ADAPTIVE DESIGN FOR PERIODIC BEACON CONTROL MECHANISMS IN VANETS

SYED ADEEL ALI SHAH

FACULTY OF COMPUTER SCIENCE AND INFORMATION TECHNOLOGY UNIVERSITY OF MALAYA KUALA LUMPUR

2016

ADAPTIVE DESIGN FOR PERIODIC BEACON CONTROL MECHANISMS IN VANETS

SYED ADEEL ALI SHAH

THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF PHD

FACULTY OF COMPUTER SCIENCE AND INFORMATION TECHNOLOGY UNIVERSITY OF MALAYA KUALA LUMPUR

2016

UNIVERSITI MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Syed Adeel Ali Shah

(I.C./Passport No.:

Registration/Matrix No.: WHA110064

Name of Degree: Doctor of Philosophy

Title of Thesis: Adaptive Design for Periodic Beacon Control Mechanisms in VANETs Field of Study: Wireless Networks

I do solemnly and sincerely declare that:

- (1) I am the sole author/writer of this Work;
- (2) This work is original;
- (3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
- (4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
- (5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
- (6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature

Date

Subscribed and solemnly declared before,

Witness's Signature

Name: Designation: Date

ABSTRACT

In the past few years, the role of Information and Communication Technology (ICT) as a co-pilot for the drivers has shown potential in improving traffic safety and efficiency. The use of ICT enables the spontaneous wireless communication among vehicles, which is a fundamental requirement for vehicular safety systems. The efficiency of vehicular safety systems lends itself to the timely delivery of 1-hop periodic messages called beacons. The periodic beacons serve two main purposes: 1) to maintain local topology view, and 2) to inform drivers about the potential hazardous road/traffic conditions. It is worth mentioning that the design of dedicated short range communication (DSRC) standard for beaconing is motivated by the spontaneous ad hoc communication requirements under mobility. Alternatively, the DSRC standard is not fully compliant with the communication requirements of vehicular applications. That is, safety applications transmit beacons periodically and at high frequencies. Therefore, channel saturation and subsequent message collisions are inevitable under high scale ITS deployment, which cannot be addressed by the DSRC alone. Thus, beaconing under DSRC standard confines the accuracy of mutual topology awareness and the desired performance of vehicular safety applications.

Clearly, the goal of this thesis is to propose adaptive designs for periodic beacon control mechanisms to improve mutual awareness and reliability of vehicular applications. Initially, this study analyses the existing adaptive beaconing approaches to identify challenges which are critical to address, such as fairness in congestion control, satisfying coverage requirement of applications, minimizing overall synchronous collisions and collisions from a specified vehicle. Subsequently, we consider the most germane parameters for designing adaptive control mechanisms, namely transmit power, contention window size and back-off selection mechanism. The first beaconing approach is based on transmit power adaptation, which provides fairness in selecting transmit power during congestion. It uses a novel cooperative game-theoretic approach to model the marginal contributions of vehicles and enable a proportional power decrease for every vehicle to minimize congestion.

Another beaconing approach is proposed to control congestion by adapting differentiating transmit powers for different message types. Explicitly, the design gives a besteffort approach to maximize coverage for the event-driven messages. This is achieved by considering the application requirements and adapting the transmit power for periodic beacons with respect to the channel states.

The problem of synchronous collisions is also tackled with a weighted contention window adaptation scheme. The proposed design replaces the aggressive behaviour of binary exponential back-off in the post-transmit phase of beacons and replaces it with a probabilistic selection of window size. In order to reduce collision in high density networks, the channel states are translated into meaningful weights for the appropriate contention window size selection.

Apart from addressing the problem of overall synchronous collisions, another beaconing approach is proposed to minimize synchronous beacon collisions transmitted from a specified vehicle. This design works on the hypothesis that synchronous beacon collisions transmitted by a subject vehicle can be reduced if all of its neighbours predict and select different back-offs than the ones selected by the subject vehicle.

The implementation of these approaches using a discrete-event simulation shows the practicality of the proposed approaches.

