant messaging, adaptive headlamp aiming, adaptive drive train management, enhanced route guidance and navigation, map download and upload, and GPS correction are all included in this category.

Chapter 3

DSRC Communication Performances without Congestion Control

There is extremely high reliability requirement in vehicle safety systems. Practical and reliable CSA will require robust and reliable message delivery services from the DSRC networks. Essentially, QoS support by DSRC networks depends directly on channel congestion control and reliability control approaches. The bottleneck of DSRC networks is on the MAC layer. Due to the shared nature of the communication medium and limited channel capacity, the wireless channel for safety applications can be easily overwhelmed if DSRC networks are not well planned and utilized. QoS performances are affected by a number of complicated intertwined factors (e.g., channel access, transmit power, message rate and the number of competing DSRC devices). Systematic investigation of QoS support by DSRC networks is challenging but vital for network and service planning as well as providing insights into robust QoS control for CSA.

In this chapter a study on the QoS performances of DSRC networks without congestion control is presented, with the objectives of understanding how severe the congestion control issue may be for DSRC based vehicle safety applications and obtaining insights into the design of effective QoS controls schemes. The study is done within the context of the IEEE 802.11p standard for vehicle network and the multi-channel DSRC structure specified in the WAVE, which are to be introduced later in this chapter. Two classes of vehicle safety applications are considered, with one being periodic safety applications and the other being emergency safety applications. Periodic safety application is used to exchange location information and establish mutual awareness by proactive periodic safety messages. Periodic safety application has the lower priority. The event-driven emergency safety messages are less frequent but require much higher QoS requirements.

For this study both analytical and simulation approaches are used. For analytical tractability a homogeneous network scenario is considered where DSRC devices have identical settings such as transmit power and message rate. A mathematical tool was developed to obtain closed-form QoS performances for broadcast messages in terms of message success probability, message delivery delay and network throughput. The mathematical tool is based on Markov chain. With the mathematical tool, efficiency and robustness of QoS support can be evaluated by varying transmit power, message rate and vehicle density. Additionally, a discrete-event driven simulator was developed and simulations were run to study the QoS performances that can be provided by DSRC networks without congestion control under various system configurations. The simulator was also used to verify the effectiveness of the theoretic analytical model.

The rest of this chapter is organized as follows. Section 3.1 presents the background on the basic channel access mechanism specified in the 802.11 standards. Multiple channel structure and operations specified by WAVE are also introduced in Section 3.1. Section 3.2 presents an Markov chain based analytic model, which can predict the QoS performances of DSRC networks without congestion control for the traffic to be sent to the wireless channel. Analytic and simulation results are presented and discussed as well in Section 3.3. Section 3.4 presents further discussions on the analytic model and network performances. Section 3.5 introduces related work on power and messages control. Finally Section 3.6 concludes this chapter.

3.1 Channel Access in 802.11 Standard

3.1.1 802.11 MAC Standard

Distributed Coordination Function (DCF) is a MAC technique of the IEEE 802.11 standard based WLAN. DCF is a fundamental access method known as Carrier Sense Multiple Accesses with Collision Avoidance (CSMA/CA). The CSMA/CA protocol is designed to increase the probability of collision when multiple nodes accessing the same medium. To avoid collision, each node will check the status of the medium. Only when the medium becomes idle, the node can proceed to start transmitting data. If the medium is busy, it means one node is transmitting data to another, all the others that are preparing to transmitting have to delay a certain time. This certain time is called Backoff time, it can be described in equation as Backoff time=random x slot time.

To determine the status of a medium, the physical and virtual carrier sensing functions are used. If either of them is busy, the medium is sensed as busy, only when both of them are idle, the medium can be consider as idle. The physical carrier sense mechanism is provided by the PHY layer. The PHY layer can sense the propagation in the medium, and it will convey this kind of information to inform MAC layer. The virtual carrier sense mechanism is provided by the MAC layer. It relies on the Network Allocation Vector (NAV). When the medium is idle the sender will send a control frame to receiver to inform and request, this control frame is called as ready to send (RTS), after received RTS, the receiver will send back a frame to accept the request, this frame is the clear to send (CTS) [19] [51] . The NAV is duration information contained in RTS and CTS, which predicts the medium traffic before the real data is exchanged. The network allocation vector may be treated as a counter which increases to zero. When NAV reduced to zero, the medium is thought idle, if not equals zero, the medium indicates busy.

Interframe space is the time interval between frames. There are 4 kinds of IFS exits in DCF function, Short Interframe Space (SIFS), PCF Interframe Space (PIFS), DCF Interframe Space (DIFS) and Extended Interframe Space (EIFS) [52]. SIFS should be used when ACK or CTS frame involved. The duration of SIFS is the shortest among the 4 IFS. It follows with data frame and RTS or

CTS, and will be used when nodes have accessed to the medium and need to keep transferring data with destination for a short period time. Because of the shortest gap time, the nodes using SIFS can prevent other nodes to access the medium, and this mechanism guarantee the nodes has the priority to finish the frame exchange between two nodes over the medium. DIFS will be used by nodes operating DCF to transmit frames. If the backoff timer count down to zero, and the PHY layer sense the medium is idle after the DIFS time, the nodes are allowed to transmit over the medium.

3.1.2 Back-off Mechanism

If one nodes desires to transfer data on medium, it should start carrier sense mechanism first. Once the medium is busy, the nodes should wait until the medium is indicated idle after a DIFS time when the last frame transferred correctly on medium. The nodes will generate a random backoff time before proceeding to transmit if the value of the backoff timer has not been set. The backoff time is an extra time that delays the transmission to start, and determined by two parameters, random and slot time. Slot time is defined by the characteristic of the PHY layer. And the random number is an integer taken from a uniform distribution over the interval [0,CW]. Contention Window (CW) is an integer between aCWmin and aCWmax, that defined by PHY. The contention window parameter takes the aCWmin as its initial value. The CW will take the value from aCWmin to aCWmax if the transmission fails, and it keeps its value unchanged after have reached aCWmax before successful transmission occurs. The CW should be reset to aCWmin after each successful transmission. A CW value is an integer with the powers of 2, minus 1. For example, assumes that aCWmin is 3 and aCWmax is 8, then the CW should be 7, 15, 31, 63, 127 and 255.

3.1.3 Basic Access

If one node desires to transmit, it first check the status of the medium, after a period time that equals or larger than DIFS time, and the medium still idle indicated by PHY with carrier sense mechanism, it starts the backoff procedure no matter it is the first attempt or not. At this time all the nodes that desires to transmit count down their backoff timer, the one who reach zero first will seize the medium and can transmit over the medium. Then all the other nodes still in the procedure of backoff will sense the medium is busy indicated by PHY, and freeze the backoff timer. The frozen timer will be active when the PHY sense the medium idle again, and continue to count down to zero after the next DIFS [53].

3.1.4 Multi-channel Access Operation

Next we give a brief overview of the multi-channel operation mechanism specified in the IEEE WAVE system for DSRC. The overall WAVE architecture includes IEEE 802.11p MAC and PHY standards and IEEE 1609.1 to 1609.4 standards (for resource management, security architecture, networking service and multi-channel operation, respectively) [30] . IEEE 802.11p uses essentially the same physical layer as 802.11a but operates in a 10 MHz wide channel instead of 20 MHz [5].

Multi-channel operation is a distinctive feature of DSRC technology. In North America, the spectrum allocated to DSRC services in the 5.9 GHz licensed band is divided into seven channels, as shown in Fig.3.1. Channel 178 is the control channel used exclusively for road safety messages and service announcements. The others are service channels, with Channel 172 dedicated for V2V communications and Channel 184 dedicated for intersections applications. SCH 174 and 176 are shared by medium-range public safety and private services, while SCH 180 and 182 are shared by short-range public safety and private services.

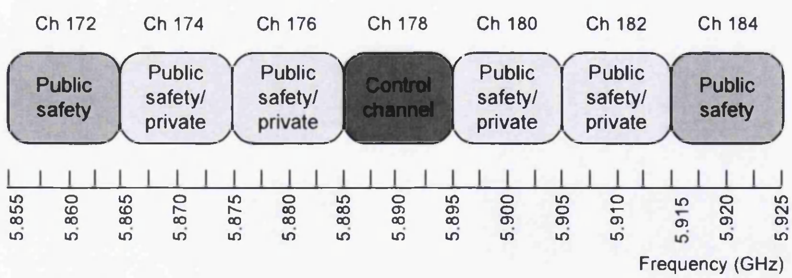

Figure 3.1: DSRC frequency plan.

To enable multi-channel coordination the IEEE 802.1609 standard for a WAVE system defines functional extensions to the IEEE 802.11 standard. The co-

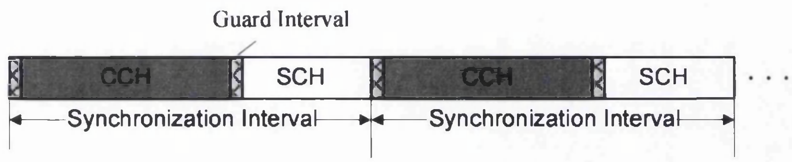

Figure 3.2: DSRC channel synchronization.

existence of safety and non-safety applications is achieved through Time Division Multiplexing (TDM). A synchronization procedure has been proposed for TDM channel coordination in the application level, for devices incapable of simultaneously monitoring the CCH and exchanging data on SCHs [54] [55]. In the procedure, a Synchronization Interval (SI) is defined which consists of a CCH interval, a SCH interval, and a guard interval, as shown in Fig.3.2.

All WAVE devices need to monitor the CCH during the CCH interval. At the beginning of each scheduled channel interval, a guard interval is used to account for variations in the channel interval and timing inaccuracies. Upon startup a device monitors the CCH until it receives an announcement of service that utilizes an SCH, or it chooses to use the SCH based on received WAVE announcement frames. Clearly, the configuration of CCH interval and SCH interval have a significant impact on the QoS for safety applications as well as on the availability of spectrum resource for non-safety applications.

3.1.5 Channel Priority

For each Access Category (AC), an Enhanced Distributed Coordination Access (EDCA) process is started to contend for Transmission Opportunities (TXOPs) using a set of distinct EDCA parameters, including AIFS instead of DIFS in DCF. AIFS[AC] is determined by AIFS[AC]=SIFS + AIFSN[AC], where AIFSN[AC] is an integer indication the number of slots that a station belong to AC should defer before either invoking a backoff or starting a transmission after a SIFS duration. AC values of 0, 1, 2 and 3 represent best effort, background, video and voice services, as shown in Table.3.1 and Table.3.2 respectively.

Table.3.2 shows the parameter set on SCH. The value of CWmin is specified in IEEE standard 802.11p, and EDCA parameter set is stored in IEEE 1609.4.

Table 3.1: Default EDCA parameter set on CCH

AC	Example	CWmin	AIFSN
AC0	BK	aCWmin	9
AC1	BE	(aCWmin+1)/2-1	6
AC2	Video	(aCWmin+1)/4-1	3
AC3	Voice	(aCWmin+1)/4-1	2

Table 3.2: Default EDCA parameter set on SCH

AC	Example	CWmin	AIFSN
AC0	BK	aCWmin	7
AC1	BE	aCWmin	3
AC2	Video	(aCWmin+1)/4-1	2
AC3	Voice	(aCWmin+1)/2-1	2

3.2 Analytic Model

In this section the analytic model for single class broadcast based frame transmission by IEEE 802.11 MAC is presented. As the purpose of this analysis is to investigate the system performance without implementation of congestion control, saturate traffic is considered to obtain the worst case of performances for vehicle safety messages.

The presented analytical model can be viewed as a simplified version of the widely used model proposed by Bianchi for unicast based frame transmission [56]. There include three major steps. Firstly a Markov chain is used to derive a transmission probability τ that a station may transmit a frame in a random time slot. Secondly the collision probability (denoted by p_c is calculated based on the transmission probability τ. Finally the per-node throughput is calculated based on the stationary transmission probabilities.

According to the 802.11 CSMA/CA algorithm, no matter successful or unsuccessful, all the stations need defer at least DIFS after each transmission. This part of deference is considered as a part of the transmission. The period of a transmission is further treated as a virtual time slot. In order to calculate the transmission probability, a simple Markov chain is developed for each node. The

Markov chain is consisted of W Markov states as shown in Fig.3.3, which correspond to the possible values of backoff counter. The transitions among the Markov states are also shown in Fig.3.3.

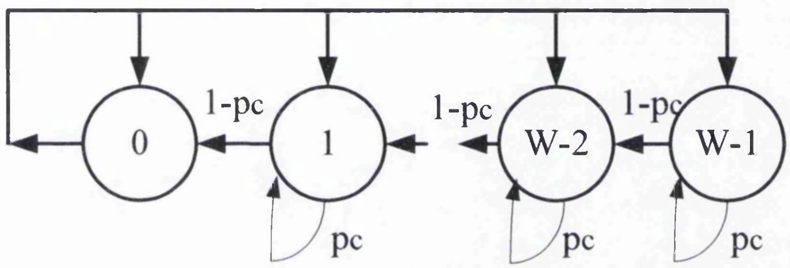

Figure 3.3: Markov chain for broadcast traffic.

According to the CSMA/CA algorithm operations, the one-step transition probability of the Markov chain states can be described by the following equations:

$$P\{j|0\} = \frac{1}{W}, j \in [0, W-1] \tag{3.1}$$

$$P\{j-1|j\} = 1 - p_c, j \in [1, W-1] \tag{3.2}$$

$$P\{j|j\} = p_c, j \in [1, W-1] \tag{3.3}$$

where p_c is the collision probability that there is at least one transmission from any other station in the time slot. Equation 3.1 means that after a transmission, the transmitting node will choose a backoff counter value which is uniformly distributed in the range [0,W-1]. The transition probability from state 0 to any state in the state space {0,...,W-1} is 1/W. Equation 3.2 shows the transition probability from any state j in {1,W-1} to $j-1$ due to an idle slot, which equals to $1 - p_c$. In constract Equation 3.3 shows the transition probability from any state j in {1,W-1} to itself due to a busy slot in which the backoff process is frozen. The self-transition probability equals to p_c.

As the collision probability p_c is normally quite small for DSRC networks, otherwise the safety messages could not be reliably delivered. With this in mind we can use simplified equations to approximate the one-step state transition probabilities by:

$$P\{j|0\} = \frac{1}{W}, j \in [0, W-1] \tag{3.4}$$
$$P\{j-1|j\} = 1, j \in [1, W-1] \tag{3.5}$$
$$P\{j|j\} = 0, j \in [1, W-1] \tag{3.6}$$

Based on the above approximated and complete one-step transition probabilities of Markov chain states, the stationary distribution of each Markov chain state could be easily obtained. Let b_j ($j \in [0, W-1]$) denoted the stationary distribution of state j. From the transition probabilities we have:

$$b_j = \frac{b_0(W-j)}{W}$$
$$\sum_{j=0}^{W-1} b_j = 1. \tag{3.7}$$

After simple derivation we can get

$$b_0 = \frac{2}{W+1}. \tag{3.8}$$
$$\tau = b_0. \tag{3.9}$$

It is noted that the transmission probability can be expressed by a simple closed-form. Interestingly in case of a large backoff window size W transmission probability τ can be approximately by:

$$\tau = \frac{2}{W}. \tag{3.10}$$

With the transmission probability τ we are ready to calculate the collision probability p_c and message success probability p_s, which are expressed by:

$$p_s = (1-\tau)^{(N-1)} \tag{3.11}$$
$$p_c = 1 - p_s. \tag{3.12}$$

Next we calculate the channel access delay for a general frame. In a generalized backoff slot, channel may be idle, or a transmission may happen. Let p_{idle} denote the probability of a slot being idle. Duration of an idle slot equals to t_{slot}. Let p_c denote the probability of at least one transmission in a slot, and T_c denote the duration of that type of slots.

For the broadcast channel access T_c is calculated by:

$$T_c = t_{difs} + t_h + \frac{L_{frm}}{R_{bc}}. \tag{3.13}$$

where t_{difs} represents the duration of 802.11 parameter DIFS, t_h represents PHY and MAC overhead, L_{frm} is the frame data payload in bits and R_{bc} is the data rate for broadcast. Then we can calculate the average duration of a slot T_{avg} by:

$$T_{avg} = (1-\tau)^N t_{slot} + [1-(1-\tau)^N]T_c \tag{3.14}$$

The average channel access delay (denoted by T_{access}) can be computed by:

$$T_{access} = \frac{WT_{avg}}{2}. \tag{3.15}$$

The average network throughput can be computed by:

$$\Theta = \frac{N\tau(1-p_c)L_{frm}}{T_{avg}}. \tag{3.16}$$

3.3 Analytic Results

With the formulas presented above analytic results for network performances could be obtained. Typical results are presented next. The system parameters are set with $t_{slot} = 20\mu s$, $t_{difs} = 40\mu s$, $t_h = 40\mu s$, $R_{bc} = 3Mbps$. Frame data payload L_{frm} is selected with 100, 300 and 500 bytes. The contention window size W and the number of competing nodes are varied to study their impact on network performances.

Fig.3.4 presents transmission probability τ calculated by (3.9). It can be observed that the transmission probability exponentially decreases with the contention window size W.

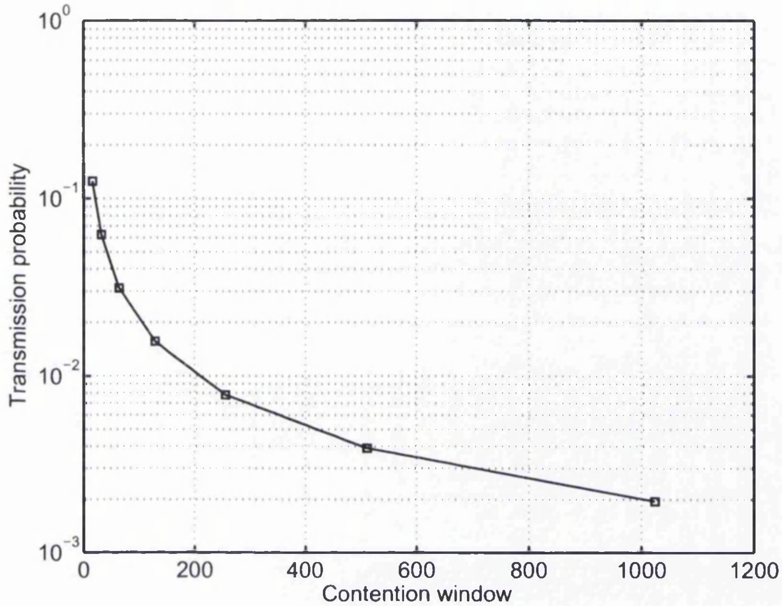

Figure 3.4: Transmission probability τ against contention window size W.

Fig.3.5 presents the frame success probability against the number of competing DSRC devices, which is a critical performance measure for vehicle safety applications. It is noted from the analytical results that the frame success probability monotonically decreases with the number of devices and increase with backoff window size W. When there are more than 20 competing devices, the frame success probability is lower than 0.55 for backoff window size smaller than or equal to 64. Therefore a reasonable backoff window size should be selected as no less than 128. To increase the frame success probability a straightforward approach is to increase the value of backoff window W if the number of devices is high.

However, the increase of backoff window W can have adverse impact on the channel access delay. From the expression for T_{access} in (3.15) the average channel access delay almost linearly with backoff window W. If W is set too large, some broadcast vehicle safety messages with excessive delay may be useless. Such impact can be observed from the results presented in Fig.3.6 to Fig.3.8 for frame data payload L_{frm} of 100, 300 and 500 bytes, respectively.

For the frame data payload of 500 bytes, the channel access delay with 30

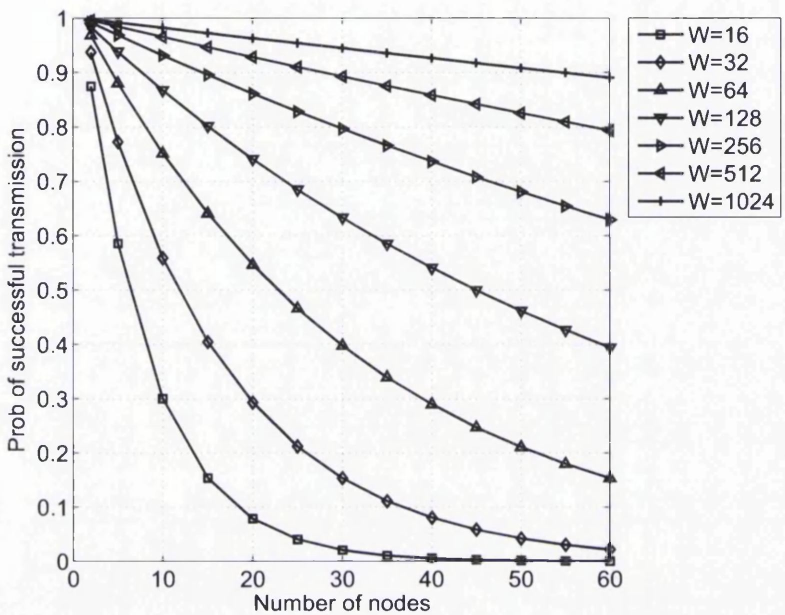

Figure 3.5: Transmission success probability against number of nodes.

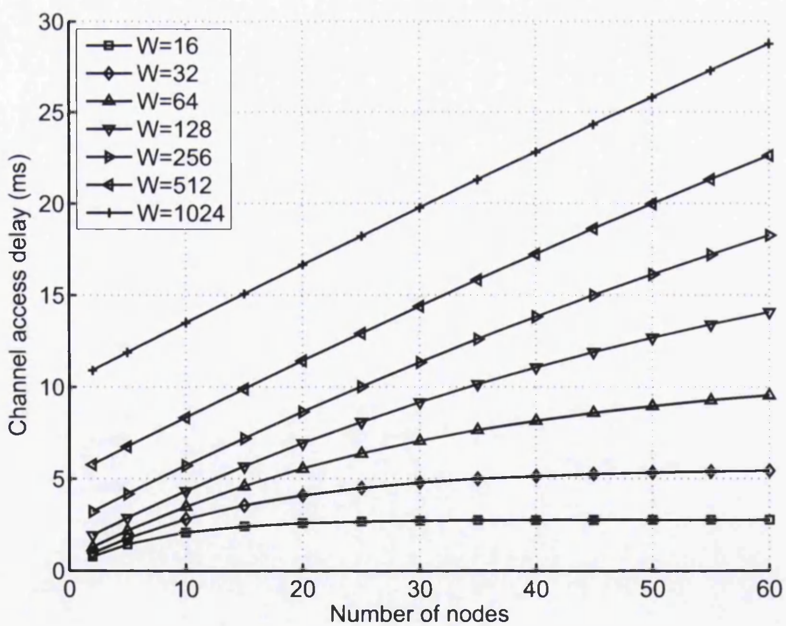

Figure 3.6: Channel access delay against number of nodes, $L_{frm} = 100$ bytes.