ABSTRAK

Pada tahun-tahun kebelakangan ini, peranan teknologi komunikasi maklumat (ICT) dan sebagai perintis bersama bagi pemandu menunjukkan potensi dalam meningkatkan keselamatan dan kecekapan lalu lintas. Penggunaan ICT telah membolehkan komunikasi tanpa wayar spontan antara kenderaan, yang merupakan keperluan asas untuk sistem keselamatan kenderaan. Keberkesanan sistem keselamatan kenderaan meminjam dirinya untuk penghantaran tepat pada masanya bagi mesej berkala 1-hop dipanggil mata arah. Mata arah berkala mempunyai dua tujuan utama: 1) untuk mengekalkan pandangan topologi tempatan, dan 2) untuk memberitahu pemandu mengenai keadaan jalan raya / trafik berbahaya yang berpotensi. Ia perlu disebut bahawa reka bentuk khusus komunikasi jarak dekat (DSRC) standard untuk mata arah adalah didorong oleh ad hoc keperluan komunikasi spontan di bawah mobiliti. Sebagai alternatif, standard DSRC yang tidak mematuhi sepenuhnya keperluan komunikasi aplikasi kenderaan. Iaitu, aplikasi keselamatan menghantar isyarat secara berkala dan pada frekuensi tinggi. Oleh itu, saluran tepu dan perlanggaran mesej berikutnya tidak dapat dielakkan di bawah tangga tinggi penggunaan ITS, yang tidak boleh ditangani oleh DSRC sahaja. Oleh itu, di bawah mata arah DSRC standard membataskan ketepatan kesedaran topologi bersama dan prestasi yang dikehendaki aplikasi keselamatan kenderaan.

Jelas sekali, matlamat tesis ini adalah untuk mencadangkan reka bentuk penyesuaian mekanisme kawalan mata arah berkala untuk meningkatkan kesedaran bersama dan kebolehpercayaan permohonan kenderaan. Pada mulanya, kajian ini meneliti pendekatan mata arah penyesuaian sedia ada untuk mengenalpasti cabaran yang kritikal untuk menangani, seperti keadilan dalam kawalan kesesakan, memuaskan keperluan liputan aplikasi, mengurangkan perlanggaran segerak keseluruhan dan perlanggaran dari kenderaan yang ditetapkan. Selepas itu, kami mengambil kira parameter yang paling berkaitan untuk merekabentuk mekanisme kawalan suai, iaitu menghantar kuasa, perdebatan saiz tetingkap dan mekanisme pemilihan *back-off*.

Pendekatan mata arah pertama adalah berdasarkan penghantar penyesuaian kuasa, yang menyediakan keadilan dalam memilih menghantar kuasa semasa kesesakan. Ia menggunakan pendekatan teori permainan yang terbaru untuk memodelkan sumbangan marginal kenderaan dan membolehkan penurunan kuasa berkadar untuk setiap kenderaan bagi mengurangkan kesesakan.

Satu lagi pendekatan mata arah adalah dicadangkan untuk mengawal kesesakan dengan menyesuaikan membezakan kuasa penghantar untuk jenis mesej yang berbeza. Secara nyata, rekabentuk yang memberikan pendekatan usaha terbaik untuk memaksimumkan perlindungan untuk mesej berkeutamaan tinggi dengan mengawal kuasa penghantar untuk mata arah berkala berkenaan dengan keadaan-keadaan saluran penghantaran.

Masalah perlanggaran segerak juga ditangani dengan skim adaptasi tetingkap perdebatan wajaran. Rekabentuk yang dicadangkan menggantikan tingkahlaku agresif binari eksponen back-off dalam fasa pasca penghantaran mata arah dan menggantikannya dengan pilihan kebarangkalian saiz tetingkap. Dalam usaha untuk mengurangkan perlanggaran dalam rangkaian berkepadatan tinggi, keadaan-keadaan saluran penghantaran diterjemahkan kepada berat yang lebih bermakna bagi pemilihan saiz tetingkap perdebatan yang sesuai.