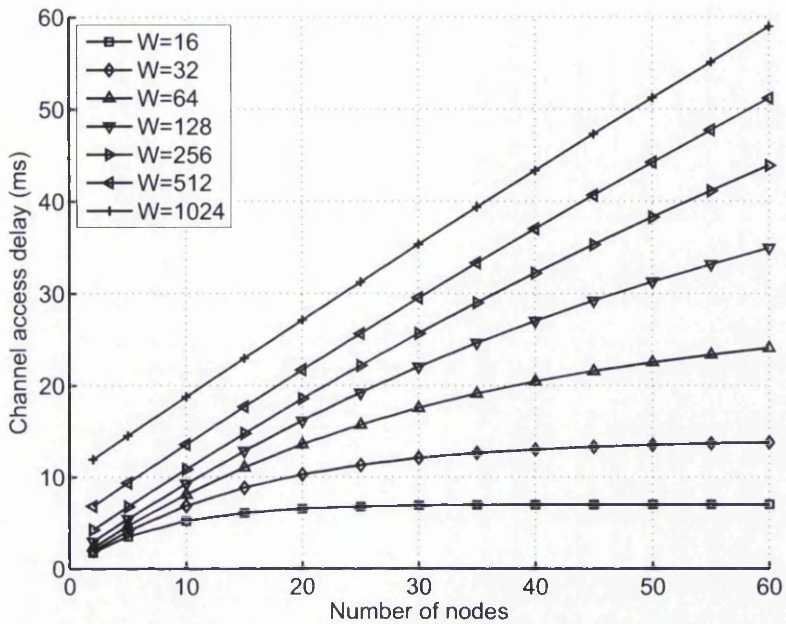

Figure 3.7: Channel access delay against number of nodes, $L_{frm} = 300$ bytes.

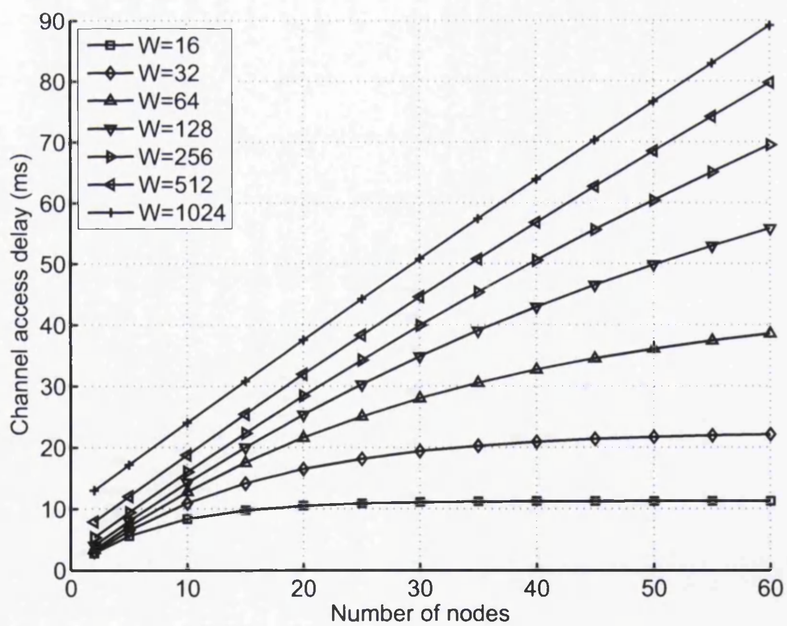

Figure 3.8: Channel access delay against number of nodes, $L_{frm} = 500$ bytes.

devices is 35 ms for $W = 128$ and 50 ms for $W = 1024$. Such channel access delay is already quite high for safety critical messages. Therefore there is a need in the control of traffic to be sent over the channel. Without congestion control the QoS of safety messages in terms of both frame success probability and channel access delay could not be guaranteed. It should be noted that the above analytic results are obtained under the assumption that the whole channel is used for safety applications. If a part of the channel is to be shared by non-safety application the performances of safety applications will be worse.

The network throughput results are presented in Fig.3.9 to Fig.3.11. Due to the impact of packet collision, the network throughput curves go down sharply with the increasing number of nodes when the contention window W is in a small value. However, larger value of contention window W may enlarge the packet latency and decrease the throughput at the same time.

From the spectrum utilization efficiency point of view it can be observed that the backoff window size of 256 is a good selection for a wide range of number of devices.

To verify the analytical model we also developed a discrete-event driven simulator. The simulation results are also included in these figures. In the figures analytic results are presented with label "Mod" and simulation results are presented with label "Sim". From the figures we can observe that the analytic results match the simulation results very well. Therefore the proposed analytical model can be said to be very simple and accurate, and can be used as an effective tool for the performance evaluation and network planning of the DSRC networks under saturate traffic conditions.

With the analytic model the impact of transmit power and vehicle density on the DSRC network performances can be easily evaluated. If the transmit power and vehicle density are given, the communication range and the number of vehicles (nodes) can be determined, and their impact can be shown by the analytic results we have obtained against the number of nodes in the presented figures.

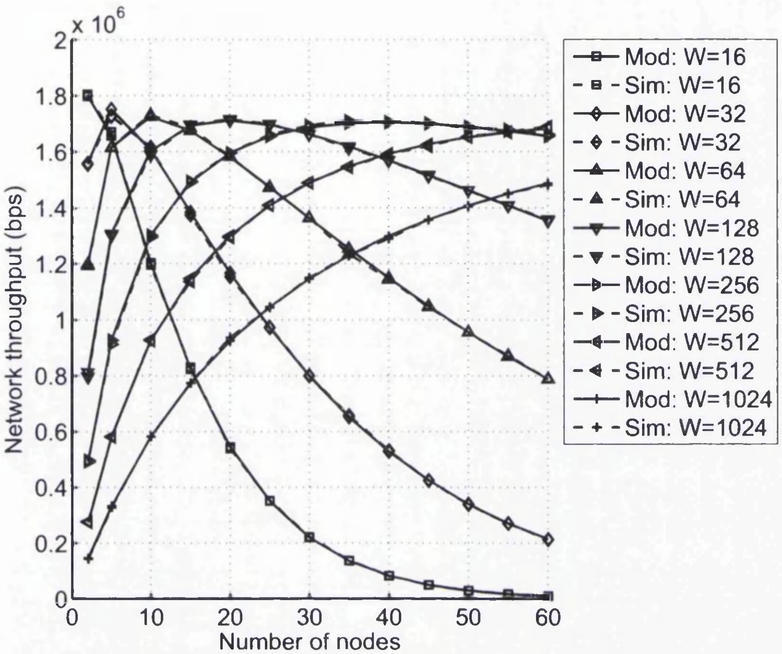

Figure 3.9: Network throughput against number of nodes, L_{frm} = 100 bytes. "Mod" for analytical results and "Sim" for simulation results.

3.4 Further Discussions on the Analytic Model

In case of a large N and the condition that $\tau N < 1$, we could have the following approximation:

$$(1-\tau)^{N-1} \approx 1 - \tau N \approx 1 - \frac{2N}{W}. \tag{3.17}$$

With the above approximation simplified expression can be obtained for the performance measures of interests. For example, the frame success probability p_s and frame collision probability p_c can be approximated by:

$$p_s = (1-\tau)^{(N-1)} \approx 1 - \frac{2N}{W} \tag{3.18}$$

$$p_c = 1 - p_s \approx \frac{2N}{W}. \tag{3.19}$$

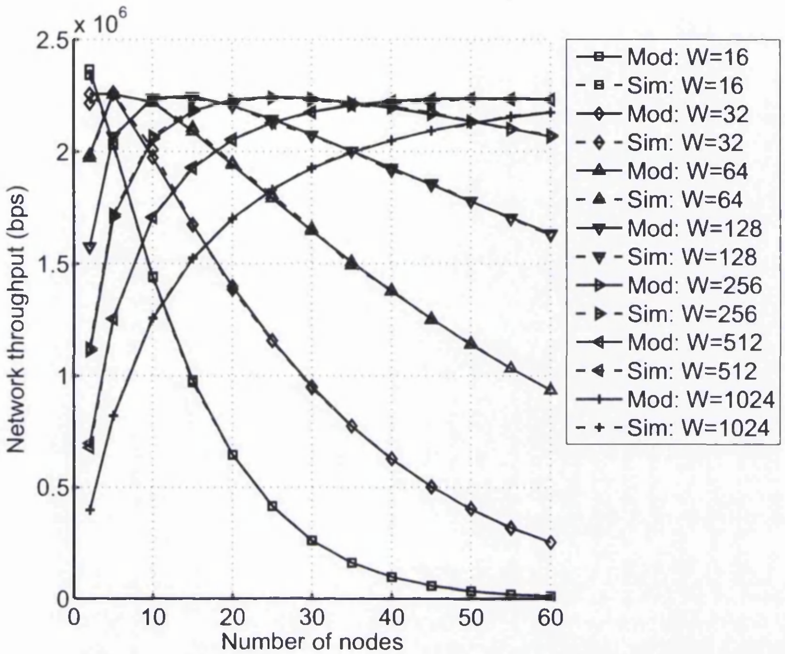

Figure 3.10: Network throughput against number of nodes, $L_{frm} = 300$ bytes. "Mod" for analytical results and "Sim" for simulation results.

Under the condition that $\tau N < 1$ the average duration of a generalized slot T_{avg} can be approximated by:

$$\begin{aligned} T_{avg} &= (1-\tau)^N t_{slot} + [1-(1-\tau)^N]T_c \\ &\approx (1-\tau N)t_{slot} + \tau N T_c \\ &\approx (1-\frac{2N}{W})t_{slot} + \frac{2N}{W}T_c. \end{aligned} \tag{3.20}$$

And the average channel access delay T_{access} can be approximated by:

$$\begin{aligned} T_{access} &= \frac{WT_{avg}}{2} \\ &\approx \frac{Wt_{slot}}{2} - Nt_{slot} + NT_c. \end{aligned} \tag{3.21}$$

The above approximation for average channel access delay T_{access} shows that when backoff window size W is large and $2N/W$ is less than 1, the delay T_{access} linearly increases with W. Such relationship can be easily verified from the analytical

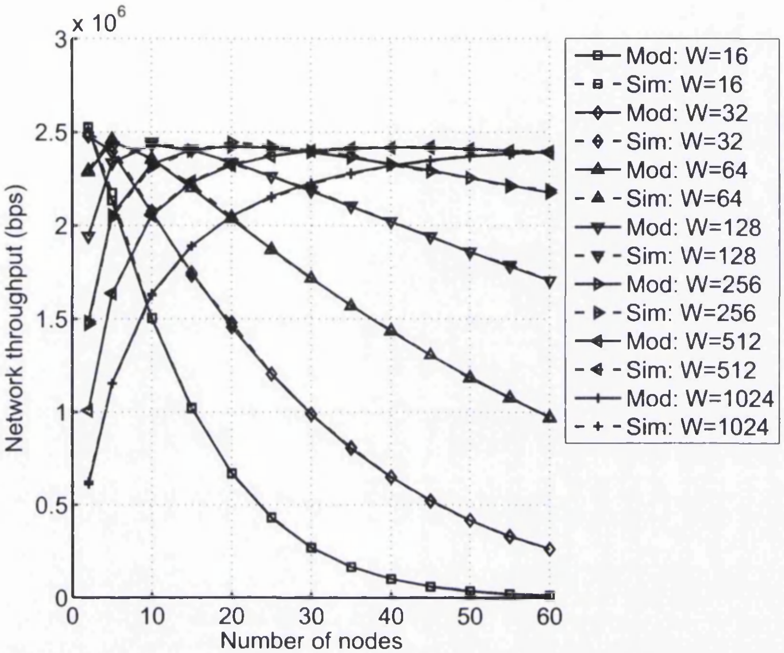

Figure 3.11: Network throughput against number of nodes, $L_{frm} = 500$ bytes. "Mod" for analytical results and "Sim" for simulation results.

results presented in Fig.3.6 to Fig.3.8.

If the condition $\tau N < 1$ is satisfied the average network throughput can be approximated by:

$$\begin{aligned} \Theta &= \frac{N\tau(1-p_c)L_{frm}}{T_{avg}} \\ &\approx \frac{N2/W(1-2N/W)L_{frm}}{2NT_c/W+(1-2N/W)t_{slot}} \\ &= \frac{N2(1-\frac{2N}{W})L_{frm}}{2NT_c+(W-2N)t_{slot}} \end{aligned} \tag{3.22}$$

3.5 Related Work

There are two main streams of works related to that presented in this thesis. The first is on the DSRC communications performance for vehicle networks and safety applications. The second is on the analytical modelling of the 802.11 and 802.11e channel access schemes.

With regards to DSRC, studies were conducted mainly based simulation to evaluate or to improve its performance [57] [58]. Limitations of 802.11a in DSRC environment are identified in [57]. Broadcast reception and channel access delay with the IEEE 802.11e EDCA priority channel access mechanisms were quantified by simulation in [59]. It was shown that for safety-critical applications, the proper design of repetition or multi-hop retransmission strategies should be used for robustness and network reliability of vehicular networks. A concept of communication density was introduced in [60], attempted to serve as a metric for channel load in vehicular communications. To adjust transmit power for V2V broadcast safety communication in vehicular ad hoc networks, a feedback-based power control algorithm is designed in [61]. The algorithm is designed to select a transmit power no greater than necessary for a targeted range. Mittag et al presented a detailed survey on congestion control and transmit power control for vehicular ad hoc networks. They also proposed a low overhead transmit power control scheme [62]. Ma and Chen presented an analytical model for the broadcast performance of the DSRC in a highway scenario [63]. Both delay and packet delivery ratio are derived. However, it is noted that only backoff contention window based priority scheme was studied. As shown in our numerical results, backoff contention window based priority scheme is much less effectively than the AIFS based priority scheme. Therefore the investigation in [63] is not sufficient for a deep and correct understanding of the DSRC communications performances.

With the rapid deployment of the IEEE 802.11 WLAN in the 1990s, the contention based DCF MAC access function has been studied extensively by analytical means. Among those analytical studies three major performance models have been proposed in parallel in order to analyse the saturation throughput performance [56][64][65][66]. Driven by the need of QoS support for real-time applications over WLAN, the basic DCF MAC access function was enhanced in the IEEE 802.11e standard [67][68]. In recent years, the performance of EDCA has also been explored by means of analytical evaluations. The EDCA analytical studies are mainly based on the modifications of DCF analysis mentioned above. Most of the analytical models proposed for EDCA modify or extend Bianchi's Markov chain model [56] to accommodate the differentiation of contention window and/or AIFS. [69][70] analyze the impacts of only contention on service differentiation, while [71][72][73] analyze the differentiation effects of both contention window and AIFS. [71] enlarges the original bi-dimensional Markov chain to tri-dimensional. [72] provides a new analytical approach to model the AIFS-based priority mechanism. In this thesis the proposed analytical model is based on the one presented in [72] with proper modifications to make the proposed model more scalable and accurate.

3.6 Conclusion

DSRC is regarded one of the most promising technology for vehicle communications. It is expected that the road safety applications will require reliable and timely wireless communications. However, the MAC layer of DSRC is based on the IEEE 802.11 DCF, which can not provide guaranteed QoS. In this chapter we propose a simple and accurate analytic model to evaluate the DSRC priority mechanism based inter-vehicle communication, with focus on a road intersection scenario. With the proposed analytic model we can also extend it to investigate the impacts of the transmission range and the channel access parameters for multiple priority services (i.e. AIFS and contention window size). We studied the network QoS performances in terms of message success probability, network throughput and channel access delay for both emerging and routine messages. The proposed analytic model was verified by simulations, which shows very high accuracy. From the numerical results it was observed that without congestion control the DSRC networks could not provide any QoS guarantee for road safety applications under some reasonable network scenarios, for example with about 50 vehicles in the communication range. Therefore effective congestion control and QoS solutions are required to be designed and implemented to provide reliable and timely communications for collaborative safety applications over DSRC networks, which are the tasks of our work to be presented in the following chapters.

Chapter 4

Centralized Adaptive QoS Control Schemes

According to that have been analysed and simulated in the previous chapter, it is obviously to see that the CSMA/CA based random channel access scheme could not effectively guarantee the QoS required by collaborative vehicle safety applications. Especially, when there is heavy traffic load over the CCH channel, the safety application performances could become unacceptable if no control action is taken.

Due to the importance of QoS for vehicle safety applications, it is critical to develop effective QoS control schemes for DSRC networks, in order to bring the collaborative vehicle safety applications closer to reality. In this thesis, the QoS control problem is tackled from two aspects, centralized congestion control for single hop infrastructured DSRC network scenarios (to be covered in Chapter 4 and Chapter 5) and distributed congestion control for ad hoc DSRC network scenarios (to be covered in Chapter 6). In the single hop infrastructured DSRC network scenarios it is assumed that there are roadside units which can take control of the network and QoS management. For the ad hoc DSRC network scenarios it is assumed that there is no centralized entity for network and QoS management, and QoS control is implemented in a collaborative and distributed way by all the involved vehicles. In reality the DSRC networks may not be operated in purely centralized or distributed way. A hybrid network may be more likely to be present. However the studies presented in this thesis should be applicable to the hybrid network scenarios where parts of the network have RSUs for centralized QoS control while the rest of the network is operated in a distributed way.

In this chapter a framework of centralized QoS control is proposed for single hop insfrastured DSRC network scenarios. Due to the existence of RSUs, QoS control issue could be largely simplified and reliable QoS services are more likely to be provided for collaborative vehicle safety applications in single hop DSRC network scenarios than in ad hoc DSRC network scenarios. And there can be many collaborative vehicle safety applications benefiting from the provisioning of reliable and robust QoS in the single hop DSRC network scenarios, for example, collision avoidance at road intersections and speeding alert at curves. Collision avoidance safety applications at road intersections are taken as example collaborative vehicle safety applications to be studied in single hop network scenarios in this thesis. In this chapter the QoS control problem is investigated by the means of centralized message rate adaptation and MAC layer channel access parameters configurations. In the next chapter the QoS control is investigated further with the control on the transmit power and CCH interval for more strict QoS guarantee.

In this chapter a two-phase QoS control scheme for DSRC vehicle networks at road intersection is proposed, where multiple road safety applications may coexist. For simplicity two safety applications (i.e. emergency safety application with high priority and periodic safety applications with low priority) are considered in this study. It is noted that the proposed centralized QoS control framework can be easily extended to collaborative safety applications with more than two priorities. The primary of the design for the two-phases QoS control scheme is to provide low latency and high reliability for ESA messages. The secondary objective of this design is to maximize channel utilization for low priority PSA messages. The reason is that low priority PSA applications which co-exist with ESA application over the DSRC control channel are also important for collaborative road safety applications. For example, periodically broadcast PSA messages which include vehicle positions enable mutual awareness.

In the first phase of the method, we use a simulation based offline approach to find out the best configurations for message rate and MAC layer parameters for given numbers of vehicles. In the second phase we use the configurations identified by simulations at roadside access point for system operation. Due to the complexity of the optimization problem in the first phase of the proposed control scheme, utilization function is used in finding the best possible configurations of message rate and MAC layer parameters to balance the QoS performances provided to multiple safety applications. It is demonstrated that the proposed QoS control scheme can largely improve the system performances when compared to fixed control method.

4.1 Design of Two-phases Adaptive Congestion Control Scheme I

As mentioned single hop network scenarios at road intersections are considered in this section. At road intersections roadside AP are assumed to be fixed with full control of the network and QoS management. An illustration of the single hop network scenario at road intersection is shown in Fig.4.1 [74]. The proposed QoS control scheme is aimed to control the traffic load over the 802.11 wireless channel to achieve preset QoS objectives. This work is different from traditional network congestion control such as the schemes specified in the TCP and TCP Friendly Rate Control (TFRC) protocols, which have been operated in a distributed manner at the transport layer [75]. The proposed QoS control scheme is also different from the distributed rate adaptation method proposed in [76] as the APs are responsible for the control of QoS at the road intersection.

For the DSRC networks the congestion of the networks over the wireless communication channel is affected by a large number of factors, such as application message rate, density of vehicles equipped with DSRC devices, MAC layer channel access parameters and etc. Without loss of generality we assume that all the vehicles in the network are equipped with DSRC devices. In addition to the above mentioned factor a MAC layer blocking mechanism is taken into account in the QoS control for the DSRC networks in this chapter. MAC layer blocking mechanism is optional for controlling transmission rate, which has been

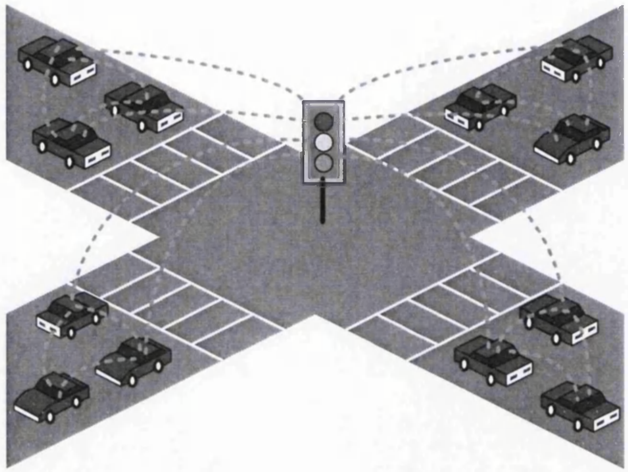

Figure 4.1: Illustration of single hop network scenario at a road intersection.

proposed at the MAC layer in the IEEE 802.11p specification in order to increase the responsiveness to channel congestion and provide high channel availability for safety-critical messages [5][76]. The MAC layer blocking mechanism is used to immediately block low priority PSA messages by a vehicle if it detects that the channel is busy for longer than a channel busy threshold in any CCH interval. The drawback of this so-called MAC layer blocking mechanism is that the MAC layer supports either full or zero transmission rate. Additionally the conditions to unblock PSA messages at MAC layer are not discussed. The MAC layer blocking mechanism is entirely node-centric, which can not efficiently solve the congestion control problem without vehicle collaboration.

Briefly speaking, the proposed QoS control scheme is operated with two phases, from which the scheme gets its name. In the first phase a simulation based offline procedure is applied to find out the optimal configurations of the parameters to be controlled for a set of given number of vehicles. These optimal configurations are then applied in the second phase where roadside APs request the vehicles to update the configuration of message rate and backoff exponent (BE) according to an estimated number of vehicles in the road intersection. More details are presented next for the proposed QoS control scheme.

4.1.1 Offline Determination of Optimal Configurations

The offline procedure is to find out the optimal configurations of message rate and BE for a set of given number of vehicles in term of system performance. For this purpose a simulator has been implemented to determine the optimal configurations for each given number of vehicles. Although it is possible to use analytical models to determine the optimal configurations, we believe analytical models may not be so efficient to take into account the complex system operations and parameters, such as unsaturated traffic load, MAC layer backoff, message blocking and multiple priorities for collaborative vehicle safety applications.

It is noted that in the papers [77] the IEEE 802.11p performances are analytically modelled with unsaturated traffic by a recursive method. However each DSRC device is supposed to transmit one and only one safety message in each CCH interval. And only one priority is assumed for the collaborative vehicle safety applications.

In contrast it is straightforward to implement simulators and flexible to use the simulators to measure the whole network performances, such as message success probability, average number of successful messages and average transmit delay for both ESA and PSA messages. Therefore the simulation based approach is taken for the offline procedure.

A challenge on determination of optimal configuration is the multiple objectives optimization for the whole vehicle network, which in this case is to provide high available channel for ESA messages and high channel utilization for PSA messages. For example, a low PSA message rate will provide higher channel availability to ESA messages at the cost of possibly low number of PSA messages transmitted successfully. To tackle the multiple objective optimization problems a utility function is therefore developed to measure the overall network performances. In the proposed utility function the number of successfully received safety messages is directly valued with different weights for the ESA and PSA messages. QoS requirements (e.g. message success probability and average transmit delay) from safety applications are also taken into account. It is noted that there could be many alternative utility functions defined for the multiple objective optimization problem. Another utility function is studied in this chapter as well. Investigation of more alternative utility functions is left for the future work.