Selain menangani masalah perlanggaran segerak keseluruhan, satu lagi pendekatan mtata arah adalah dicadangkan untuk mengurangkan perlanggaran segerak dari kenderaan yang ditetapkan. Rekabentuk ini berfungsi pada hipotesis bahawa perlanggaran segerak kenderaan tertakluk boleh dikurangkan jika semua jiran meramal dan memilih nilai *back-off* yang berbeza seperti yang dipilih oleh kenderaan subjek dalam fasa pasca penghantar.

Pelaksanaan pendekatan ini menggunakan simulasi diskret-acara bagi menunjukkan pendekatan praktikal yang dicadangkan.

ACKNOWLEDGEMENTS

'All praise is to the Almighty alone'

Thereafter, profound gratitude goes to my supervisor, Dr. Rafidah Noor. My Ph.D. has been eventful and I thank my supervisor for being supportive and knowing that my personal life extends beyond my Ph.D. Besides, her tremendous academic ability and support have helped me in writing this thesis.

I would like to express my gratitude to the examiners of this thesis, Prof Dr. Farid Naït Abdesselam and Prof. Dr Daojing He, for their constructive comments and appreciation of the thesis.

Last but not the least, without the encouragement, love and prayers of my parents, sister, brothers, wife and kids, none of this would have been possible. Explicitly, to the Almighty, I am indebted to have such wonderful parents and I dedicate this thesis to my treasured mother and father. Finally, I am grateful to have been blessed with a very patient wife and three lovely kids, who have been a constant source of love and strength all these years.

TABLE OF CONTENTS

ORIGINAL LITERARY WORK DECLARATION	ii
ABSTRACT	iii
ABSTRAK	V
ACKNOWLEDGEMENTS	vii
TABLE OF CONTENTS	viii
LIST OF FIGURES	xiv
LIST OF TABLES	xviii
LIST OF APPENDICES	xxii
CHAPTER 1: INTRODUCTION	1
1.1 Motivation and Significance	3
1.2 Problem Statement	4
1.3 Objectives	6
1.4 Research Methodology	9
1.5 Thesis Layout	10
CHAPTER 2: SURVEY OF ADAPTIVE BEACONING APPROACHES	11
2.1 Introduction	11
2.2 Contributions	12
2.3 Anatomy of Beaconing	12
2.3.1 Schematic Layered Illustration of Beaconing	13
2.3.2 Multichannel Communications	14
2.4 Performance Requirements and Beaconing Design	16

viii

	2.4.1	Performance	es Requirements	16
		2.4.1.1	Reduced Beaconing Load	17
		2.4.1.2	Application Diversity	17
		2.4.1.3	Fairness in Beacon Transmission	17
		2.4.1.4	Reliable Beacon delivery	18
	2.4.2	Design of A	daptive Beaconing Approaches	18
		2.4.2.1	Application Requirements	19
		2.4.2.2	Network State	19
		2.4.2.3	Traffic Scenario	19
		2.4.2.4	Mixed	20
2.5	Desigr	n-based Taxor	nomy	20
	2.5.1	Beaconing (Category	20
	2.5.2	Information	Dependency	21
	2.5.3	Objective Fu	unctions	22
2.6	Survey	of Adaptive	Beaconing Approaches	23
	2.6.1	Message Fre	equency Control Approaches	23
		2.6.1.1	MFC based on traffic situation	23
		2.6.1.2	MFC based on position prediction	23
		2.6.1.3	MFC based on fairness	24
		2.6.1.4	MFC for overtaking assistance	25
	2.6.2	MFC for not	n-safety applications	25
	2.6.3	Transmit Po	wer Control Approaches	26
		2.6.3.1	TPC based on fairness	27
		2.6.3.2	TPC with random power level	27
		2.6.3.3	TPC for spatial reuse	27
		2.6.3.4	TPC based on feedback	28
	2.6.4	Miscellaneo	us Approaches	29
		2.6.4.1	Desynchronized beacon transmissions	30
		2.6.4.2	Adapting physical data rate	30
		2.6.4.3	Adapting contention window	31

			2.6.4.4	Beaconing based on carrier sense Threthold	33
		2.6.5	Hybrid Cont	rol Approaches	34
	2.7	Capabi	lity Evaluatio	n	38
		2.7.1	Beaconing L	oad	38
		2.7.2	Congestion (Control Strategy	39
		2.7.3	Fairness		39
		2.7.4	Reliability		41
		2.7.5	Data Utility		42
		2.7.6	Co-existing l	Message Dissemination Evaluation	42
	2.8	Compa	rison		43
		2.8.1	Classification	n Approach	43
		2.8.2	Comparison	Among Beaconing Approaches	44
			2.8.2.1	Communication Scope	44
			2.8.2.2	Execution Definition	45
			2.8.2.3	Information Acquisition Definition	47
			2.8.2.4	Number of Radios	48
			2.8.2.5	Channel Access Definition	48
			2.8.2.6	Evaluation Approach	49
			2.8.2.7	Metric Type	50
	2.9	Challer	nges and Desi	gn Considerations	50
		2.9.1	Power Contr	ol Design	51
		2.9.2	Contention V	Vindow Design	53
		2.9.3	Layered View	w of the Proposed Approaches	55
	2.10	Conclu	sion		56
	СНА	PTER	3: TRANSN PERIOD	AIT POWER CONTROL DESIGNS FOR IC BEACONS	58
	3.1	Introdu	iction		58
	3.2	Motiva	tion and Prob	lem Statement of AC3	59
-	3.3	AC3: A	Adaptive trans	mit power Cooperative Congestion Control (AC3) Design	61

	3.3.1	System Model	62
	3.3.2	Implications of Fairness using Shapely value	63
	3.3.3	Player Specification Rules	64
	3.3.4	Work flow of AC3	66
	3.3.5	Analysing Fairness in Power Reduction	68
	3.3.6	Mechanism for Information Distribution	70
	3.3.7	Algorithm:AC3	73
3.4	MPC:	A Multi-metric Tx-Power Control Design	76
	3.4.1	Metric Composition	78
		3.4.1.1 Quality of Channel q_{cch}	78
		3.4.1.2 The Application Requirements app_{req}	80
		3.4.1.3 Determining Transmit Power p_{tx}	81
	3.4.2	MPC Algorithm and Organizational Processes	83
3.5	Conclu	ision	85
CHA	APTER	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING	87
CH <i>A</i> 4.1	APTER Introdu	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING	87 87
CH ⁴ 4.1 4.2	APTER Introdu Analys	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING action sing Collisions from Contention Window Size Perspective	87 87 88
CH44.14.2	APTER Introdu Analys 4.2.1	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING action sing Collisions from Contention Window Size Perspective Design Considerations	87 87 88 88
CH44.14.24.3	APTER Introdu Analys 4.2.1 Weight	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING notion sing Collisions from Contention Window Size Perspective Design Considerations ted Contention Window Adaptation Design	87 87 88 88 88 91
CH44.14.24.3	APTER Introdu Analys 4.2.1 Weight 4.3.1	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING action sing Collisions from Contention Window Size Perspective Design Considerations ted Contention Window Adaptation Design Behaviour at a Microscopic Level	87 87 88 88 91 92
CH44.14.24.3	APTER Introdu Analys 4.2.1 Weight 4.3.1 4.3.2	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING action sing Collisions from Contention Window Size Perspective Design Considerations ted Contention Window Adaptation Design Behaviour at a Microscopic Level Algorithm: Contention Window Adaptation	87 87 88 88 91 92 95
 CH4 4.1 4.2 4.3 4.4 	APTER Introdu Analys 4.2.1 Weight 4.3.1 4.3.2 Prelim	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING nction sing Collisions from Contention Window Size Perspective Design Considerations ted Contention Window Adaptation Design Behaviour at a Microscopic Level Algorithm: Contention Window Adaptation inaries for Proposed Back-off Selection Design	87 88 88 91 92 95 97
 CHA 4.1 4.2 4.3 4.4 4.5 	APTER Introdu Analys 4.2.1 Weight 4.3.1 4.3.2 Prelim Analys	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING netion sing Collisions from Contention Window Size Perspective Design Considerations ted Contention Window Adaptation Design Behaviour at a Microscopic Level Algorithm: Contention Window Adaptation inaries for Proposed Back-off Selection Design	87 87 88 88 91 92 95 97 97
 CH4 4.1 4.2 4.3 4.4 4.5 4.6 	APTER Introdu Analys 4.2.1 Weight 4.3.1 4.3.2 Prelim Analys PRNG	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING action sing Collisions from Contention Window Size Perspective Design Considerations ted Contention Window Adaptation Design Behaviour at a Microscopic Level Algorithm: Contention Window Adaptation inaries for Proposed Back-off Selection Design sing Collisions in 802.11p -inspired Back-off Selection	87 88 88 91 92 95 97 98
 CH4 4.1 4.2 4.3 4.4 4.5 4.6 	APTER Introdu Analys 4.2.1 Weight 4.3.1 4.3.2 Prelim Analys PRNG 4.6.1	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING action sing Collisions from Contention Window Size Perspective Design Considerations ted Contention Window Adaptation Design Behaviour at a Microscopic Level Algorithm: Contention Window Adaptation inaries for Proposed Back-off Selection Design sing Collisions in 802.11p -inspired Back-off Selection Use of Pseudo Random Number Generator (PRNG) in Post-transmit Phase	 87 87 88 88 91 92 95 97 98 100 102
 CH4 4.1 4.2 4.3 4.4 4.5 4.6 	APTER Introdu Analys 4.2.1 Weight 4.3.1 4.3.2 Prelim Analys PRNG 4.6.1 4.6.2	4: ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING Intion sing Collisions from Contention Window Size Perspective Design Considerations ted Contention Window Adaptation Design Behaviour at a Microscopic Level Algorithm: Contention Window Adaptation inaries for Proposed Back-off Selection Design sing Collisions in 802.11p -inspired Back-off Selection Use of Pseudo Random Number Generator (PRNG) in Post-transmit Phase Artefact of Implementing PBS Using Discrete-event Simulation	 87 87 88 88 91 92 95 97 98 100 102 104