Let D_e and D_p denote message delivery delay for ESA messages and PSA messages, respectively. Let R_e and R_p denote the selected message rate for ESA application and PSA application, respectively. Furthermore, let $D_{thr,e}$ and $D_{thr,p}$ be preset thresholds for delivery delay of ESA and PSA applications, respectively. Rec_e and Rec_p denote the number of network wide successfully received message in one second for ESA messages and PSA messages, respectively. We can have the following proposed utility function (denoted by Θ):

$$\Theta = \omega Rec_e \times (D_{thr,e} - D_{,e})^+ / R_e + (1 - \omega) Rec_p \times (D_{thr,p} - D_p)^+ / R_p \tag{4.1}$$

where variable ω is a weight to measure the contribution to the system utility from a successful ESA message, while $(1 - \omega)$ is the weight to measure the contribution from a successful PSA message. The threshold function $(x)^+$ in the utility function is expressed by:

$$(x)^+ = 0, \; if \; x \leq 0 \tag{4.2}$$

$$(x)^+ = 1, \; if \; x > 0 \tag{4.3}$$

The reason of using the threshold function in the utility function is for maintaining certain QoS for the ESA and PSA applications, e.g. message deliver delay. A message with a transmit delay larger than some delay thresholds may be useless, as the position of the transmitting vehicle may have changed largely. If the delivery delay requirement for an application is not satisfied no utility is assumed to be contributed to the utility function from that application.

With the utility functions and the preset parameters we can determine the optimal configuration of message rate and BE which maximizes the utility function for any given number of vehicles preset in the vehicle network. Note that the determination of the optimal configurations needs only to be done at the AP.

4.1.2 Online Adaptive Configurations

The online procedure is relatively simple compared to the offline procedure. In this procedure the AP located at the roadside applies the findings from the offline procedure on the optimal configurations of BE and message rate for PSA applications. The procedure operates as follows. Firstly the AP estimates the number of vehicles (denoted by N_{est}) at the road intersection for every T_{est} seconds through the received PSA messages. The PSA messages are broadcasted by the vehicles at the road intersection. According to the estimated the number of vehicles the AP looks up the table that has been created in the offline procedure for optimal BE and message rate configurations, for the estimated number of vehicles and the preset QoS requirements.

The optimal configuration is then broadcast by the AP as ESA messages to the vehicles in the intersection. Vehicles received the AP ESA messages update their configurations according to the AP's instruction. It is noted that due to packet collisions PSA messages broadcast by the vehicles in the intersection may not be successfully received by the AP, which results in an inaccurate estimation of the number of vehicles in the intersection by the AP. In the next section we will briefly investigate the impact of such inaccurate estimation on the overall performance of the proposed adaptive congestion control method.

4.1.3 Numeric Results with Adaptive QoS Control Scheme I

We have built a discrete event driven simulator to evaluate the performances of the proposed adaptive congestion control method. In the simulations we assume a single hop environment with no hidden nodes. All vehicle nodes are placed with uniform distribution at a road intersection. Carrier sensing range is set to 200 m. For simplicity we assume there are two classes of vehicle nodes in the network. The first class of nodes transmits only ESA messages while the second class of nodes transmits only PSA messages. Message blocking event at MAC layer is enabled to provide high available bandwidth for ESA messages in a single synchronization interval (SI). All messages are assumed to have the same length of 250 bytes and are broadcast at the rate of 3 Mbps. An ideal channel is assumed where a message can be successfully received if no collision happens.

In this section we have used the following configuration for the thresholds and utility weights for the proposed utility function: $\omega = 0.8$, $D_{thr,e} = 0.02$ second, $D_{thr,p} = 0.1$ second. With those parameter configurations we obtained the optimal configuration of message rate and BE in term of system utility. As safety applications are assumed to coexist with non-safety applications, safety applications should use the control channel with as less as possible time. In this section for the DSRC control channel CCH interval is as 25 and 35 ms, which is correspondingly 50% and 70% of a 50 ms SI, respectively. The impact of MAC blocking on the system performances and congestion control strategies is also studied by varying the MAC layer PSA message blocking threshold among 50%, 70% and 90%.

We assume that there are three first class nodes, which periodically send ESA messages. System utilities with both ESA and PSA applications can be calculated by utility Function 4.1.

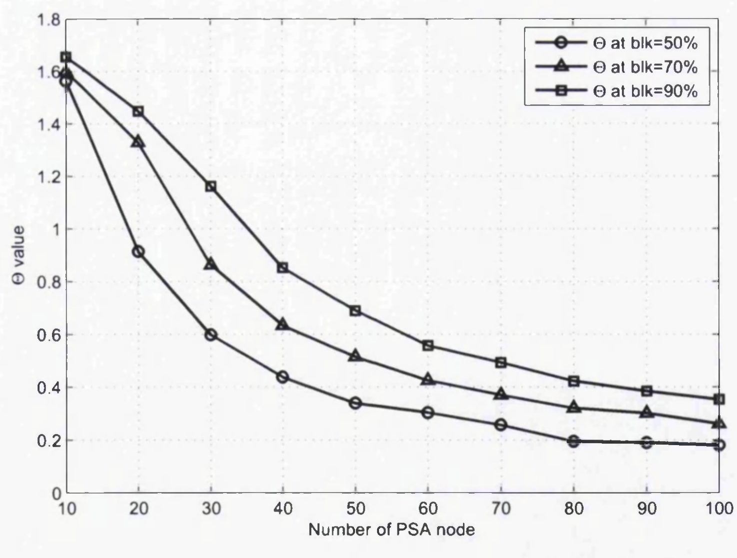

Figure 4.2: System utility against the number of PSA nodes with CCH=35ms.

The system utility obtained by simulations is plotted in Fig. 4.2 and Fig. 4.3 against number of PSA vehicles with blocking thresholds of 50%, 70% and 90%. It can be observed again that system utility decreases with increasing number of

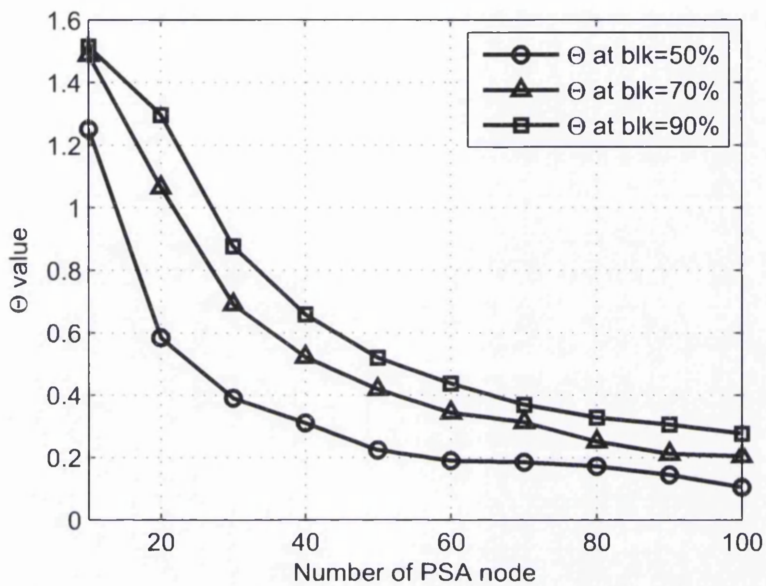

Figure 4.3: System utility against the number of PSA nodes with CCH=25ms.

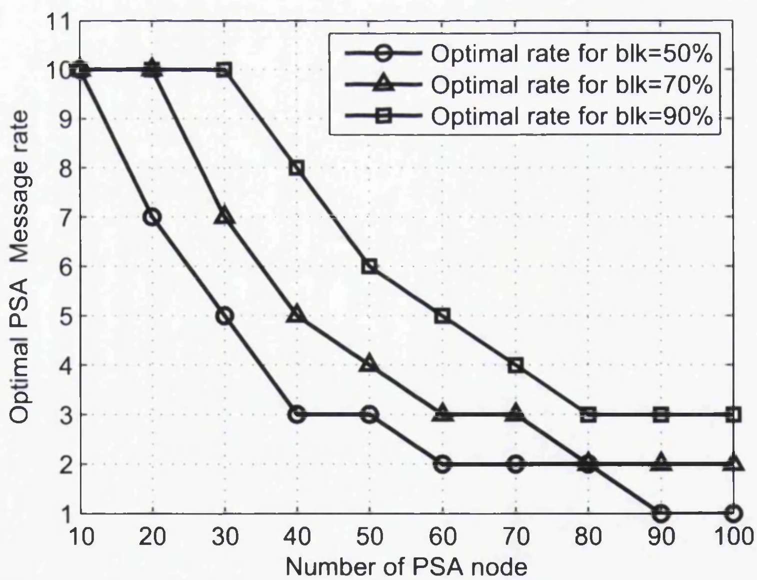

Figure 4.4: Optimal message against the number of PSA nodes with CCH=35ms.

PSA node. It becomes relatively stable when there are more than 60 PSA vehicles. Fig. 4.4 and Fig. 4.5 show the selected message rate by which the optimal

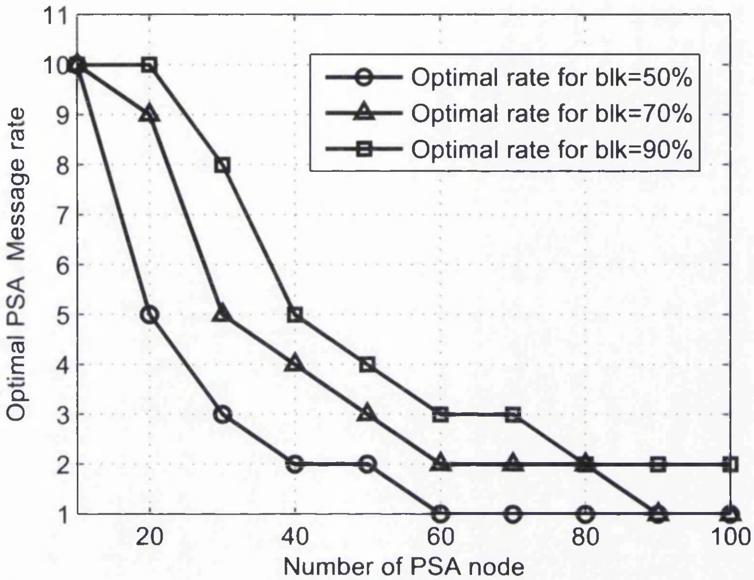

Figure 4.5: Optimal message against the number of PSA nodes with CCH=25ms.

utility is achieved. Message delivery ratios and transmit delay for both ESA and PSA messages are plotted in Fig. 4.6, Fig. 4.7, Fig. 4.8 and Fig. 4.9, respectively. It is noted that with presence of ESA messages PSA message performances degrade significantly even when there are only a few PSA vehicles. In contrast the performance of ESA messages is relatively stable even when there are a large number of PSA vehicles. Blocking threshold showed a large impact again on the system utility and QoS performances. Lower blocking threshold results in a large the message delay as shown in Fig. 4.8 and Fig. 4.9. This phenomenon comes from the fact that blocking events are triggered much more frequently, which means that each node has to wait for more than one SI before the value of contention window counting down to zero. It also can be observed from the Fig. 4.4 and Fig. 4.5 that blocking threshold should be no less than 50% in high density network. For example, when there are more than 80 PSA nodes, the selected message rate with CCH=35ms is still at 3 messages per second with block of 90% while in the condition of 50% blocking threshold the selected message rate is only 1 message per second. Under a given utility function, with increasing number of nodes in the networks for different scenarios, the optimal parameters chosen by the control schemes such as the message rate, CCH interval and backoff exponent will change accordingly but not necessarily increase or decrease monotonically with increasing number of nodes. Therefore local peak behaviors may appear.

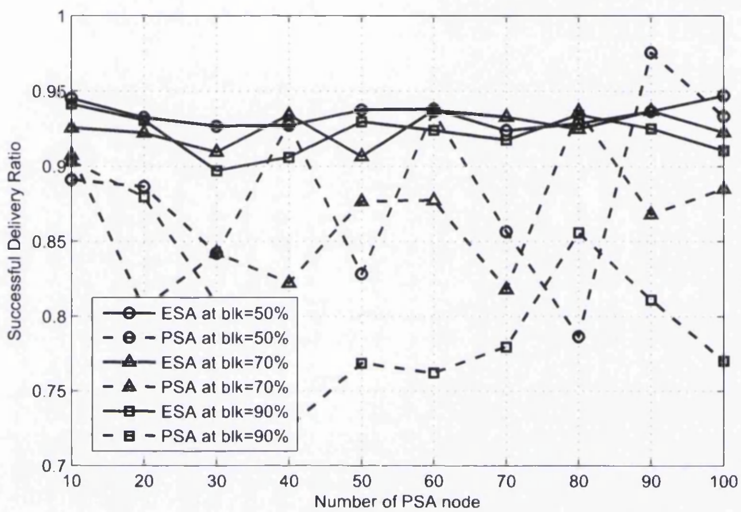

Figure 4.6: Delivery ratio against the number of PSA nodes with CCH=35ms.

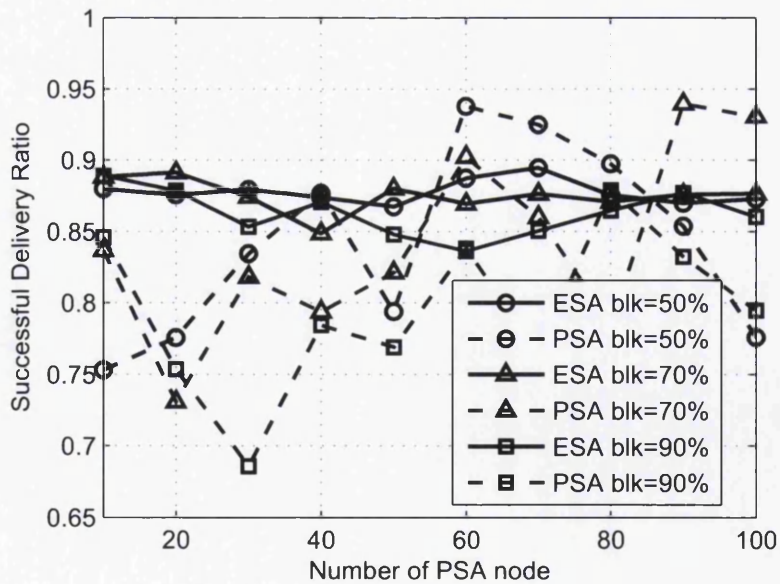

Figure 4.7: Delivery ratio against the number of PSA nodes with CCH=25ms.

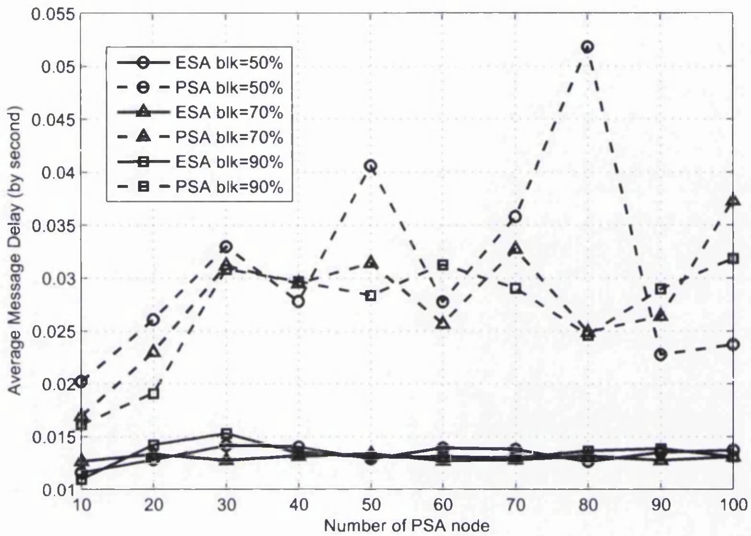

Figure 4.8: Message delay against the number of PSA nodes with CCH=35ms .

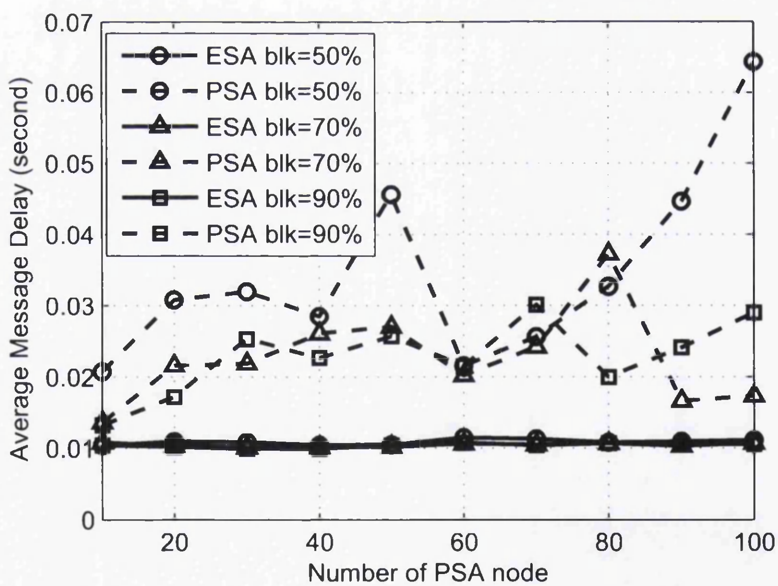

Figure 4.9: Message delay against the number of PSA nodes with CCH=25ms.

In the above subsection we have mentioned that the roadside AP can use the received broadcast messages received from surrounding vehicles to estimate the number of vehicles in the networks. It is obviously such estimation can be inaccurate for online system operation as the AP may not be able to timely and correctly receive messages from all the vehicles. In this subsection we present the online system performance when the estimation of number of vehicles is inaccurate, in order to examine the robustness of the adaptive congestion control method. For simplicity we consider two types of inaccurate estimation: over-estimation with 10 more vehicles estimated than actual and under-estimation with 10 less vehicles estimated than actual. As we assume that the estimation inaccuracy comes mainly from the unsuccessful reception of broadcast messages, it is not common to have 10 more or less estimated vehicles as they correspondingly to at least 10% message loss ratio. The system utilities with ideal vehicle estimation (labelled as "optimal") and inaccurate estimation are plotted in Fig. 4.10 and Fig. 4.11 with only 70% MAC layer blocking threshold. As our objective is to study the QoS services that could be provided by the DSRC networks under worst cases, we simply set the number of overestimated or underestimated nodes to 10. An alternative approach to set the number of overestimated or underestimated nodes is to use a fixed proportion of the overall nodes in the network, which is left for our future work

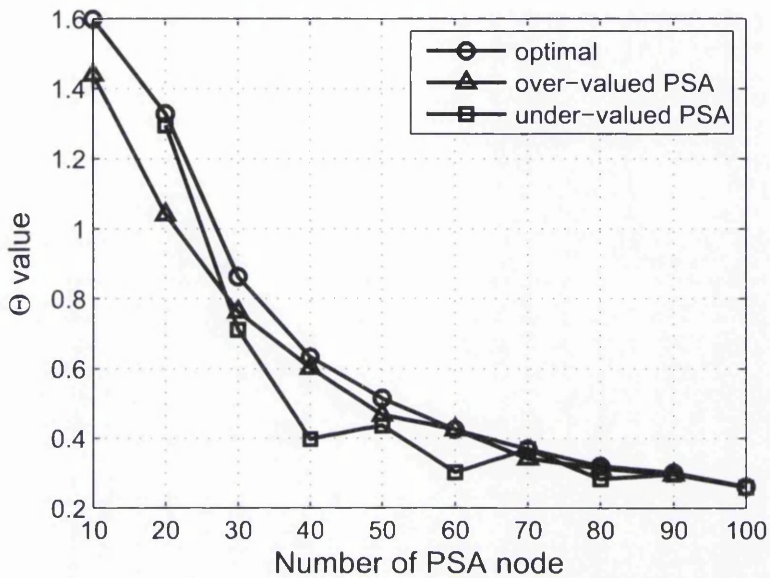

Figure 4.10: System utility with accurate and inaccurate estimation with blocking threshold of 70%, CCH=35ms.

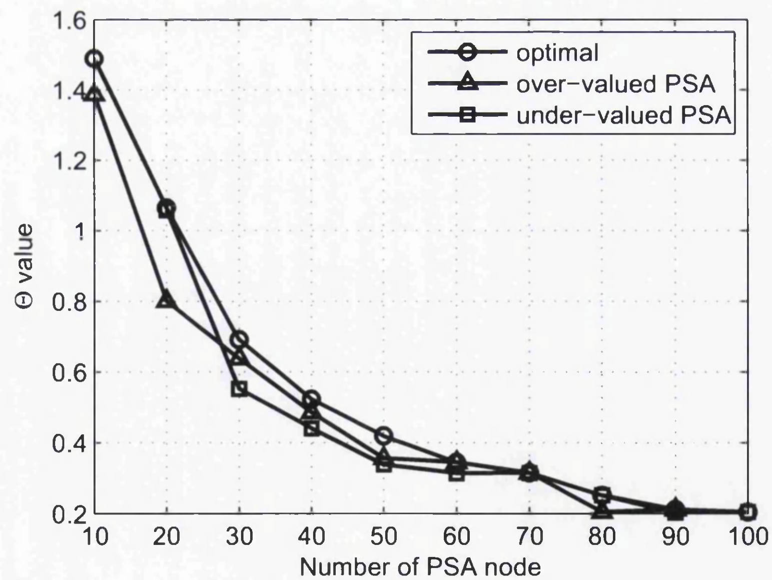

Figure 4.11: System utility with accurate and inaccurate estimation with blocking threshold of 70%, CCH=25ms.

From Fig. 4.10 and Fig. 4.11 it can be found that when the blocking threshold is set to 70% the impact of inaccurate vehicle estimation on system utility does not deviate much from that with accurate estimation. We can see acceptable gaps between the utilities with ideal and inaccurate estimation on the number of vehicles. These results mean the proposed adaptive congestion control method is quite robust for practical operations.

From Fig. 4.13 and Fig. 4.15, it can be observed that higher block threshold has less deviation to the accurate estimation.
Fig. 4.12 and Fig. 4.14 show that lower block threshold will lead to a acceptable deviation from that with accurate estimation when vehicle less than 20 in the network. It performs more accurately when 20 or more vehicles in the system network.

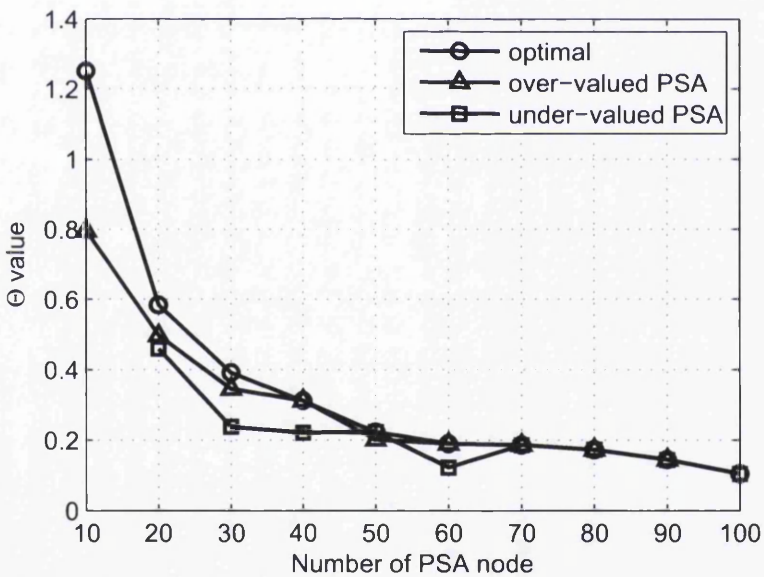

Figure 4.12: System utility with accurate and inaccurate estimation with blocking threshold of 50%, CCH=25ms.