		4.6.3.1	System Model	106
4.7	Conclu	usion		109
CH	APTER	5: PERFO	RMANCE EVALUATION	110
5.1	Introdu	uction		110
5.2	Simula	ators for Vehic	cular Network Simulations	110
	5.2.1	Network Sir	nulators	111
	5.2.2	Vehicular M	obility Simulators	112
	5.2.3	Simulation I	Framework used in Thesis	113
		5.2.3.1	Veins Framework: An Overview	114
5.3	Perfor	mance Evalua	tion	116
	5.3.1	Evaluation of	of AC3	117
		5.3.1.1	Simulation Setup	117
		5.3.1.2	Verfication of the Approach	117
		5.3.1.3	CBT for different values of α	119
		5.3.1.4	Channel Access Time	119
		5.3.1.5	Packet Delivery Ratio	121
		5.3.1.6	Average per-vehicle throughput	122
	5.3.2	Evaluation of	of MPC	123
		5.3.2.1	Simulation Setup	123
		5.3.2.2	Verfication of the Approach	124
		5.3.2.3	Reliability	125
		5.3.2.4	Per-vehicle Message Reception Rates	127
		5.3.2.5	Collision Rates	127
	5.3.3	Evaluation of	of Contention Window Adaptation	128
		5.3.3.1	Simulation Setup	128
		5.3.3.2	Verfication of the Approach	128
		5.3.3.3	Fairness Index	129
		5.3.3.4	Awareness quality	131
		5.3.3.5	Overall Throughput	132

	5.3.4	Evaluation of	of the PBS	133
		5.3.4.1	Verification of the Approach	133
		5.3.4.2	Message Reception and Reliability	134
		5.3.4.3	Implications of the PBS Design	138
5.4	Conclu	usion		140
CHA	APTER	6: CONCL	USION	141
6.1	Summ	ary of Contrib	outions	141
6.2	Future	Work		143
	6.2.1	Possible Ext	ension of this Research	144
	6.2.2	Flexible Cha	annelization for Spatial Reuse	145
	6.2.3	Heterogeneo	ous Network Communication for Scalability	146
REF	FEREN	CES		147