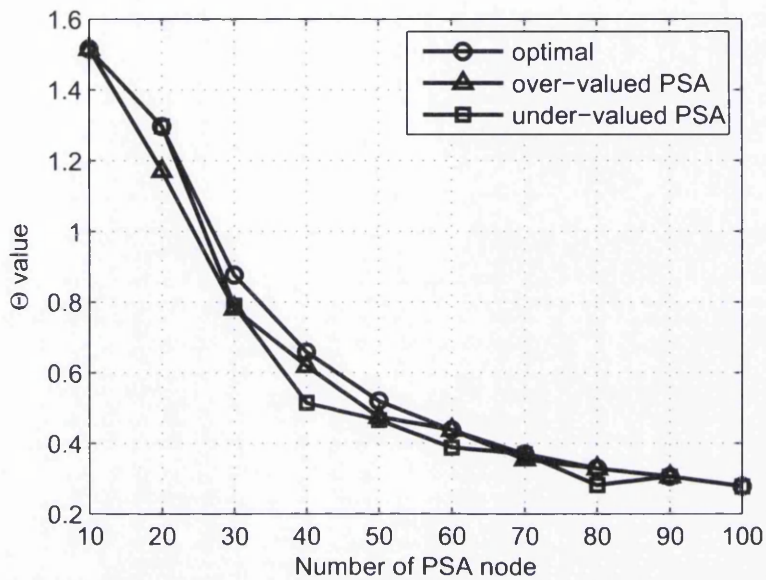

Figure 4.13: System utility with accurate and inaccurate estimation with blocking threshold of 90%, CCH=25ms.

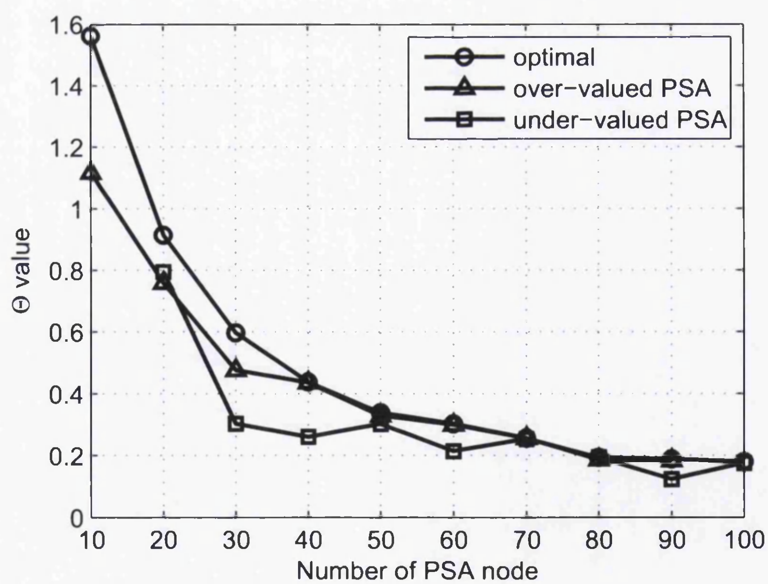

Figure 4.14: System utility with accurate and inaccurate estimation with blocking threshold of 50%, CCH=35ms.

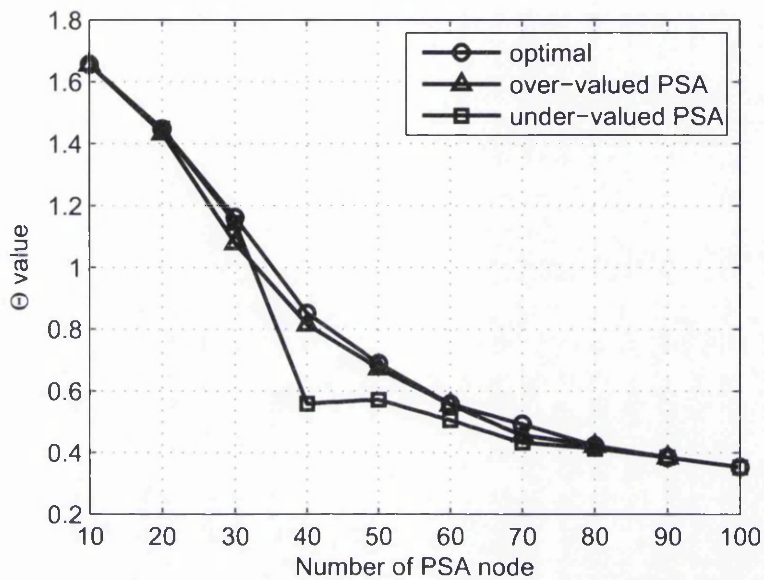

Figure 4.15: System utility with accurate and inaccurate estimation with blocking threshold of 90%, CCH=35ms.

4.2 Adaptive QoS Control Scheme II

4.2.1 Alternative Utility Function

In the previous section an adaptive QoS control scheme is presented for DSRC network based collaborative vehicle safety applications. One of the challenging problems to be solved for the proposed adaptive QoS control scheme is the multiple objective optimization problem in which performances of the overall network as well as the individual safety application need to be considered. A utility function has been proposed to facilitate on solving the multiple objectives problem. In the utility function the QoS performances in terms of message delivery delay and the ratio of the number of successfully received messages to the selected application message rate for each safety application are multiplied before the results are weighted and summed up.

As discussed previously the utility function has a direct strong impact on the optimal message rate and MAC parameter configurations to be identified. There could be many alternative utility functions for the multiple objective optimization problem. In this section we propose a new adaptive QoS control scheme (called Scheme II) in which an alternative utility function is used. Except the new utility function the main frame of the adaptive QoS control scheme II is similar to that of the control scheme I with both offline and online procedures. The new utility function is an extension of the one proposed in the previous section. In the new utility function, the message rate and probability of successful message transmission for each safety application contribute to the new utility in a separated item from that contributed by the average message delivery delay. With this new utility function design it is easier to set separate QoS requirements on the message success probability and message delivery delay. And the new utility function can be used by the system manager to show different QoS preferences from those with the utility function used in control scheme I. More details on the utility function design are presented next.

Let $P_{s,e}$ and $P_{s,p}$ denote message success probability for ESA messages and PSA messages, respectively. Let D_e and D_p denote message delivery delay for ESA messages and PSA messages, respectively. Let R_e and R_p denote selected message rate for ESA messages and PSA messages, respectively. The proposed utility function (denoted by Θ) can be expressed by:

$$\begin{aligned}\Theta = R_e W_{s,e}(P_{s,e} - P_{thr,e})^+ + R_p W_{s,p}(P_{s,p} - P_{thr,p})^+ \\ -W_{d,e}(D_e - D_{thr,e})^+ - W_{d,p}(D_p - D_{thr,p})^+ \end{aligned} \quad (4.4)$$

where $P_{thr,e}$ and $P_{thr,p}$ are preset thresholds for message success probability of ESA and PSA messages, respectively. $D_{thr,e}$ and $D_{thr,p}$ are preset thresholds for delivery delay of ESA and PSA messages, respectively. $W_{s,e}$ and $W_{s,p}$ are preset utility weights for message success probability of ESA and PSA messages, respectively. $W_{d,e}$ and $W_{d,p}$ are preset utility weights for delivery delay of ESA and PSA messages, respectively, With the utility function and the preset parameters we can set an optimal configuration table for message rate and BE which maximizes the utility function Θ for a given number of vehicles in the vehicle network.

4.2.2 Numerical Results

The discrete event driven simulator developed for adaptive QoS control scheme I is used to evaluate the control scheme II for DSRC vehicle networks. Again we assume a single hop ad hoc network environment without hidden terminals. For the DSRC control channel CCH interval is set to 35 ms, which is 70% of a 50 ms SI. All vehicle nodes are placed with uniform distribution on an intersection road. Carrier sensing range is set to 200 m. Similarly we assume there are two classes of vehicle nodes in the network. The first class of nodes only transmit ESA messages while the second class of nodes transmit only PSA messages. Message blocking event at MAC layer is triggered to provide high available channel for ESA messages with a MAC blocking threshold of 50% in a single SI. In the simulations we simply assume that there are three first class nodes, which send eight ESA messages in each second. All messages are assumed to have the same length of 250 bytes and are broadcast at the rate of 3 Mbps. An ideal channel is assumed, which means a message can be successfully received if no collision happens.

We have used the following configuration for the thresholds and utility weights for the proposed utility function. $P_{thr,e} = 0.9$, $P_{thr,p}$ ranges from 0.7 to 0.9, $W_{s,e} = 0.7$, $W_{s,p} = 0.3$,$W_{d,e} = 10$, $W_{d,p} = 20$. Other configurations of these parameters could be used, which will be studied in our future work. With the above parameter configurations we set up the optimal configuration table for message rate and BE in term of system utility. The utility Θ for the optimal configurations with $P_{thr,p} = 0.7$ is plotted in Fig. 4.16 against the number of vehicle nodes in the network. Note that the optimal configuration may be different for different number of nodes in the networks. For performance comparison purpose the system utility Θ obtained with several fixed configurations of message rate is also presented in Fig. 4.16. The BE in the fixed configurations is set to 7.

It can be observed that the performance with optimal configuration is significantly better than that with fixed rate. The corresponding message rate R for PSA application and backoff exponent which maximize the utility function (for $P_{thr,p} = 0.7, 0.8, 0.9$) are presented in Fig. 4.17 and Fig. 4.18, respectively.

It can be observed from Fig. 4.17 that to achieve higher delivery ratio, i.e. 90%, PSA message rate needs to be kept at a lower level, even in a low density

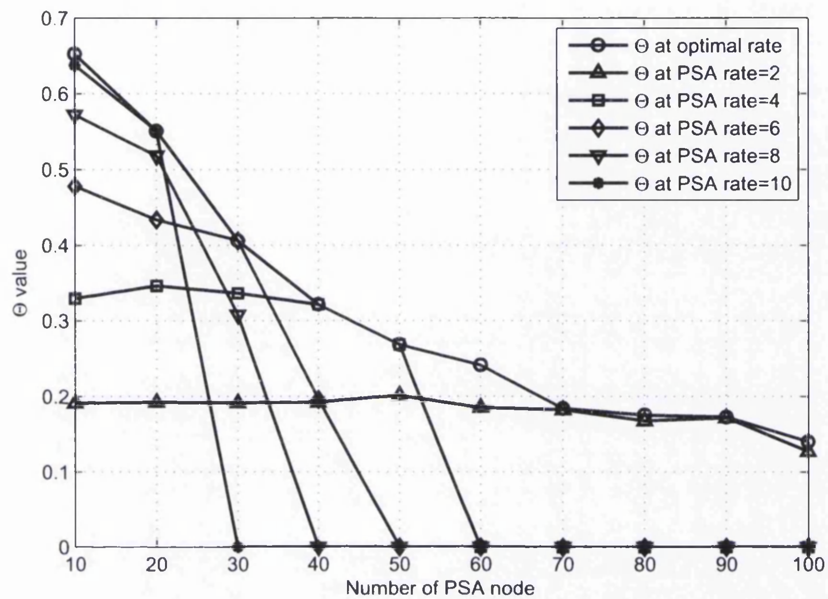

Figure 4.16: System utility Θ with optimal configuration and fixed configuration against the number of PSA nodes, $P_{thr,p} = 0.7$.

network. With the proposed utility function we can also find that the optimal backoff exponent does not change much with increase of vehicle nodes. However the optimal message rate to be used drops significantly with increasing number of vehicle nodes.

We plot in Fig. 4.19 and Fig. 4.20 the message success probability and message delivery delay for both ESA and PSA messages obtained with the optimal configurations shown in Fig. 4.17 and Fig. 4.18, respectively.

As the estimated number of vehicle nodes by the AP may not be accurate, it is worthwhile to study the impact of inaccurate estimation of vehicles on the performance of the adaptive congestion control scheme II. For this purpose the approach used in previous section (by comparing the optimal system utilities with accurate estimation of vehicle number and those with ten overestimated or underestimated vehicles) is applied for control scheme II. The results are presented in Fig.4.21. It is observed that the utility with inaccurate estimation does not deviate much from that with accurate estimation, which means the proposed adaptive

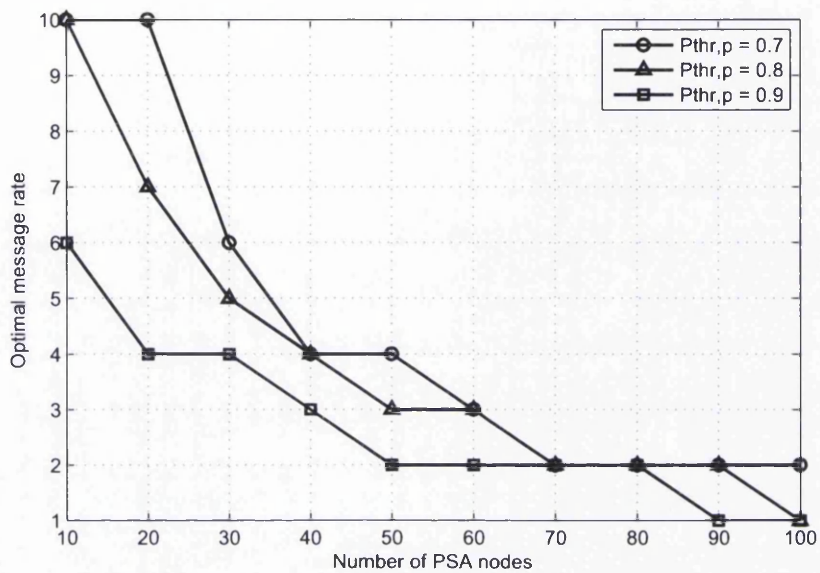

Figure 4.17: Optimal message rate against the number of PSA nodes, for $P_{thr,p} = 0.7, 0.8, 0.9$.

congestion control scheme II is also quite robust under inaccurate estimation of vehicle number.

4.3 Conclusion

QoS provisioning is critical for the success of DSRC vehicle network based collaborative safety applications. From the previous section it has been demonstrated by both analytical and simulation results that the application performances, in terms of message delivery delay, message success probability and message rate, can be severely affected if the traffic to be sent over the wireless channel is not controlled. In this section a framework of centralized QoS control for single hop DSRC network scenarios is proposed, which is mainly consisted of an offline procedure and an online procedure. Offline procedure is used to identify the best possible configurations of message rate and MAC layer channel access parameters for given number of vehicles. A utility function is used to solve the multiple objectives optimization problem as both overall network performances and individual

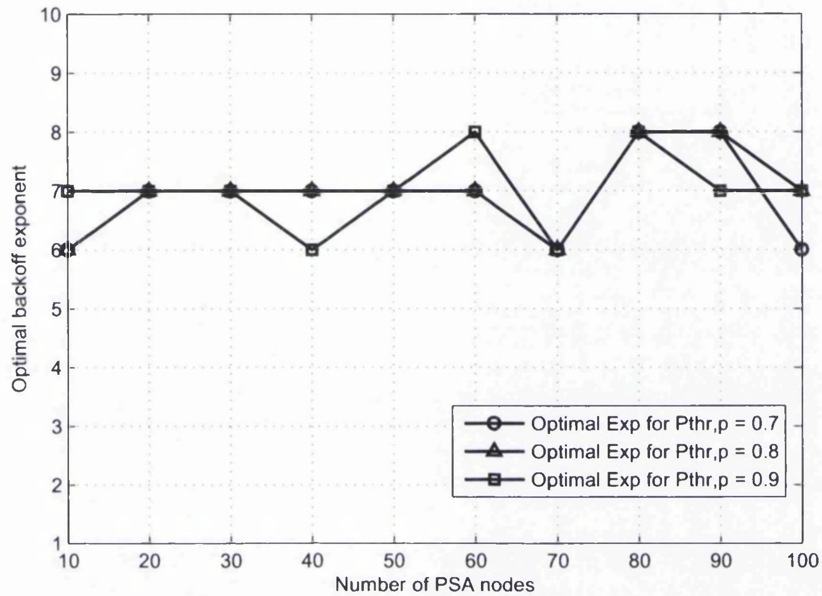

Figure 4.18: Optimal backoff exponent against the number of PSA nodes, for $P_{thr,p} = 0.7, 0.8, 0.9$.

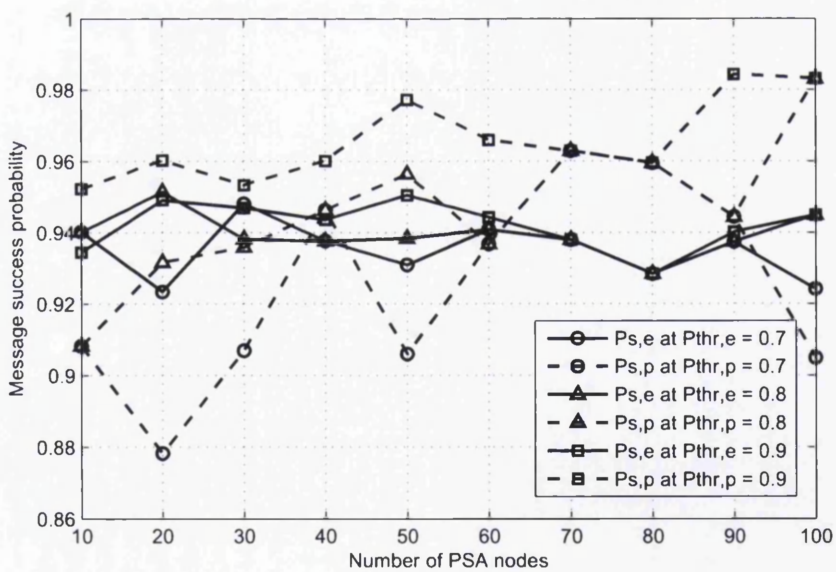

Figure 4.19: Message success probability.

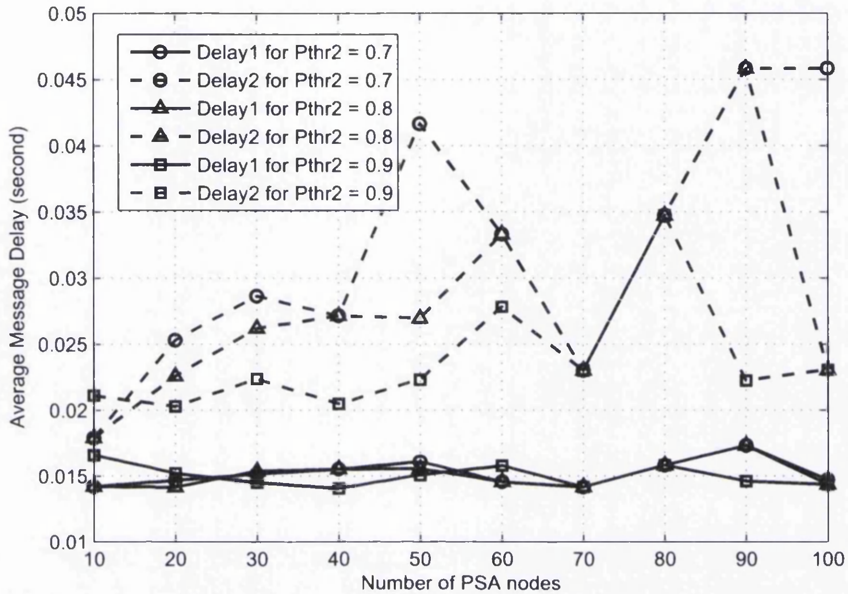

Figure 4.20: Average message delivery delay.

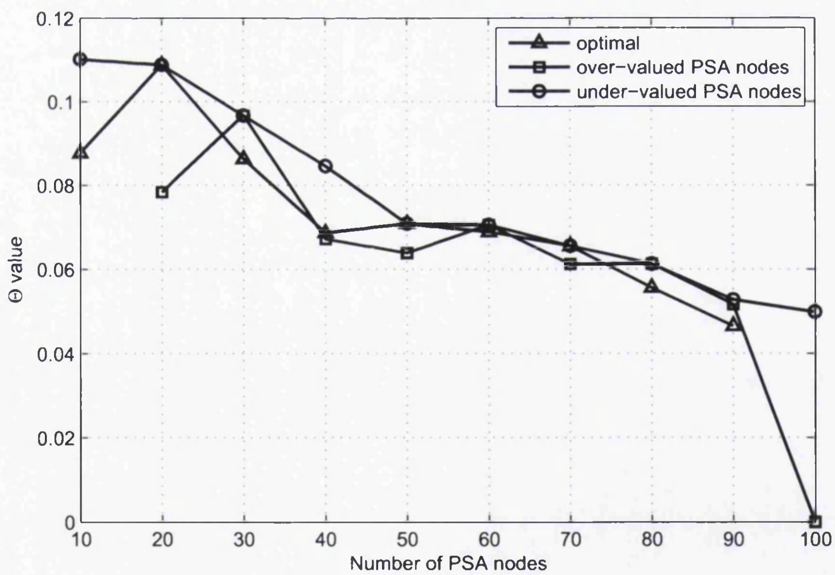

Figure 4.21: System utility with accurate and inaccurate estimation of the number of vehicles in the network.

safety application performances are to be considered jointly. The identification of the best possible configurations is to be done by the APs alone. The online procedure is to apply the obtained optimal parameter configurations to the real network operations.

Based on the QoS control framework, two adaptive QoS control schemes are proposed with difference only on the design of utility function. These two adaptive QoS control schemes can be used for different preferences on the target QoS performances, which may be required by different types of safety applications. The simulation results show that the design of utility functions can have a decisive impact of the identified optimal configurations. But both schemes have been observed to perform much better than the fixed rate schemes, especially when the network conditions may change (such as changing number of vehicles in the networks and QoS requirements from the road safety applications). Although the estimated number of vehicle nodes may not be accurate it has been shown by simulations that the proposed adaptive congestion control schemes are robust in providing good QoS for practical operations.

Chapter 5

Adaptive QoS Control with QoS Guarantee for Single Hop Infrastructured DSRC Networks

In Chapter 4, adaptive QoS control schemes have been proposed to control traffic congestion over wireless control channels for DSRC networks. The QoS control is achieved by the means of application layer message rate control and adaptive configuration of MAC layer channel access parameters. It has been demonstrated that the proposed adaptive QoS control schemes can largely outperform fixed rate scheme under dynamic channel load conditions. However, it is also observed that when the number of DSRC devices is large, the network QoS performances can be unacceptably low, which can cause big problems for collaborative vehicle safety applications.

In view of the importance of QoS guarantee and the corresponding technical challenges for vehicle safety applications, in this chapter the QoS guarantee problem for DSRC networks is investigated. Firstly a framework of providing guaranteed QoS for collaborative vehicle safety applications is proposed. The major modules within the framework for reliable and robust QoS are introduced, which include adaptive application module, cooperative and adaptation module, and MAC layer adaptation module. Secondly, following the ideas of the framework for reliable and robust QoS provisioning, an enhanced centralized adaptive

QoS control scheme is proposed in which the CCH interval configuration is taken into account. With the additional control of CCH interval for single hop DSRC network scenarios, it is aimed to provide as much as possible channel resources for non-safety application. It is noted that CCH interval adaptation can be very challenging for distributed QoS control in multiple hop ad hoc DSRC network scenarios. But for the single hop network scenarios it is relatively easy to achieve the CCH interval configuration through the previously introduced framework of centralized adaptive QoS control. After the investigation of adaptive CCH interval configuration, the QoS guarantee issue for single hop DSRC network scenarios is studied with the additional control of transmit power. It is straightforward that by the control of transmit power, the APs can control the number of DSRC devices to be included in the transmission range. Therefore it is possible to achieve QoS guarantee if the number of competing DSRC devices in the communication range of the APs can be strictly controlled.

The rest of this chapter is organized as follows. Section 5.1 briefly introduces related work on the power control and QoS guarantee for DSRC networks. Then the framework of adaptive congestion control with QoS guarantee is presented in Section 5.2. Section 5.3 presents the enhanced adaptive congestion control for single hop network scenarios with additional control of CCH interval, with QoS concerns on both safety applications and non-safety applications. Section 5.4 presents a further enhanced adaptive congestion control scheme with addition control of transmit power, with design objective of guaranteeing QoS for collaborative vehicle safety applications. Simulation results are presented and discussed. Section 5.5 concludes this chapter.

5.1 Related Work

QoS control by the means of power control has been widely studied for cellular networks and general mobile ad hoc networks [78] [79]. The most common control mechanisms include call/connection admission control, QoS routing and message scheduling [80] [81] [82] . However, DSRC network based vehicle safety application are mainly characterized by broadcast communications, ad hoc networking and strict QoS requirements. These unique features make the QoS control schemes proposed for traditional cellular networks and MANETs not direct solutions to QoS control for vehicle safety applications. QoS control for DSRC based vehicle safety application is still a relatively new research area. It can be achieved through the power control, data rate control and reliability control. Next we review some initial research efforts towards adaptive power control and congestion control for DSRC networks.

5.1.1 Feedback-based power control

Guan et al. proposed a feedback-based power control algorithm for vehicular ad hoc networks [61]. The main idea is that given a target communication range designated by a vehicle safety application, the power control algorithm should select a transmission power no greater than needed for the target range. The vehicles located beyond the target range of a message selectively sends feedback to the message's sender. The sender counts the number of feedbacks received for that message and compares the number to a predefined threshold. If the number is larger than the threshold, then the transmission power is incremented by a fixed step, otherwise it is decremented by a fixed step. The idea is simple but the main focus is to reduce power consumption. The algorithm has not considered congestion control and QoS issues. An issue of instability can arise when the channel becomes congested. Under channel congestion, the number of received feedbacks can be small due to message collisions. But the transmit power will be increased according to the power control algorithm, which in turn causes heavier channel congestion.

5.1.2 Collaborative power control

Mittag et al. proposed a distributed power control scheme for vehicle safety applications [62] . The design aims to ensure strict fairness for the control of periodic safety messages and leave more space for safety-critical messages. The scheme consists of three main steps:

- Each vehicle creates a list for vehicles in the carrier sense range by exchanging periodic messages.

- Each vehicle uses a theoretic model to independently determine the maximal transmit power that can satisfy the minimal channel load requirement for all the vehicles in the list.

- The theoretically determined maximal transmit power is exchanged among vehicles within the transmission range. Each vehicle set its transmit power to the minimal among the transmit powers determined theoretically by the vehicles in the transmission range.

The proposed power control scheme is collaborative and offers a high level of fairness. But a serious problem is that the maximal transmit power is determined based on theoretically computed channel load and channel load threshold. If the actual channel load is heavy, channel congestion will occur and continue on as no reaction to actual channel congestion have been considered. Another problem is that convergence speed of the proposed congestion control method can be very low in a dynamic network environment.

5.2 A Framework for Cooperative and Adaptive QoS Control

There are many system parameters that have significant impact on the QoS performance provided to vehicle safety applications, e.g. transmit power, message rate, CCH interval and broadcast message redundancy. To date the reported QoS control for DSRC vehicle based safety applications has not been efficient. An effective framework for QoS control of DSRC vehicle networks is highly needed to bring the CSA closer to practice. That framework should allow control of system parameters systematically or individually. It should also effectively cope with dynamic vehicle scenarios and maximize the QoS performance for vehicle safety applications. We propose a QoS control framework for vehicle safety applications over the control channel. It is shown in Fig. 5.1 with the following design goals:

- assured high QoS for safety-critical messages;

- adaptivity to traffic variations;

- fair channel access;
- high spectrum utilization.

The keys in the QoS control framework to achieve the goals are systematic and cross-layer design, vehicle cooperation and QoS adaptation. As single-layer based QoS control is unlikely to successfully provide QoS for CSA, we exploit systematic and cross-layer design. Vertically the QoS control functions are implemented over three layers, namely application layer, transport layer and MAC layer. Horizontally vehicles cooperate with their neighbours. Feedback and channel/QoS monitoring are used for QoS adaptation in order to provide required QoS and high spectrum utilization. Three main modules are proposed in the QoS control framework with each locating in the three layers to achieve the QoS control functions: Adaptive Safety Applications (ASA) module at the application layer, Cooperation And Adaptation (CAA) module at transport layer, and MAC layer Message Rate Control (MMRC) module at MAC layer. The detailed functions and interfaces of the modules are explained in the following subsections.

5.2.1 Adaptive Safety Applications

The ASA module is responsible for three functions: feedback control, QoS monitoring and message rate adaptation. Cooperation among the vehicles and adaptation of system parameters are key design considerations. Adaptivity is highly dependent on availability and accuracy of network and channel condition information. Through feedback and channel monitoring, a vehicle can calculate an approximate estimate of surrounding radio and network conditions. Each vehicle can easily monitor the channel load and the transmission activities of neighbour vehicles. But it still needs feedback from neighbour vehicles to make right adaptation and cooperation decisions. As safety applications are normally broadcast and non-interactive, it is not straightforward to provide feedback at MAC layer without significant modification on the 802.11 MAC layer specification. On the other hand, vehicle safety applications generate safety messages and request QoS from the underlying networks. The ASA module can easily provide the feedback on the received QoS for safety applications and is the ideal place to implement feedback control function.

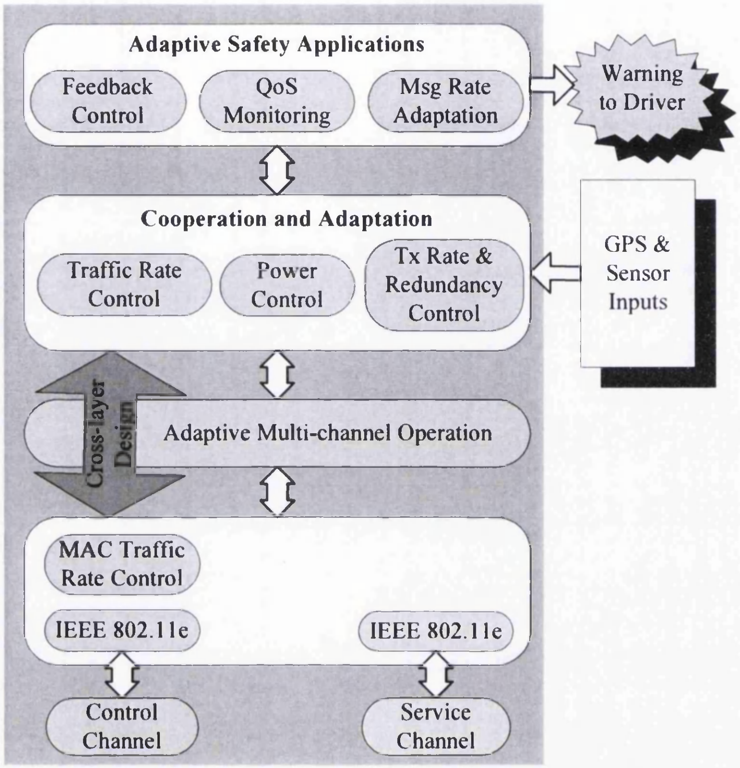

Figure 5.1: QoS control framework.

With regard to feedback control, a device can provide feedback about the transmissions from an individual neighbour vehicle (e.g. statistical successful message receptions) as well as transmissions from all the surrounding vehicles (e.g. measured channel load). Feedback can be requested actively or periodic feedback can be waited passively from other vehicles. Feedback can be sent in stand-alone messages or piggybacked on periodic safety messages. An issue is the trade-off between the overheads generated by feedback messages and the completeness and timeliness of feedback information.

The QoS monitoring function in the ASA module is responsible for measuring the actual QoS (such as latency and reception rate) seen by the vehicle safety applications. QoS monitoring should be performed for a relatively long time to make the monitoring results statistically meaningful. If the measured QoS performance is lower than required, the ASA module notifies the CAA module to take necessary actions such as traffic rate control and power control. Additionally the QoS measurement data are sent to neighbour vehicles upon request.

The message rate adaptation function in the ASA module is fairly simple. It informs the CAA module about the range of message rates for different vehicle safety applications. It is a task of the CAA module to determine proper message rates according to safety application requirements and channel congestion levels. The determined message rate is then sent back to the ASA module for use by vehicle safety applications for rate adaptation.

5.2.2 Cooperation and Adaptation

Among the three modules in the proposed QoS control framework, the CAA module plays a crucial role because it interacts with both ASA and MMRC modules. The CAA module is responsible for most of the network QoS control functions, e.g. message rate control, transmit power control, selection of data rate and message redundancy mode. Traffic rate, transmit power, data rate and message redundancy can significantly affect the QoS seen by safety messages. Implementing these functions in the CAA module together can promote intelligent designs.

Interactions between the CAA module and the ASA module have been mentioned in subsection 5.2.1, mainly on the exchange of feedback, QoS and message rate information. The CAA module also has interactions with the MMRC module. As to be introduced in 5.2.3, the MMRC module is responsible for fast reaction to temporary channel congestion by blocking PSA messages at the MAC layer. Once the percentage of channel occupancy time is monitored to be more than a threshold (e.g. 50%), the MMRC module informs the CAA module about the temporary blocking of PSA messages at the MAC layer. The MMRC module also takes necessary actions if it is requested by the CAA module in case of low QoS being observed at the ASA module.

Message rate control and power control are mainly used to address channel congestion in the CAA module. Unlike the very simple message blocking function in the MMRC module, Both rate control and power control at the CAA module are much more dynamic and complex with multiple levels. According to the monitored QoS and channel load levels, the CAA module can cooperatively and jointly adjusts the power level, message rate and other QoS control measures.

5.2.3 MAC Layer Message Rate Control

The MMRC module is located at the MAC layer to provide fast congestion mitigation. If a congestion event occurs, low priority PSA messages are blocked immediately at the MAC layer for a certain time. Message rate control at the MAC layer is quite simple with only two states, *unblocked* and *blocked*. In the *unblocked* state, all messages entering the MAC queue will attempt transmissions. In the *blocked* state, low priority PSA messages are transmitted at a low rate to update statuses (e.g. congestion state, position, speed, direction, etc).

If a vehicle's MAC layer is *blocked*, a closely related issue is when the MAC *blocked* state should be returned to *unblocked*. Two MAC unblocking algorithms are suggested below.[74]

- *Fixed Unblock*: PSA messages are unblocked if no congestion event happens in the following $T_{blk,f}$ synchronization intervals since the last congestion event happened. As the channel congestion may happen simultaneously for a cluster of vehicles, the unblocking action for those vehicles can be synchronized. For example, in a single hop DSRC vehicle network, all vehicles sense the same channel load. Therefore MAC blocking and unblocking are fully synchronized for the vehicles, resulting in possible high message collisions and low channel utilization.

- *Random Unblock*: A simple way to solve the synchronization problem of the *Fixed Unblock* algorithm is to randomize the waiting times for unblocking. For example, once a vehicle is blocked due to a congestion event, it chooses to wait for a random time in the range of $[1, T_{blk,r}]$ before being unblocked. Here $T_{blk,r}$ is a configurable parameter.

The MAC unblocking algorithms can be used alone or be used jointly with the transport layer algorithms for congestion control.

5.3 Investigation of QoS Control with CCH Interval Adaptation

5.3.1 QoS Control Scheme with CCH Interval Adaptation

In Chapter 4 adaptive QoS control schemes are proposed to achieve the optimal QoS in terms of message delivery delay, message success probability and the number of successfully received messages. The QoS control schemes work based on the adaptation of the message rate and MAC layer channel access parameters according to the network conditions. Following the adaptive QoS control framework proposed for single hop DSRC network scenarios in Chapter 4, this section presents a study on the additional CCH interval adaptation for DSRC network QoS control. The main concern for the study on CCH interval adaptation is that CCH interval does not only directly affect the QoS performances of safety applications but also those of non-safety applications. And such adaptation is more likely to be a network wide adaptation and be more challenging. By contrast to the adaptations of message rate and MAC channel access parameters can be implemented by individually and not necessary to be in a distributed manner.

It is noted that the same adaptive QoS control framework as that proposed in Chapter 4 is applied with both offline and online procedures. The only difference is that for both simulation approach based offline procedure and online adaptation procedure CCH interval is integrated into the adaptation of message rate and MAC channel access parameters. The same utility function as shown in section 4.1.1 is used for this identification of the best possible configurations for CCH interval, message rate and MAC channel access parameters (backoff exponent).

In the offline procedure a configuration table is determined by simulations, given the minimal CCH interval and the optimal configuration of message rate and BE which meet given QoS requirements with various number of vehicles in the network. In online procedure the AP applies the findings from the offline procedure on the minimal CCH interval and the optimal configurations of message rate for PSA applications. The procedure operates as follows. Firstly the AP estimates the number of vehicles (N_{est}) at the road intersection as before for every T_{est} seconds through the received PSA messages, which are broadcast by the vehicles at the road intersection. We set $T_{est} = 60$. According to the estimated number of vehicles and the preset QoS requirements the AP looks up the configuration table to get the minimal CCH interval and the optimal configurations of message rate and BE. The value of CCH interval and the optimal configuration is then broadcast in ESA messages by the AP at different time scales (every TS_{cch} seconds for CCH interval broadcast and every TS_{rate} for message rate broadcast) to the vehicles at the intersection. In default TS_{cch} is set to 300 seconds and TS_{rate} is set to 30 seconds. Vehicles received the AP configuration instructions update their configurations accordingly. In addition the AP keeps monitoring the safety applications QoS performances during the system operations. If the perceived QoS performances are better than the required, the CCH interval is increased with a step of 10 ms to improve the QoS performances for safety applications. In reverse the CCH interval is reduced with the same step if the QoS performances are poor than the QoS requirements.

5.3.2 Numerical Results

For simplicity we assume there are two classes of vehicles in the network. The first class of vehicles transmit only ESA messages while the second class of vehicles transmit only PSA messages. Message block event at MAC layer is triggered to provide high available bandwidth for ESA messages with a MAC blocking threshold of 70% in a single SI. Performance for MAC blocking thresholds of 50% and 90% is also investigated in the simulations. For simplicity we assume that there are three first class vehicles, which periodically send eight ESA messages per second. All safety messages have the same length of 250 bytes and are broadcast at the rate of 3 Mbps. An ideal channel is assumed where a message can be successfully received if no collision happens.

We have used the following configurations for the thresholds in the proposed utility function: $R_e = 7$, R_p ranging from 2 to 8, $P_{thr,e} = 0.9$, $P_{thr,p} = 0.9$, $D_{thr,e} = 0.02$ and $D_{thr,p} = 0.1$. The CCH interval is configurable in the set [15, 25, 35, 45] ms, which corresponds to 30%, 50%, 70% and 90% of a 50 ms synchronization interval, respectively.

With the above parameter configurations we obtained the optimal configuration of message rate, BE and CCH interval length. The minimal CCH interval length satisfying the preset QoS requirements and the corresponding optimal configurations of BE and message rate are plotted against the number of vehicles in Fig. 5.2, Fig. 5.3 and Fig. 5.4, respectively. The preset QoS requirements are with message success probability $P_{thr,p} = 0.9$ and message rate $R_{thr,e}$=7, $R_{thr,p}$=2 and 4.

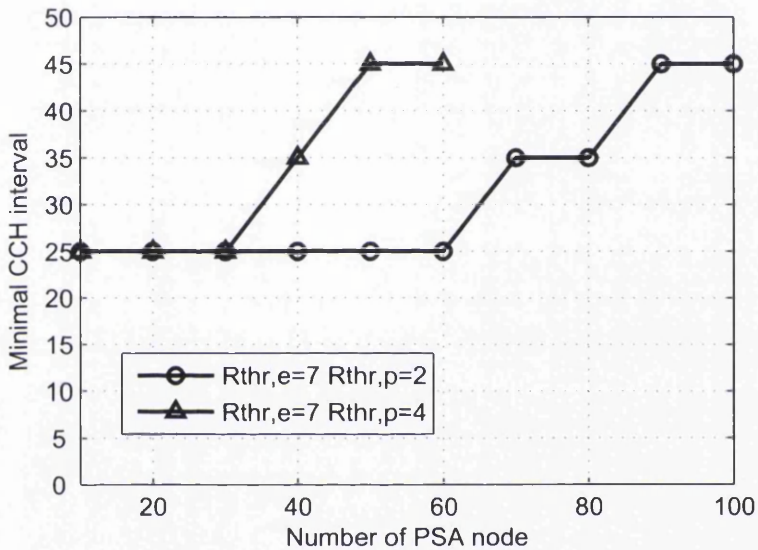

Figure 5.2: Minimal CCH interval satisfying the preset QoS requirements with $R_{thr,p}$=2 and 4.

It can be observed from Fig. 5.4 that message rate must be at least 5 messages per second to satisfy the QoS requirement $R_{thr,p}$=4. However, the minimal CCH interval length is increased to 45 ms with 60 vehicles and $R_{thr,p}$=4. With more than 60 vehicles in the network, none combination of CCH interval and message rate can satisfy the QoS requirement. In these cases message rate, BE and CCH interval length are plotted as 0 in the figures.

Fig. 5.5 and Fig. 5.6 present the performances of message success probability and delivery delay under the QoS requirement of $R_{thr,p}$=2 and 4. It can be seen that the combination of BE, rate and CCH interval length selected by the offline procedure performs well in QoS provisioning, i.e. ESA messages delay is lower than 20ms, message success probability for both ESA and PSA are over than 90%

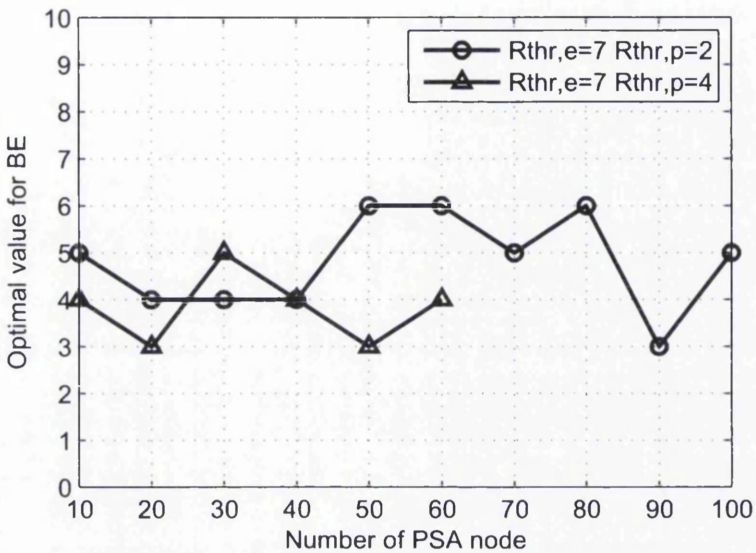

Figure 5.3: Optimal BE against the number of PSA vehicles with $R_{thr,p}$=2 and 4.

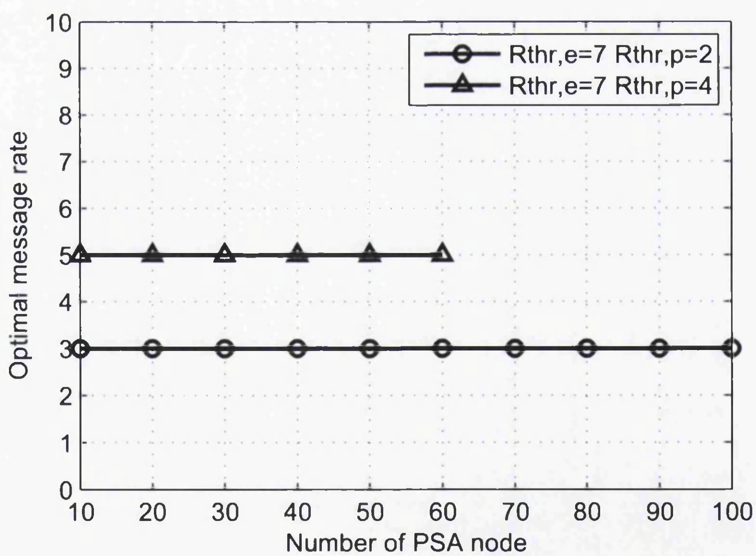

Figure 5.4: Optimal message rate against the number of PSA vehicles with $R_{thr,p}$=2 and 4.

as required.

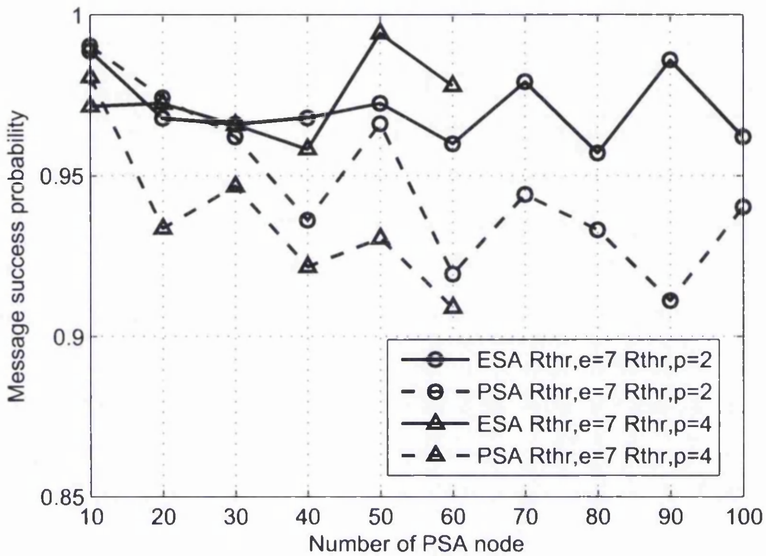

Figure 5.5: Message success probability against the number of PSA vehicles with $R_{thr,p}$=2 and 4.

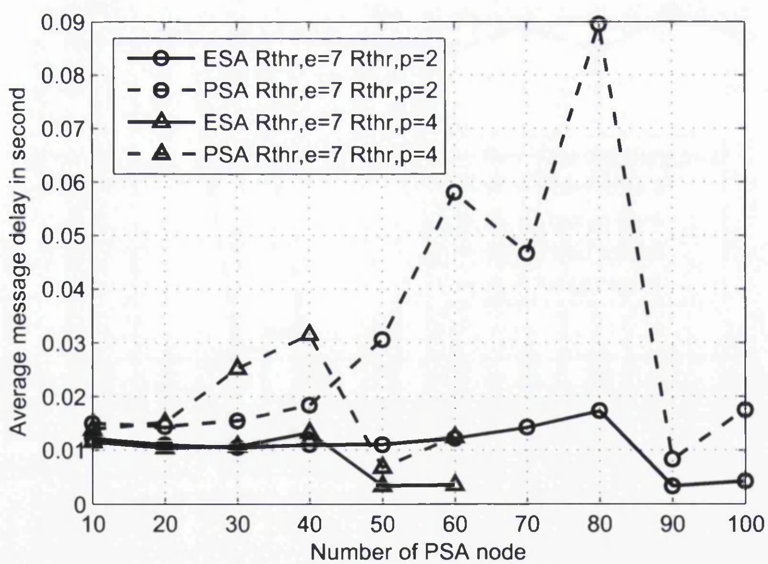

Figure 5.6: Message delivery delay against the number of PSA vehicles with $R_{thr,p}$=2 and 4.

We plot the utility value Θ for QoS requirement of $R_{thr,p}$= 2 and 4 in Fig. 5.7 and Fig. 5.8. For performance comparison we plot the results obtained for a type fixed control scheme (called Type I FCS), in which the CCH interval and message rate are fixed irrespective of the dynamic traffic loads. For the Type I FCS we set BE to 4 and CCH interval length to 35 ms. Several fixed message rates are selected for comparison. It is observed from the figures that the adaptive control scheme can achieve larger utility the Type I FCS in most of the cases. And more importantly the adaptive control scheme can use much smaller CCH interval length to satisfy safety applications QoS, which means non-safety applications are left with more channel time. In Fig. 5.9 and Fig. 5.10, we plot the corresponding average message delay and success probability of ESA and PSA messages for Type I FCS.

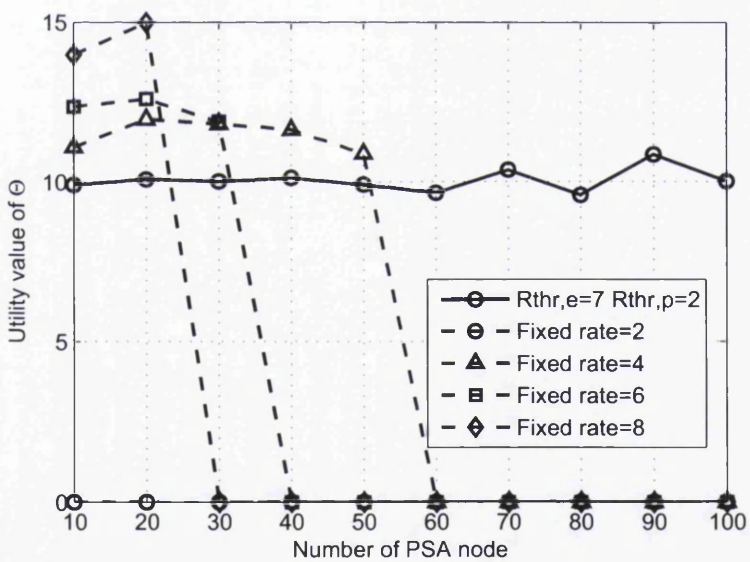

Figure 5.7: Utility Θ of adaptive control and Type I FCS for $R_{thr,p}$=2.

Next we compare the performance of the adaptive control scheme with that of another type of fixed control scheme (called Type II FCS), which uses the CCH interval length identified in the adaptive control scheme but uses fixed message rate for PSA. The utility values of the adaptive control scheme and the Type II FCS are plotted in Fig. 5.11 and Fig. 5.12 for the QoS requirements of $R_{thr,p}$=2

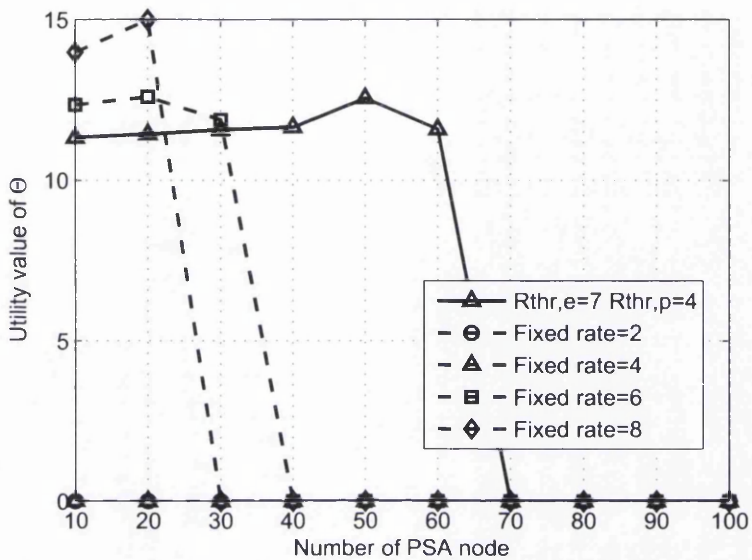

Figure 5.8: Utility Θ of adaptive control and Type I FCS for $R_{thr,p}$=4.

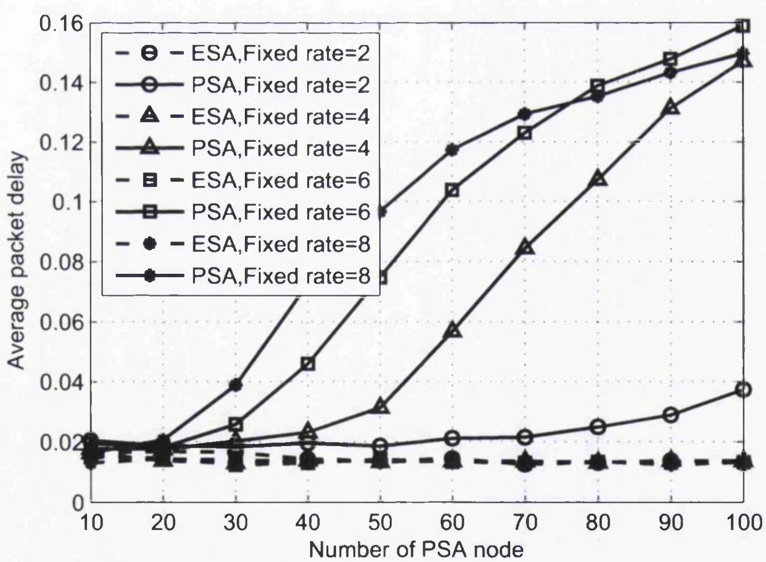

Figure 5.9: Message delay of Type I FCS.

and 4, respectively. The optimal message rate and BE for PSA are plotted in Fig. 5.13 and Fig. 5.14, respectively. We can see from Fig. 5.11 and Fig. 5.12 that

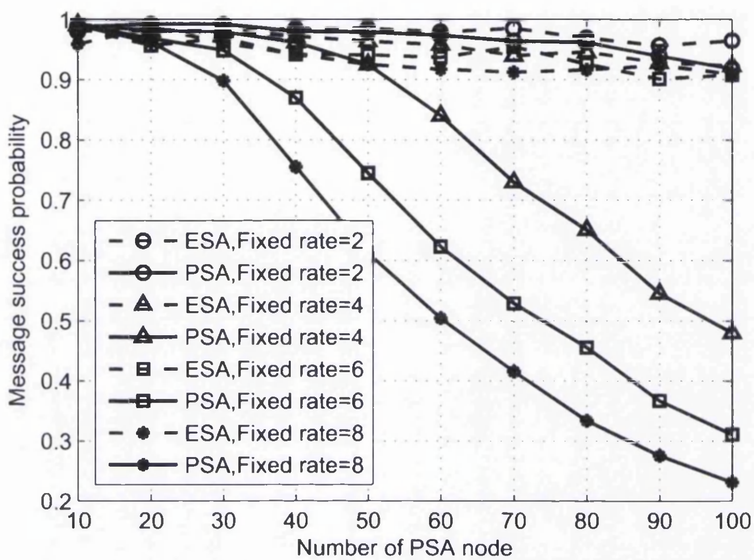

Figure 5.10: Message success probability of Type I FCS.

although Type II FCS can leave the same amount of channel time to non-safety applications as the adaptive control scheme, it has much smaller utility values than the adaptive control scheme due to the use of fixed message rates in the FCS.

We presented further results on study of the impact of CCH threshold on QoS provisioning performance. And we also propose a new utility function, in which the number of successfully received safety messages is the main concern, and the QoS requirements from the multiple coexisting safety application are taken into account in design of the utility function.

5.4 DSRC Network QoS Guarantee with Transmit Power Control

5.4.1 QoS Control Scheme with Transmit Power Control

After the investigation of CCH interval adaptation, this section deals with additional adaptation of transmit power. The purpose is to achieve QoS guarantee

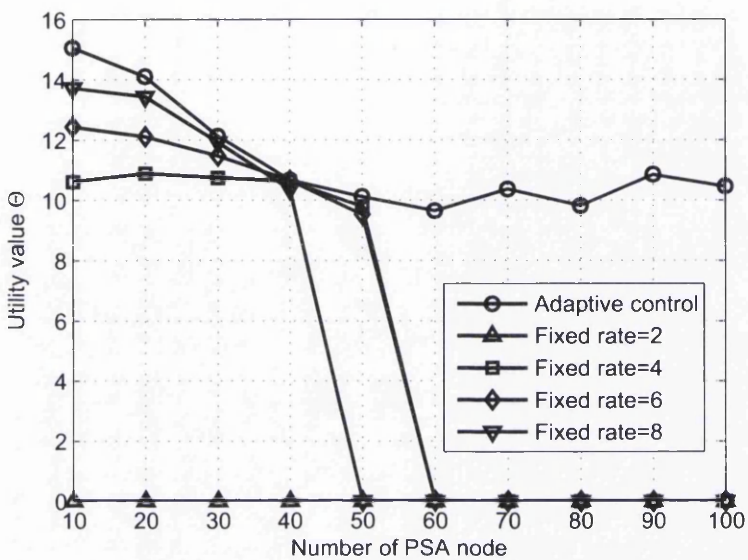

Figure 5.11: Utility Θ of adaptive control and Type II FCS for $R_{thr,p}$=2.

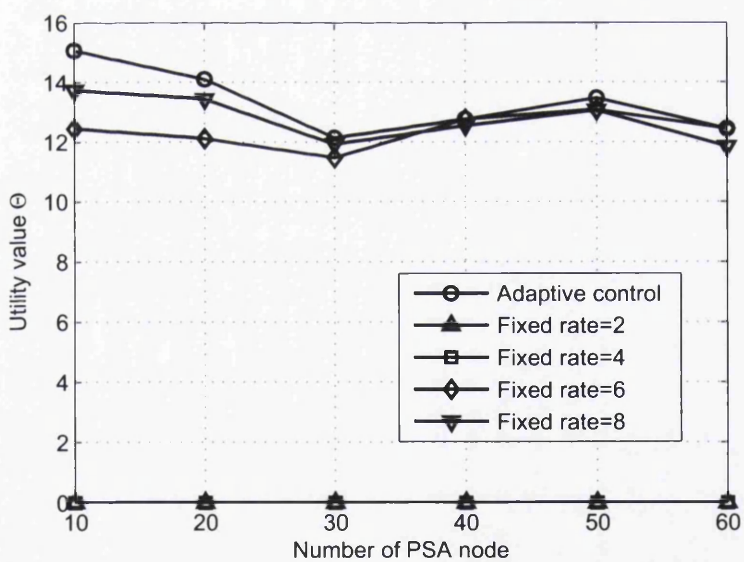

Figure 5.12: Utility Θ of adaptive control and Type II FCS for $R_{thr,p}$=4.

for DSRC networks based collaborative vehicle safety applications. In the previous presented adaptive QoS control schemes, network QoS performances are

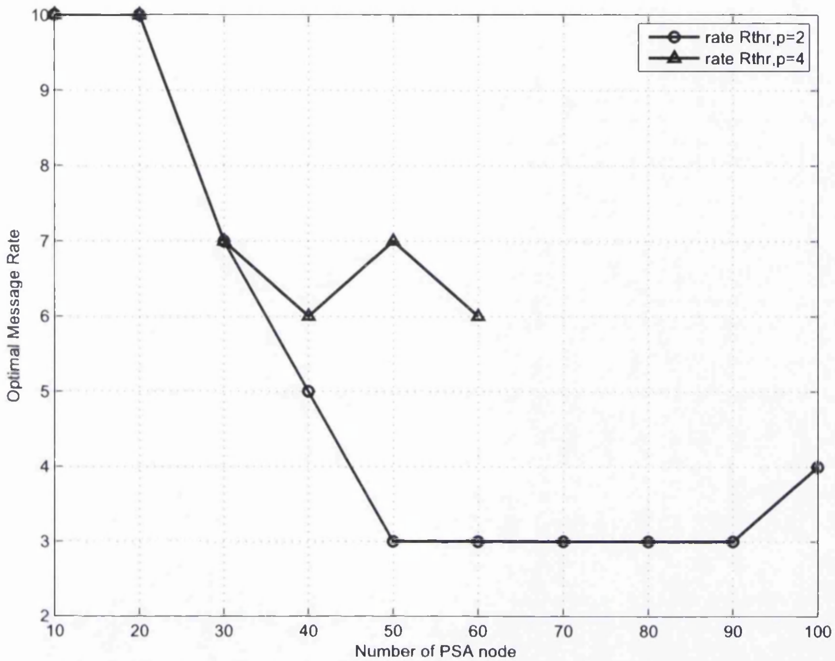

Figure 5.13: Optimal message rate of adaptive control scheme.

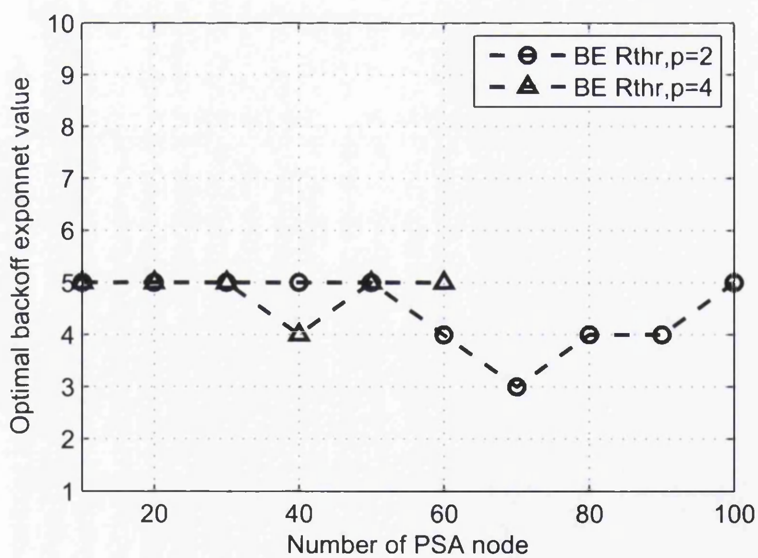

Figure 5.14: Optimal BE of adaptive control scheme.

optimized in terms of the system utilities but the QoS requirements of safety applications are not necessary satisfied, which have been shown by the simulation results presented in Chapter 4 and the previous section. Although there could be a number of approaches which may improve the QoS performances of DSRC networks, transmit power control can be simple and effective for QoS guarantee.

For the design of the adaptive QoS control scheme with additional adaptation of transmit power, again the same two-phases based control framework and the utility function shown in 4.1.1 are applied. The reason of not using adaptive modulation is that the modulation scheme for broadcast is fixed. Therefore adaptive modulation is not an option that can be used to control transmission range for message broadcast. For this study we fix CCH interval and use offline procedure to find out the optimal configurations of message rate and transmit power for a set of given number of vehicles. These optimal configurations are then applied to online procedure where roadside AP requests the vehicles to update the configurations of transmit power, message rate and BE according to an estimated number of vehicles in the road intersection.

5.4.2 Numerical Results

We assumes a single hop ad hoc network environment without hidden terminals. For the DSRC control channel we set CCH interval as 35 ms, which is 70% of a 50 ms Synchronization Interval. Two classes of vehicle nodes are assumed in the network. The first class of nodes only transmit ESA messages while the second class of nodes transmit only PSA messages. In the simulations we simply assume that there are three first class nodes, which send eight ESA messages in each second. All messages are assumed to have the same length of 250 bytes and are broadcast at the rate of 3 Mbps. An ideal channel is assumed, which means a message can be successfully received if no collision happens.

In this section we have used the following configuration for the thresholds and utility weights for the proposed utility function. $P_{thr,e} = 0.9$, $P_{thr,p}$=0.8, $W_{s,e} = 0.7$, $W_{s,p} = 0.3$,$W_{d,e} = 10$, $W_{d,p} = 20$. With the above parameter configurations we set up the optimal configuration table for message rate and transmit power. The utility Θ for the optimal configurations is plotted in Fig. 5.15 against the number of vehicle nodes in the network. For performance comparison purpose the system utility Θ obtained with a fixed control scheme which uses fixed message rates and transmit power is also presented in Fig. 5.15. The corresponding message rate R for PSA application which maximize the utility function are presented in Fig. 5.16. We plot in Fig. 5.17 the message delivery delay for both ESA and PSA messages obtained with the optimal configurations.

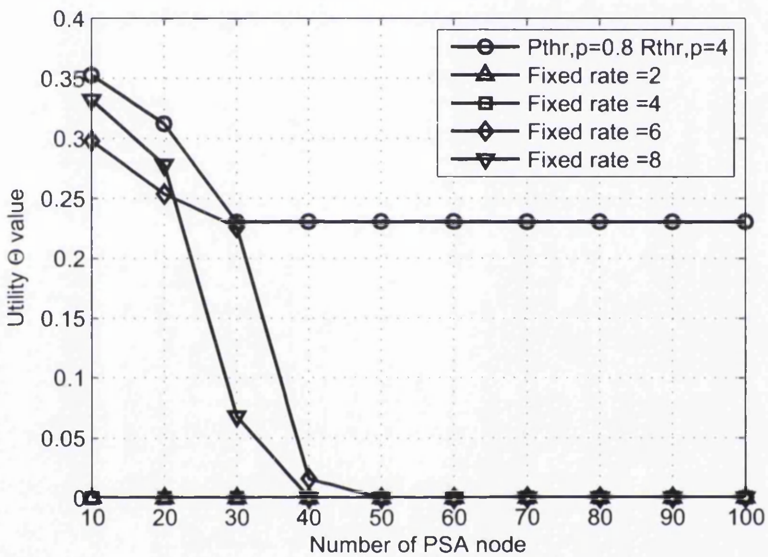

Figure 5.15: System utility Θ with optimal configuration and fixed configuration against the number of PSA nodes.

It can be observed that the performance with optimal configuration is consistently significantly better than that with fixed rate and transmit power. And more specifically when the number of vehicles in the network is high, controlling message rate alone could not guarantee the required QoS for safety applications. In these cases the new QoS control scheme could provide guaranteed QoS with joint control of message rate and transmit power.

5.5 Conclusion

This chapter extended the previous work of adaptive QoS control presented in Chapter 4 to address the QoS guarantee issues for single hop DSRC network sce-

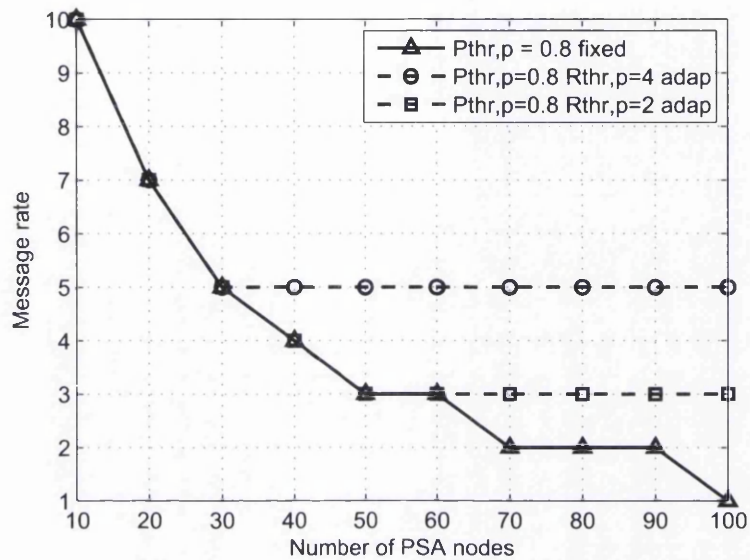

Figure 5.16: Optimal message rate against the number of PSA nodes, for $P_{thr,p} = 0.8$.

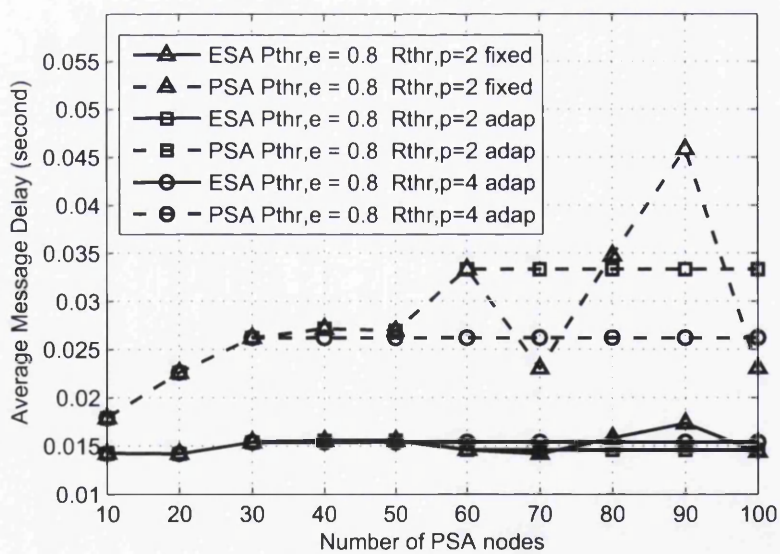

Figure 5.17: Average message delivery delay.

narios. Firstly a framework of cooperative and adaptive QoS control is presented for DSRC networks, which can be used for both centralized QoS control in single hop network scenarios and distributed QoS control in multiple hop ad hoc network scenarios. The impact of CCH interval adaptation on the QoS performances of safety applications and non-safety applications is also studied. By integrating the CCH interval adaptation to the adaptive QoS control framework proposed in Chapter 4, the impact of CCH interval adaptation is shown by simulation results. Additionally this chapter presented a study on the additional control of transmit power, aiming to provide QoS guarantee for collaborative vehicle safety applications. Simulation results demonstrated the effectiveness of QoS guarantee by the control of message rate and transmit power.

Chapter 6

Decentralized Adaptive QoS Control Schemes for Ad Hoc DSRC Networks

In the previous chapters the QoS problem has been studied by both analytic and simulation approaches for single hop DSRC network scenarios. Adaptive QoS control schemes have been proposed to provide reliable and robust QoS for collaborate vehicle safety applications, by the means of adapting the application message rate, MAC layer channel access parameters, CCH interval and transmit power. With assumption of available roadside APs in the single hop infrastructured DSRC networks it is possible and beneficial to implement centralized QoS control schemes. Simulation results have demonstrated that centralized adaptive QoS control schemes can largely improve DSRC network QoS performances over fixed rate schemes. However, due to the extremely high cost to implement roadside APs along all the roads, it is also possible to have large scale ad hoc vehicle networks. Obviously, QoS control over such ad hoc vehicle networks is much more challenging. In this chapter, distributed QoS control is investigated for ad hoc vehicle networks based collaborated vehicle safety applications. Two adaptive message rate control algorithms are proposed for the QoS control purpose in order to provide highly available channel to high priority emergency messages and improve channel utilization. Unlike the centralized QoS control schemes studied in the previous chapters in the proposed distributed QoS control algorithms each vehicle monitors channel loads and independently controls message rate by a modified additive increase and multiplicative decrease (AIMD) method. Simulation results are obtained to evaluate the effectiveness of the proposed rate control algorithms in adapting to dynamic traffic load.

6.1 Related Work

In the literature, there has been some work reported on the QoS control for ad hoc DSRC networks. QoS control based on event-driven congestion control method was adopted in [83] and [84]. With the event-driven detection method, each node freezes all MAC transmission queues except for the safety queue with the highest priority. For example, when a node detects an event-driven safety message either generated from its own application layer or received from another device, it will launch congestion control immediately to guarantee the delivering of event-driven safety message [83].

On the other hand, QoS control can also be implemented based on measurement-based congestion control, by which each device periodically senses the channel and measure the channel congestion level based on predefined thresholds such as channel usage level [83], number messages queue [84] and channel occupancy time [76]. The predefined thresholds play important role in the performance of the wireless network by monitor and detect congestion of communication channels.

The research in [76] uses channel occupancy time as predefined threshold. If channel occupancy time of CCH channel measured at a node is longer than a given predefine threshold, all beacon messages will be blocked immediately. Research in [84], a threshold for queue length in SCHs channels is used. If the queue length of non-safety applications exceeds a predefine threshold, congestion is indicated and the preceding node is notified in order to decrease its transmission rate. To ensure performance of event-driven safety message, CCH communication channel should be controlled rather than SCHs channels.

In [76], MAC blocking detection mechanism is used for immediate and aggressive control of beacon message transmissions to mitigate congestion, and adaptive traffic rate control is used for congestion avoidance. The MAC blocking detection method applied in [76]. For example, if MAC blocking happens at a node due to excessively long channel occupancy time, the channel is considered as congested for event-driven safety messages. The congestion signal is sent to the application layer, triggering traffic rate control actions.

6.2 Design of Application Message Rate Control Schemes

6.2.1 Design Goals

Similar to the objectives of centralized QoS control for infrastructured DSRC networks, the distributed QoS control schemes are designed with the following two goals:

- First of all to provide a highly available low latency channel for ESA messages;
- Secondly to maximize channel utilization for PSA messages which is important to build mutual awareness, provided that QoS for ESA messages is satisfied.

In order to achieve the above goals, cross-layer design methodology is applied with short-term message blocking used at the MAC layer and long-term additive increase multiplicative decrease (AIMD) method used by rate control schemes at the transport layer. An alternative option is to implement the rate control schemes at MAC layer. As congestion control is traditionally regarded as a function of transport layer, we consider the implementation of the rate control schemes at the transport layer. Before we present two AIMD based adaptive rate control schemes in the next subsections, we briefly introduce MAC layer blocking mechanism.

For both rate control and MAC blocking, local channel busy time is used as the indicator of channel congestion level. A vehicle keeps monitoring the channel. If the sensed channel busy time in a monitoring window (e.g. a synchronization interval) is higher than 50%, PSA message are blocked immediately from transmitting to the channel for the remaining of the monitoring window. With such MAC blocking mechanism it is possible to increase responsiveness to channel congestion and provide high channel availability for safety-critical messages. However, it is noted that MAC blocking alone can not achieve the second design goal as blocking of messages and channel congestion are likely to be synchronized.

6.2.2 Adaptive Rate Control Scheme I

The first adaptive rate control scheme we proposed (shortened as ARCS-I) is based on AIMD method with two phases, namely fast start phase and congestion avoidance phase. These two phases of ARCS-I are illustrated in Fig. 6.1 and described in more details.

6.2.2.1 Fast Start Phase

For ARCS-I rate control starts in fast start phase when a vehicle node joins a vehicle network. Let R denote message rate for PSA in the unit of message per second (mps). R is initially set to $R_{\min}$ and increases by one for every T synchronization intervals. Assume that $R_{\min} \leq R \leq R_{\max}$, where $R_{\min} = 1$ and $R_{\max} = 10$. The rate increment stops when either message rate R reaches to $R_{\max}$ or a congestion event occurs. Congestion event is independently detected by vehicles and occurs if the ratio of channel busy time to the duration of a SI is larger than a pre-defined threshold (e.g. 50%). When a congestion event occurs, half of the current traffic rate, R_{thr}, is recorded as a so-called fast start threshold, and PSA messages from the vehicles that detected congestion are blocked at the MAC layer for one SI. After one SI PSA messages are unblocked for those vehicles and those vehicles move to fast start phase operating from $R_{\min}$.

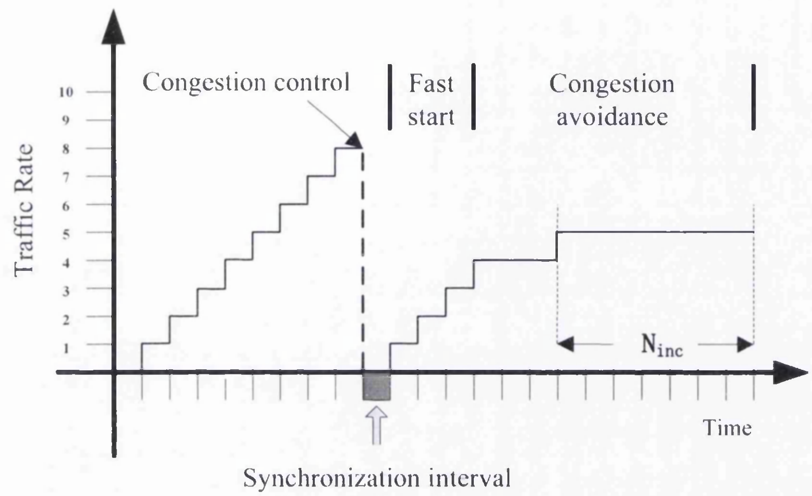

Figure 6.1: AIMD rate control scheme

6.2.2.2 Congestion Avoidance Phase

After a vehicle enters fast start phase upon detection of congestion, it gradually increases message rate by one for every N_{inc} SIs until it reaches the fast start threshold R_{thr} if no further congestion happens. Once message rate R reaches the fast start threshold the vehicle node moves to congestion avoidance phase. During the congestion avoid phase, channel busy level in the previous SIs are monitored and recorded (denoted by L_{cb}). The channel busy level is taken into account in adjusting the time required for message rate to be increased by one mps. Let N_{inc} denote the number of SIs that is required to be waited for before message rate can be increased. N_{inc} is updated in real time by the following formula:

$$N_{inc} = \lceil (10 \times L_{cb}) \times (R_{max} - R_{thr})/C_a \rceil.$$

Here, C_a denotes a configurable constant used for adjusting N_{inc}. We set $C_a = 3$ in this section.

If the channel busy level is approaching channel congestion threshold, the tagged vehicle should choose to wait for long time before increase message rate in order to prevent congestion occurring too frequently. On the contrary short time is needed to wait for if channel busy level is low. For example, if $L_{cb} = 50\%$

and the latest $R_{thr} = 2$, we have $N_{inc} = 14$, which means the vehicle needs to waits for 14 SIs to reach the next rate level. During this period if a congestion event occurs N_{inc} is recalculated after PSA messages are unblocked. A flow chart of the proposed ARCS-I is presented in Fig. 6.2.

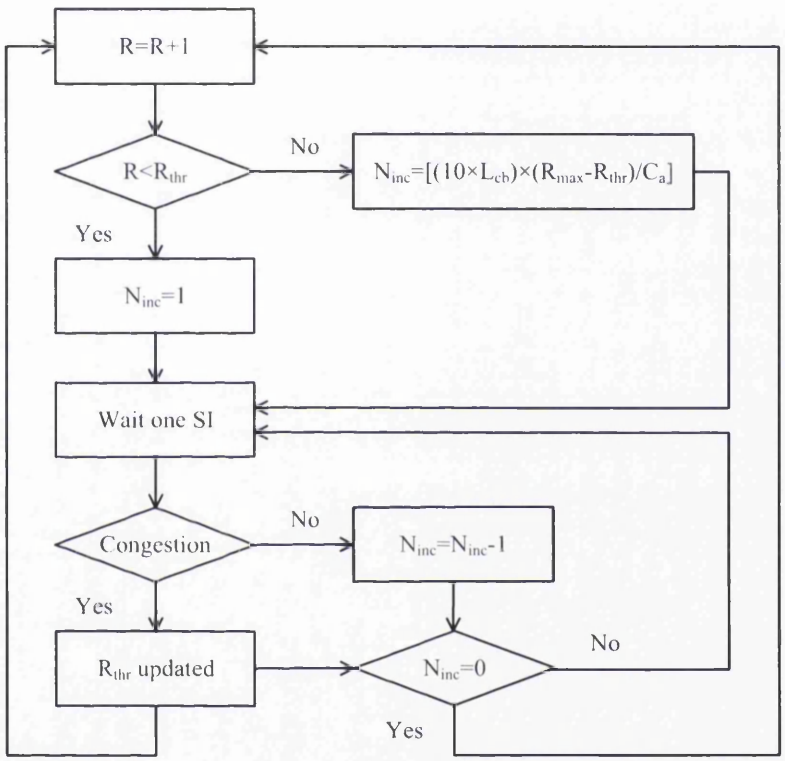

Figure 6.2: Adaptive rate control flow chart

6.2.3 Adaptive Rate Control Scheme II

ARCS-I is a little bit conservative as it tries to avoid channel congestion by introducing both fast start phase and congestion avoidance phases. The consequence is that while the message collision rate can be kept low the channel may not be fully utilized. Therefore we propose another adaptive rate control scheme (called ARCS-II), which has only one phase, namely fast recovery phase. It is more aggressive in increasing message rate compared to ARCS-I.

Similarly when the channel busy time measured by a vehicle is higher than the pre-defined threshold, congestion is assumed to happen and MAC blocking is active for this vehicle in the next SI. As network topology is reasonably stable for short time period and message rates leading to channel congestion are reduced by half, congestion event may not happen quickly again. Therefore the vehicles that detected congestion may not need to enter the fast start phase. Instead the vehicles can move to the fast recovery directly, which is illustrated in Fig. 6.3. At the end of MAC blocking due to congestion events, the current message rate is set to the fast recovery threshold R_{thr} directly, and then is increased for every N_{inc} SIs. Here N_{inc} is a configurable fixed number for ARCS-II. In our study it has been set to 1 to maximize channel utilization for PSA messages, as more PSA messages are broadcasted with higher message rate level. Fast recovery threshold R_{thr} is updated in the same way as in ARCS-I.

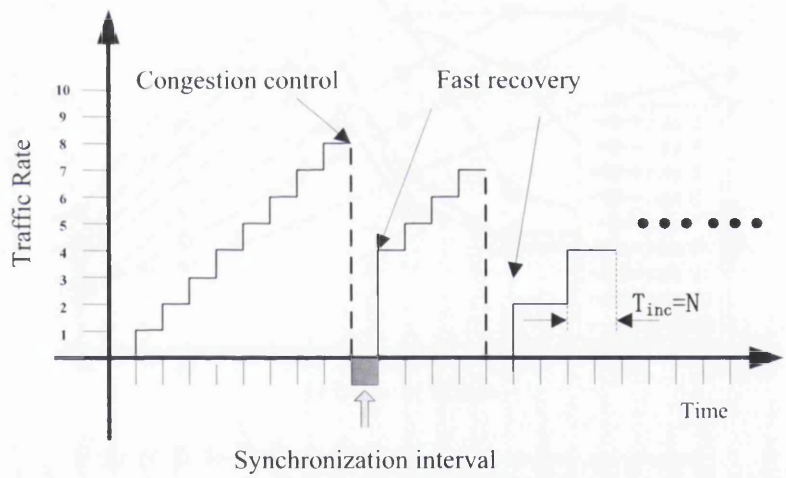

Figure 6.3: Fast recovery rate control scheme

6.3 Simulation Results

We have implemented a discrete-event driven simulator to evaluate the proposed DSRC rate control schemes. The simulated network topology represents an urban intersection with lane length of 350 m but there is no roadside AP to implement centralized QoS control. Both transmission and carrier sensing ranges are set to be 200 m. The interference signal strength based physical model [85] is used to determine a successful reception of transmission. A configurable number of nodes are randomly placed with a uniform distribution over the lanes. Each PSA message has a fixed length of 300 bytes. IEEE 802.11p is configured with initial backoff contention window $W_{\min}=2^8$ for PSA messages and a physical data rate of 3 Mbps. Synchronization parameters are set as $t_{syn}=50$ ms and $t_{cch}=35$ ms. In the simulations, each point is obtained by taking the average value of 20 iterations.

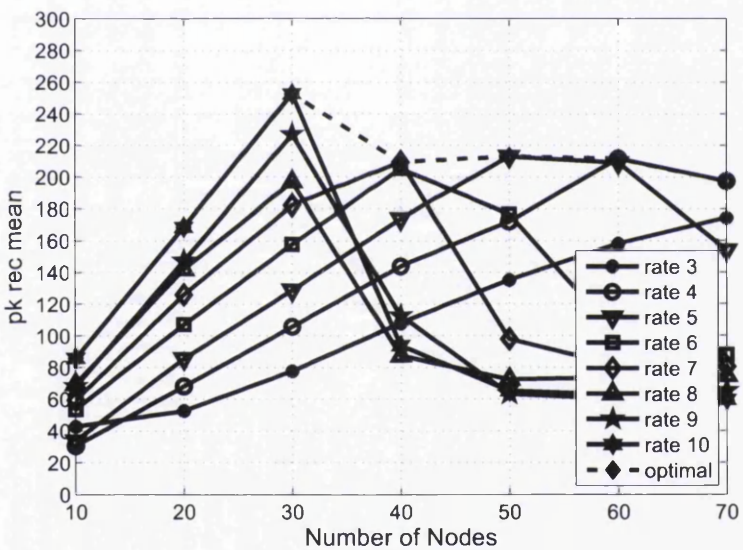

Figure 6.4: Average number of received messages.

6.3.1 Fixed Rate Scheme

We first study the performance of a fixed rate scheme, which simply set the message rate to a fixed rate for all vehicles in the network. Fig. 6.4 presents the number of successfully received messages in a second averaged over all the vehicles in the network, for the the fixed rate scheme with message rates of 3 to 10 mps. Also shown in Fig. 6.4 is an optimal rate scheme. The optimal rate scheme is designed simply by setting the message rate that maximizes the performance of fixed rate scheme for all vehicles for each scenario with fixed number of vehicles in the network. Obviously optimal rate scheme is only ideal for performance comparison purpose. It is not practical to be used in real systems. Due to the use of MAC layer blocking ESA messages are supposed to achieve high channel availability and can achieve good QoS. From 6.4 it can be observed that fixed rate scheme is not efficient in channel utilization without adapting message rate to the number of vehicle nodes in the network. For example, in the case of 30 vehicles in the network, fixed rate of 10 mps has the highest number (250 mps) of successfully received messages, while fixed rate of 3 mps has the lowest (80 mps). But with the number of vehicles increased to 50, the number of received messages for fixed rate of 10 mps drops dramatically to 60 mps, while fixed rate of 5 mps has the highest (220 mps). The results show that we need efficient rate control schemes that can adaptively adjust message rate to achieve the highest possible channel utilization for PSA messages.

6.3.2 Adaptive Rate Control Schemes

Next we investigate the performances of adaptive control schemes by comparing them to the fixed rate scheme and the optimal rate scheme. Fig. 6.5 presents the average number of successfully received messages for the schemes. Fixed rate scheme with rate of 4 mps and 8 mps is compared. We can observe that both adaptive rate control schemes perform much better than the fixed rate scheme. They can achieve performance close to that of the optimal rate scheme for all the investigated network scenarios. ARCS-II is relatively better than ARCS-I in high density traffic circumstance ($N > 40$), with a performance gain of 20% for 70 vehicles. However this is not a surprise as ARCS-II has been designed to be a little bit more aggressive than ARCS-I in utilizing channel for PSA messages.

Fig. 6.6 presents simulation results of network wide averaged probability of successful packet reception (denoted by p_{rec}). As the optimal rate scheme that achieves the highest number of messages does not necessarily achieve the highest p_{rec}, Results of optima rate scheme is not presented in Fig. 6.6. It is observed that all the compared schemes can provide a reasonably good performance in terms of

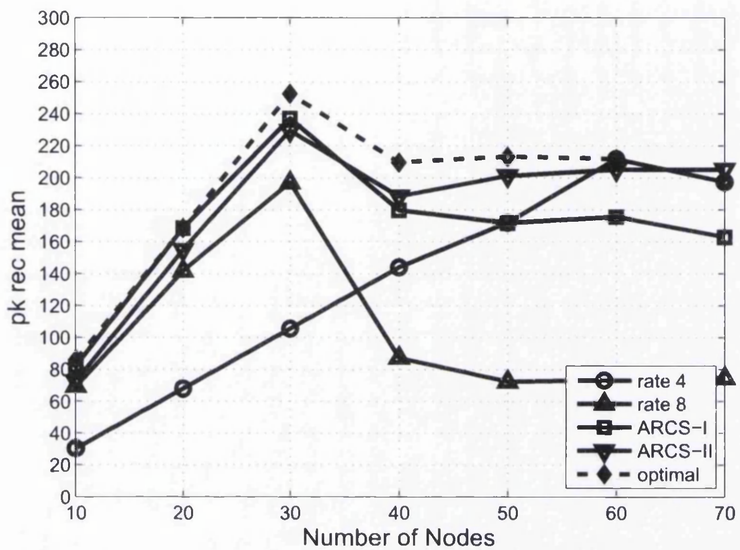

Figure 6.5: Comparison of two adaptive rate control schemes with optimal rate.

p_{rec} (which is around 0.9). But ARCS-I shows higher p_{rec} than ARCS-II, which has been rewarded due to ARCS-I's conservativeness in increasing message rate and avoiding channel congestion. Therefore there is a tradeoff to be made for the two adaptive rate control schemes in terms of channel utilization (number of received messages) and probability of successful message reception.

Fig. 6.7 represents the network wide average probability that PSA messages are blocked at MAC in one SI. The metric of message blocking probability is important as vehicles that are blocked are not able to broadcast their positions and mutual awareness may be damaged. It is observed that the probability of MAC blocking tends to be zero with a fixed rate of 4 mps. However, for fixed rate of 8 mps, the probability of MAC blocking increases rapidly with N up to 0.44, which is due to the lack of adaptation for increasing traffic load. ARCS-I has a relatively low MAC blocking probability even when N increases. It is also shown that ARCS-II plays a trade-off between the MAC blocking time and the correct message reception.

Messages delay performance is presented in Fig. 6.8. Message delay increases with N in general. Due to the constrains of N_{inc} by previous channel busy time L_{cb} and R_{thr}, delay for ARCS-I is relatively high compared to other schemes but

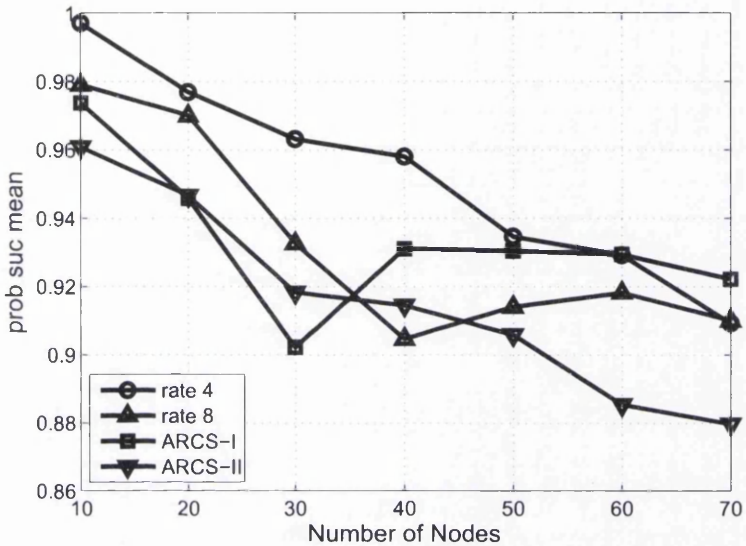

Figure 6.6: Probability of successful packet reception.

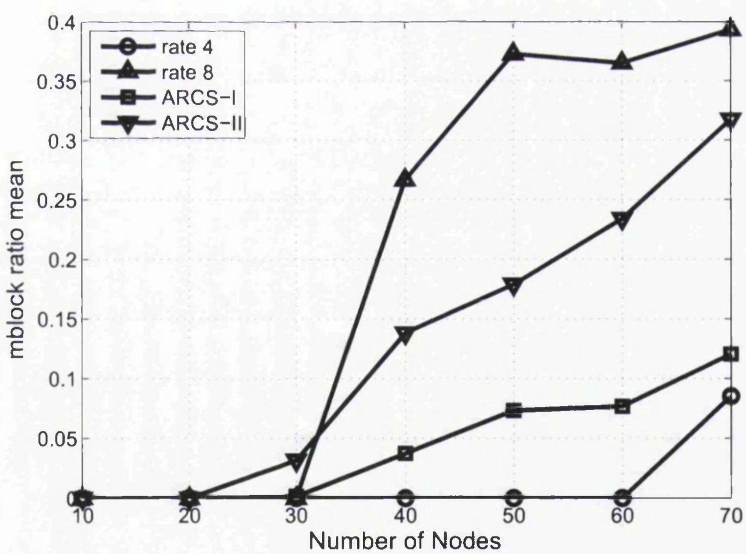

Figure 6.7: Average probability of MAC layer message blocking.

is still less than 12 ms On the other hand, ARCS-II achieves lower messages delay. The ARCS-II has relative low packet delay with the maximal sending rate.

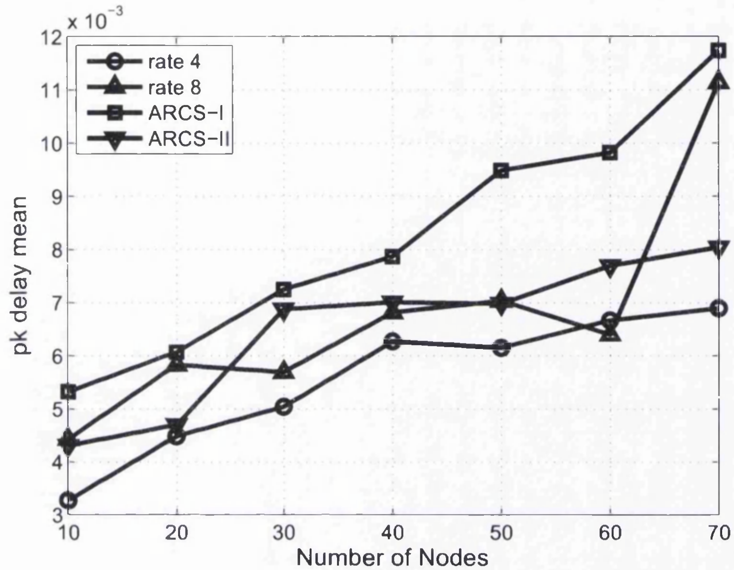

Figure 6.8: Average message delay.

6.4 Conclusion

In this chapter two distributed adaptive message rate control schemes are proposed for ad hoc DSRC networks to control CCH channel congestion and provide QoS for collaborative vehicle safety applications. Two classes of vehicle safety applications are considered, namely high priority emergency safety applications and low priority routine safety applications. However it is noted that the design of the distributed adaptive message rate control schemes can be extended to the networks with more than two classes of safety applications. The algorithm design objectives are set to provide highly available channel for emergency messages and try to maximize channel utilization for low priority messages. For both distributed message rate control schemes local channel busy time has been used as the indicator of network congestion, and message rates are adaptively adjusted by the rate control schemes according to the CCH channel congestion levels. The difference between the two adaptive rate control schemes is that the first scheme is a little more conservative in terms of increasing message rate to avoid channel congestion. Simulation results demonstrate the effectiveness of the proposed rate control schemes, which have achieved the design goals of improving channel utilization and providing good QoS for high priority safety applications. Both adaptive schemes performs much better than fixed rate scheme.

Chapter 7

Conclusion and Future Work

Road safety and especially vehicle safety is a worldwide concern. Due to the advances in wireless communications recently there has been increasing interest on applying vehicle communication and networking to collaborative vehicle safety applications to tackle vehicle safety problems. However the success of wireless communication and vehicle network based collaborative vehicle safety application will depend tightly on the QoS that can be provided by the vehicle networks.

This thesis presents a systematic study on the application of DSRC vehicle networks to support collaborative vehicle safety applications with high QoS requirements. The focuses of this thesis are on the analysis of DSRC network QoS performances and limitations, design and evaluation of adaptive QoS control schemes for both centralized single hop infrastructured DSRC networks and distributed ad hoc DSRC networks. The main objectives have been set to provide a high availability and low latency channel for high priority safety applications and leave as much as possible channel time for low priority safety applications and non-safety applications. The major research activities and outcomes are summarized in this chapter. A proposal of future work is also presented.

7.1 Conclusion

In Chapter 2 a thorough review is presented on the competitive wireless technologies that can be used for collaborative vehicle safety applications. Vehicle ad hoc networking technologies are introduced. The main challenges associated with DSRC networks for vehicle safety applications are also analysed.

In Chapter 3 the QoS performances of DSRC networks are evaluated without employing any QoS control mechanisms. This part of work is to identify the potential problems with DSRC networks in terms of QoS provisioning for collaborative vehicle safety applications and provide insights into the design and optimization of adaptive QoS control schemes. Both analytic and simulation approaches are applied for the performance evaluation task. For the analytic approach single service priority and saturated traffic load are assumed. A simple analytic model is proposed which can predict the major performance measures of interests, such as message success probability, message delivery delay and channel throughput against the number of DSRC devices in the network. The impact of MAC layer channel access parameters is modelled as well. Further simplification of the analytic model is also presented. A system-level discrete-event driven simulator is also developed for the performance evaluation task. Both periodic safety applications and emergency safety applications are considered. From both analytic and simulation results it has been observed that the QoS performances provided by DSRC networks are acceptable with light traffic loads but tend to be worse and unacceptable with increasing traffic load. As the collaborative vehicle safety applications prove to be effective and gain large scale deployment, these applications are expected to generate heavy traffic. Therefore the results show clearly that there is a strong need of implementing effective QoS control schemes in DSRC networks in order to meet the QoS requirements posed by collaborative vehicle safety applications.

After the evaluation of QoS performances provided by DSRC networks without QoS control, Chapter 4 presented the research work on the design of centralized QoS control for single hop infrastructured DSRC networks. The assumption of single hop infrastructured DSRC networks makes the QoS control problem simplified and centralized QoS control is a possible option. A framework for centralized QoS control in infrastructure DSRC networks was proposed, which is mainly consisted of an offline procedure and an online procedure. Offline procedure is based on simulation approach and operated by the APs only, aiming to identify the best possible configurations of message rate and MAC layer channel access parameters for given number of vehicles. Due to the existing of multiple objectives optimization problem on balancing both overall network performances and individual safety application performances, a utility function is used in the offline procedure. With the best message rates and channel access parameters configurations identified by the offline procedure, online procedure is to apply these outcomes to configure the DSRC devices adaptively according to the real network operations. Based on the QoS control framework, two adaptive QoS control schemes with different utility functions are proposed, which can be used for different design preferences on the target QoS performances. Different target QoS performances may be required by different types of safety applications. Simulation results showed that the design of utility functions can have a decisive impact on the identified optimal configurations. But both adaptive control schemes have been observed to perform much better than the fixed rate schemes, especially when the network conditions may change (such as changing number of vehicles in the networks and QoS requirements from the road safety applications). Although the estimated number of vehicle nodes may not be accurate, it has been shown by simulations that the proposed adaptive congestion control schemes are robust in providing good QoS for practical operations.

The adaptive QoS control schemes proposed in Chapter 4 can largely improve QoS performances provided by DSRC networks compared to fixed rate schemes. However, it is noted that the adaptive QoS control schemes does not provide any QoS guarantee for collaborative vehicles safety applications, as only application message rate and MAC layer channel access parameters are controlled by these QoS control schemes. As reliable message delivery is critical for collaborative vehicle safety applications, Chapter 5 extended the work presented in Chapter 4 and investigated QoS guarantee problem for DSRC networks. A framework of providing guaranteed QoS for collaborative vehicle safety applications was proposed for single hop infrastructured DSRC networks. which includes three major modules, namely adaptive application module, cooperative and adaptation module, and MAC layer adaptation module. Then an enhanced centralized adaptive QoS control scheme was proposed in which the CCH interval configuration is jointly controlled with message rate and MAC channel access parameters. The additional control of CCH interval can maximize the QoS performances for non-safety applications after that sufficient resources have been allocated to safety applications to ensure safety applications receive satisfactory QoS. Furthermore, the QoS guarantee issue for single hop DSRC network scenarios was studied with the additional control of transmit power. With the control of transmit power the APs can control the number of DSRC devices to be included in the transmission range. Therefore, QoS guarantee could be supported by the DSRC networks if the number of competing DSRC devices in the communication range of the APs can be strictly controlled. Simulation results demonstrated the effectiveness of QoS guarantee by the control of message rate and transmit power. It is noted that with different utility functions the values of optimal parameters proposed by the two phases centralized QoS control scheme will be different. The conclusions obtained with the proposed scheme are dependent on the chosen utility functions. But the proposed two phases centralized QoS control scheme is general and is applicable to different utility functions.

Chapter 6 extended the QoS control work for single hop infrastructured DSRC networks to ad hoc DSRC vehicle network scenarios. Over the ad hoc DSRC vehicle networks QoS control is much more challenging compared to infrastructured DSRC networks. In this chapter, distributed QoS control is investigated for ad hoc vehicle networks based collaborated vehicle safety applications. Two distributed adaptive message rate control algorithms are proposed for the QoS control purpose, in order to provide highly available channel to high priority emergency messages and improve channel utilization. Unlike the centralized QoS control schemes studied in the previous chapters, in the proposed distributed QoS control algorithms each vehicle monitors channel loads and independently controls message rate by a modified additive increase and multiplicative decrease (AIMD) method. Two classes of vehicle safety applications are considered, namely high priority emergency safety applications and low priority periodic safety applications. However, it is noted that the design of the distributed adaptive message rate control schemes can be extended to the networks with more than two classes of safety applications. The algorithm design objectives are set to provide highly available channel for emergency messages and try to maximize channel utilization for low priority messages. For both distributed message rate control schemes, local channel busy time has been used as the indicator of network congestion, and message rates are adaptively adjusted by the rate control schemes according to the CCH channel congestion levels. System level discrete-event driven simulator was developed for performance evaluation of the distributed QoS control schemes. Simulation results demonstrated the effectiveness of the proposed rate control schemes, which have achieved the design goals. Both adaptive QoS control schemes performed much better than fixed rate scheme.

7.2 Future Work

This thesis has presented an analysis, design and optimization of QoS control for DSRC networks in order to provide satisfactory QoS support to collaborative vehicle safety applications. Both single hop infrastructured DSRC network and ad hoc DSRC network scenarios are considered. The proposed adaptive QoS control schemes can largely outperform fixed rate schemes. It is believed that the research work and results presented in this thesis can help understand the QoS performances provided by DSRC networks for vehicle safety application, and also provide deep insights into advanced QoS control schemes.

However, it is noted that as DSRC network QoS control is a system wide research problem, there are still some interesting but challenging problems to be studied to provide a complete reliable QoS solution for collaborate vehicle safety applications. Below is a list of a few research issues that we think deserve to be further investigated from the research work undertaken in this thesis.

Firstly, simple and efficient performance analytical models can provide deep insights to the capability of DSRC networks on providing QoS for collaborative vehicle safety applications and the design of effective QoS control schemes. In Chapter 3 a simple analytic model was presented for single hop infrastructured DSRC networks to predict the DSRC network QoS performances. It is noted that saturated traffic model has been used for simplicity. Extending the analytical model to unsaturated traffic model and multiple service classes will be an interesting future research item. In addition, analytically modelling the QoS performances of DSRC networks in ad hoc network scenarios is an interesting but very challenging problem. which deserves further investigation.

Secondly, for single hop infrastructure DSRC networks, this thesis has presented research work on the QoS control by the adaptation of message rate, MAC channel access parameters, CCH interval and transmit power. Good QoS performance can be obtained for single hop infrastructure DSRC networks. However, for the ad hoc DSRC networks distributed QoS control is mainly focused on the message rate control. It is interesting to extend the existing research work to design distributed QoS control schemes with joint adaptation of message rate, CCH interval and transmit power.

Lastly, the safety application messages are assumed to be broadcast to one hop neighbours only in this thesis. They are not forwarded to extended the reach of these safety application messages. Forwarding safety application messages over multiple hops is a possible research issue in the future. In addition, some reliable measures such as transmitting duplicate safety messages with one transmission opportunity may improve the reliability of the safety application messages. However the duplicate safety messages may increase the CCH channel congestion level. Therefore, it is interesting to see if the reliability measures can bring performance improvement and if so how to adaptive control the reliable message transmit schemes.

Bibliography

[1] Reported road casualties great britain: main results 2011. Technical report, Department for Transport, 2011.

[2] Enabling accelerated installation of aftermarket on-board equipment for connected vehicles. Technical report, Industrial Technology Research Institute California PATH of the University of California at Berkley Visteon Corporation, 2012.

[3] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich. Design of 5.9 ghz dsrc-based vehicular safety communication. *Wireless Communications, IEEE*, 13(5):36–43, 2006.

[4] Dedicated short range communications (dsrc) home: http://www.leearmstrong.com/dsrc/dsrchomeset.htm.

[5] IEEE 802.11p/d3.05. Draft aendment for wireless access for the vehicular environment (wave), March 2008.

[6] R. Uzcategui and G. Acosta-Marum. Wave: a tutorial. *Communications Magazine, IEEE*, 47(5):126–133, 2009.

[7] R. Bishop. *Intelligent vehicle technology and trends*. 2005.

[8] N.P. Wisitpongphan, OK Tonguz, JS Parikh, P. Mudalige, F. Bai, and V. Sadekar. Broadcast storm mitigation techniques in vehicular ad hoc networks. *Wireless Communications, IEEE*, 14(6):84–94, 2007.

[9] Federal communications commission. fcc 03-324. fcc report and order. Technical report, Feburary 2004.

[10] L. Cheng, B.E. Henty, D.D. Stancil, and F. Bai. Doppler component analysis of the suburban vehicle-to-vehicle dsrc propagation channel at 5.9 ghz. In *Radio and Wireless Symposium, 2008 IEEE*, pages 343–346. IEEE, 2008.

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

[12] S. Zeadally, R. Hunt, Y.S. Chen, A. Irwin, and A. Hassan. Vehicular ad hoc networks (vanets): status, results, and challenges. *Telecommunication Systems*, pages 1–25, 2010.

[13] A. Khan, S. Sadhu, and M. Yeleswarapu. A comparative analysis of dsrc and 802.11 over vehicular ad hoc networks. *Project Report, Department of Computer Science, University of Californai, Santa Barbara*, pages 1–8, 2009.

[14] A. Chen, B. Khorashadi, D. Ghosal, and C.N. Chuah. Impact of transmission power on tcp performance in vehicular ad hoc networks. In *Wireless on Demand Network Systems and Services, 2007. WONS'07. Fourth Annual Conference on*, pages 65–71. IEEE, 2007.

[15] M. Bechler, S. Jaap, and L. Wolf. An optimized tcp for internet access of vehicular ad hoc networks. *NETWORKING 2005. Networking Technologies, Services, and Protocols; Performance of Computer and Communication Networks; Mobile and Wireless Communications Systems*, pages 869–880, 2005.

[16] Vehicle safety communications project - final report. Technical Report DOT HS 810 591, CAMP IVI Light Vehicle Enabling Research Program, 2006.

[17] J. Santa, A.F. Gómez-Skarmeta, and M. Sanchez-Artigas. Architecture and evaluation of a unified v2v and v2i communication system based on cellular networks. *Computer Communications*, 31(12):2850–2861, 2008.

[18] R.J. Weiland and L.B. Purser. Intelligent transportation systems. *Transportation in the New Millennium*, 2000.

[19] IEEE Std. 802.11. Part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications, August 1999.

[20] C. Eklund, R.B. Marks, K.L. Stanwood, and S. Wang. Ieee standard 802.16: a technical overview of the wirelessman/sup tm/air interface for broadband wireless access. *Communications Magazine, IEEE*, 40(6):98–107, 2002.

[21] SIG Bluetooth. Specification of the bluetooth system, version 1.1. *http://www. bluetooth. com*, 2001.

[22] J.C. Haartsen. Bluetooth radio system. *Encyclopedia of Telecommunications*, 2003.

[23] J.D. Taylor. *Introduction to ultra-wideband radar systems*. CRC, 1994.

[24] R. Abou-Jaoude. Acc radar sensor technology, test requirements, and test solutions. *Intelligent Transportation Systems, IEEE Transactions on*, 4(3):115–122, 2003.

[25] Ieee 802.11n: enhancements for higher throughput in wireless lans. 12(6):82–91, 2005.

[26] 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 5: Enhancements for higher throughput. *IEEE Std 802.11n-2009 (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, and IEEE Std 802.11w-2009)*, pages 1–565, 29 2009.

[27] Ieee draft standard for it - telecommunications and information exchange between systems - lan/man - specific requirements - part 11: Wireless lan medium access control and physical layer specifications - amd: Enhancements for very high throughput for operation in bands below 6ghz. *IEEE P802.11ac/D2.0, January 2012*, pages 1–359, 17 2012.

[28] Ieee draft standard for local and metropolitan area networks - specific requirements - part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications - amendment 3: Enhancements for very high

throughput in the 60 ghz band. *IEEE P802.11ad/D7.0, April 2012 (Draft Amendment based on IEEE 802.11-2012)*, pages 1–661, 28 2012.

[29] Q. Chen, D. Jiang, and L. Delgrossi. Ieee 1609.4 dsrc multi-channel operations and its implications on vehicle safety communications. In *Vehicular Networking Conference (VNC), 2009 IEEE*, pages 1–8. IEEE, 2009.

[30] Ieee standard for wireless access in vehicular environments (wave). *IEEE Std 1609.4-2010 (Revision of IEEE Std 1609.4-2006)*, pages 1–89, 7 2011.

[31] M. Lacage, M.H. Manshaei, and T. Turletti. Ieee 802.11 rate adaptation: a practical approach. In *Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*, pages 126–134. ACM, 2004.

[32] Supplement to ieee standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements. part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications: High-speed physical layer in the 5 ghz band. *IEEE Std 802.11a-1999*, page i, 1999.

[33] Long term evolution (lte): A technical overview. Technical report, Motorola, Retrieved July 3, 2010.

[34] H.G. Myung. Technical overview of 3gpp lte. *Polytechnic University of New York*, 2008.

[35] S. Parkvall, E. Dahlman, A. Furuskar, Y. Jading, M. Olsson, S. Wanstedt, and K. Zangi. Lte-advanced-evolving lte towards imt-advanced. In *Vehicular Technology Conference, 2008. VTC 2008-Fall. IEEE 68th*, pages 1–5. IEEE, 2008.

[36] A. Festag, H. Fußler, H. Hartenstein, A. Sarma, and R. Schmitz. Fleetnet: Bringing car-to-car communication into the real world. *Computer*, 4(L15):16, 2004.

[37] L. Nuaymi. *WiMAX: technology for broadband wireless access*. Wiley, 2007.

[38] B.R. Elbert. *Introduction to satellite communication.* Artech House Publishers, 2008.

[39] A. El-Rabbany. *Introduction to GPS: the global positioning system.* Artech House Publishers, 2002.

[40] Charles E. Perkins and Pravin Bhagwat. Highly dynamic destination-sequenced distance-vector routing (dsdv) for mobile computers. In *Proceedings of the conference on Communications architectures, protocols and applications*, SIGCOMM '94, pages 234 244, New York, NY, USA, 1994. ACM.

[41] P. Jacquet. Optimized link state routing protocol (olsr). 2003.

[42] S.R. Das, E.M. Belding-Royer, and C.E. Perkins. Ad hoc on-demand distance vector (aodv) routing. 2003.

[43] D.B. Johnson and D.A. Maltz. Dynamic source routing in ad hoc wireless networks. *Mobile computing*, pages 153 181, 1996.

[44] Z.J. Haas, M.R. Pearlman, and P. Samar. The zone routing protocol (zrp) for ad hoc networks. *draft-ietf-manet-zone-zrp-04. txt*, 2002.

[45] M. Raya and J.P. Hubaux. Securing vehicular ad hoc networks. *Journal of Computer Security*, 15(1):39 68, 2007.

[46] T.D.C. Little and A. Agarwal. An information propagation scheme for vanets. In *Intelligent Transportation Systems, 2005. Proceedings. 2005 IEEE*, pages 155 160. IEEE, 2005.

[47] K.C. Lee, U. Lee, and M. Gerla. Survey of routing protocols in vehicular ad hoc networks. *Advances in Vehicular Ad-Hoc Networks: Developments and Challenges, IGI Global*, 21, 2009.

[48] W. Zhang, A. Festag, R. Baldessari, and L. Le. Congestion control for safety messages in vanets: Concepts and framework. In *ITS Telecommunications, 2008. ITST 2008. 8th International Conference on*, pages 199 203. IEEE, 2008.

[49] J. Peng and L. Cheng. A distributed mac scheme for emergency message dissemination in vehicular. *Vehicular Technology, IEEE Transactions on*, 56(6):3300–3308, 2007.

[50] F.J. Martinez, J.C. Cano, C.T. Calafate, P. Manzoni, and J.M. Barrios. Assessing the feasibility of a vanet driver warning system. In *Proceedings of the 4th ACM workshop on Performance monitoring and measurement of heterogeneous wireless and wired networks*, pages 39–45. ACM, 2009.

[51] P. Brenner. A technical tutorial on the ieee 802.11 protocol. *BreezeCom Wireless Communications*, pages 1–24, 1997.

[52] M. Gast. *802.11 wireless networks: the definitive guide*. O'Reilly Media, Incorporated, 2005.

[53] B. O'hara and A. Petrick. *IEEE 802.11 handbook: a designer's companion*. Standards Information Network, 2005.

[54] T.K. Mak, K.P. Laberteaux, R. Sengupta, and M. Ergen. Multichannel medium access control for dedicated short-range communications. *Vehicular Technology, IEEE Transactions on*, 58(1):349–366, 2009.

[55] M. Amadeo, C. Campolo, A. Molinaro, and G. Ruggeri. A wave-compliant mac protocol to support vehicle-to-infrastructure non-safety applications. In *Communications Workshops, 2009. ICC Workshops 2009. IEEE International Conference on*, pages 1–6. IEEE, 2009.

[56] G. Bianchi. Performance analysis of the ieee 802.11 distributed coordination function. *IEEE Journal on Selected Areas in Communications,*, 18(3):535–547, 2000.

[57] Jijun Yin, Tamer ElBatt, Gavin Yeung, Bo Ryu, Stephen Habermas, Hariharan Krishnan, and Timothy Talty. Performance evaluation of safety applications over dsrc vehicular ad hoc networks. In *Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks*, VANET '04, pages 1–9, New York, NY, USA, 2004. ACM.

[58] Ravi M. Yadumurthy, Adithya C. H., Mohan Sadashivaiah, and Ranga Makanaboyina. Reliable mac broadcast protocol in directional and omni-directional transmissions for vehicular ad hoc networks. In *Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks*, VANET '05, pages 10–19, New York, NY, USA, 2005. ACM.

[59] Marc Torrent-Moreno, Daniel Jiang, and Hannes Hartenstein. Broadcast reception rates and effects of priority access in 802.11-based vehicular ad-hoc networks. In *Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks*, VANET '04, pages 10–18, New York, NY, USA, 2004. ACM.

[60] D. Jiang, Qi Chen, and L. Delgrossi. Communication density: A channel load metric for vehicular communications research. In *Proc. IEEE Internatonal Conf. Mobile Adhoc and Sensor Systems MASS 2007*, pages 1–8, 2007.

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

[62] J. Mittag, F. Schmidt-Eisenlohr, M. Killat, J. Härri, and H. Hartenstein. Analysis and design of effective and low-overhead transmission power control for vanets. In *Proceedings of the fifth ACM international workshop on VehiculAr Inter-NETworking*, pages 39–48. ACM, 2008.

[63] X. Ma and X. Chen. Delay and broadcast reception rates of highway safety applications in vehicular ad hoc networks. In *2007 Mobile Networking for Vehicular Environments*, pages 85–90. IEEE, 2007.

[64] G. Bianchi. Ieee 802.11-saturation throughput analysis. *Communications Letters, IEEE*, 2(12):318–320, 1998.

[65] F. Calì, M. Conti, and E. Gregori. Dynamic tuning of the ieee 802.11 protocol to achieve a theoretical throughput limit. *Networking, IEEE/ACM Transactions on*, 8(6):785–799, 2000.

[66] YC Tay and K.C. Chua. A capacity analysis for the ieee 802.11 mac protocol. *Wireless networks*, 7(2):159–171, 2001.

[67] IEEE Std. 802.11e. Wireless lan medium access control (mac) enhancements for quality of service (qos), 2005.

[68] Sunghyun Choi, J. del Prado, Sai Shankar N, and S. Mangold. Ieee 802.11 e contention-based channel access (edcf) performance evaluation. In *Proc. IEEE Int. Conf. Communications ICC '03*, volume 2, pages 1151–1156, 2003.

[69] Jianhua He, Lin Zheng, Zhongkai Yang, and Chun Tung Chou. Performance analysis and service differentiation in ieee 802.11 wlan. In *Proc. 28th Annual IEEE Int. Conf. Local Computer Networks LCN '03*, pages 691–697, 2003.

[70] Yang Xiao. Backoff-based priority schemes for ieee 802.11. In *Proc. IEEE Int. Conf. Communications ICC '03*, volume 3, pages 1568–1572, 2003.

[71] Jun Zhao, Zihua Guo, Qian Zhang, and Wenwu Zhu. Performance study of mac for service differentiation in ieee 802.11. In *Proc. IEEE Global Telecommunications Conf. GLOBECOM '02*, volume 1, pages 778–782, 2002.

[72] G. Bianchi and I. Tinnirello. Analysis of priority mechanisms based on differentiated inter frame spacing in csma-ca. In *Proc. VTC 2003-Fall Vehicular Technology Conf. 2003 IEEE 58th*, volume 3, pages 1401–1405, 2003.

[73] H. Zhu and I. Chlamtac. An analytical model for ieee 802.11e edcf differential services. In *Proc. 12th Int. Conf. Computer Communications and Networks ICCCN 2003*, pages 163–168, 2003.

[74] J. He, Z. Tang, T. O'Farrell, and T.M. Chen. Performance analysis of dsrc priority mechanism for road safety applications in vehicular networks. *Wireless Communications and Mobile Computing*, 11(7):980–990, 2009.

[75] J. Padhye and J. Widmer. Tcp friendly rate control (tfrc): Protocol specification. 2003.

[76] J. He, H.H. Chen, T.M. Chen, and W. Cheng. Adaptive congestion control for dsrc vehicle networks. *Communications Letters, IEEE*, 14(2):127–129, 2010.

[77] A. Vinel, V. Vishnevsky, and Y. Koucheryavy. A simple analytical model for the periodic broadcasting in vehicular ad-hoc networks. In *GLOBECOM Workshops, 2008 IEEE*, pages 1–5, 30 2008-dec. 4 2008.

[78] P. Mohapatra, J. Li, and C. Gui. Qos in mobile ad hoc networks. *IEEE Wireless Communications*, 10(3):44–53, 2003.

[79] K. Wu, J. Harms, et al. Qos support in mobile ad hoc networks. *Crossing Boundaries-the GSA Journal of University of Alberta*, 1(1):92–106, 2001.

[80] E.M. Royer and C.K. Toh. A review of current routing protocols for ad hoc mobile wireless networks. *Personal Communications, IEEE*, 6(2):46–55, 1999.

[81] Y. Fang and Y. Zhang. Call admission control schemes and performance analysis in wireless mobile networks. *Vehicular Technology, IEEE Transactions on*, 51(2):371–382, 2002.

[82] C.R. Lin and J.S. Liu. Qos routing in ad hoc wireless networks. *Selected Areas in Communications, IEEE Journal on*, 17(8):1426–1438, 1999.

[83] Y. Zang, L. Stibor, X. Cheng, H.J. Reumerman, A. Paruzel, and A. Barroso. Congestion control in wireless networks for vehicular safety applications. In *Proceedings of the 8th European Wireless Conference*, volume 7, 2007.

[84] M. S. Bouassida and M. Shawky. On the congestion control within vanet. In *Proc. 1st IFIP Wireless Days WD '08*, pages 1–5, 2008.

[85] P. Gupta and P. R. Kumar. The capacity of wireless networks. *Information Theory, IEEE Transactions on*, 46(2):388–404, 2000.