REFERENCES

LIST OF FIGURES

Figure 1.1	Some example applications of Vehicular ad hoc Networks	3
Figure 1.2	Traffic scenario requiring a highly reliable delivery of messages from the RSU to the vehicles approaching an intersection	8
Figure 1.3	Thesis Layout Representation	10
Figure 2.1	(a) Schematic layered Illustration of Beaconing in Vehicular ad hoc Networks, (b) Transmitter and Receiver perspective of information flow	13
Figure 2.2	Single and dual radio configurations for beaconing: (a) IEEE WAVE radio configuration options (b) ETSI radio configuration options	15
Figure 2.3	Design-based Taxonomy of adaptive beaconing approaches	20
Figure 2.4	Illustration of the access mechanism using contentions and back-offs	29
Figure 2.5	Classification of Beaconing with respect to the Architectural Components including coordination mechanisms, implementation logic and available resources	45
Figure 2.6	Illustration of the evolving channel busy ratio for one vehicle in a network (on the left), and average busy time of all the nodes with respect to densities (on the right)	52
Figure 2.7	Comparing reliability of beacon reception from a source vehicle on different vehicles with respect to increasing distances	53
Figure 2.8	Total synchronous collisions recorded for different vehicular densities	55
Figure 2.9	The protocol stack view of proposed awareness and congestion control schemes	56
Figure 3.1	Illustration of congested zone on a highway	60
Figure 3.2	Illustration of coalition formation with reduced size using the specified rules in AC3.	65
Figure 3.3	Work flow of AC3, which includes seven steps from congestion event distribution to the transmit power convergence after power decrease.	66
Figure 3.4	Schematic illustration of the fair power decrease in a coalition of four vehicles	67
Figure 3.5	Player selection for the 16 player example	68

Figure 3.6	Comparison in the power decrease between proposed AC3 and the AIMD approach	69
Figure 3.7	Flow diagram demonstrating the transmit power sharing and congestion event distribution mechanism	71
Figure 3.8	Information in the beacon frame append with an extra 8-bit $tx - power$ field and 1-bit <i>flag</i> field.	71
Figure 3.9	Example scenario of event-driven messages requiring adequate coverage.	76
Figure 3.10	Illustration of computational and organizational processes in multi-metric power control approach	84
Figure 4.1	Successful transmission probability with respect to the increasing contention window size	90
Figure 4.2	Behaviour of contention window adaptation for different transmission	93
Figure 4.3	Example of an influential vehicle with a high longitudinal and lateral dynamics	97
Figure 4.4	Example illustration of hidden node and exposed node problem	98
Figure 4.5	Space-time illustration of synchronous collision due to same back-off selection time and back-off value	99
Figure 4.6	Space-time illustration of synchronous collision due to back-off expiry at the same time	100
Figure 4.7	Abstract view of the functional blocks of PRNG-inspired Back-off Selection technique	101
Figure 4.8	Flow diagram of PRNG-inspired Back-off Selection technique as implemented in the post-transmit phase	102
Figure 4.9	Illustration of comparative values of e , ζ and their <i>ratio</i>	105
Figure 4.10	Illustration of a complete collision and partial collision. The proposed approach only addresses the complete collision	108
Figure 5.1	Basics components in VANET simulation	111
Figure 5.2	OMNet++ simulation anatomy of vehicular ad hoc networks	114
Figure 5.3	OMNet++ simulation anatomy of vehicular ad hoc networks	115
Figure 5.4	The car compound module in Veins	116
Figure 5.5	An excerpt showing the transmit power adaptation in AC3 before and after a congestion event	118

XV

Figure 5.6	Run-time adaptive transmit power of two geographically apart vehicles	119
Figure 5.7	Comparison of the channel busy time (cbt) in case of different values of <i>al pha</i>	120
Figure 5.8	Comparison of the channel access time with respect to the simulation time, which indicates the increasing channel load	121
Figure 5.9	Comparison of overall packet delivery ratio (PDR) metric of AC3 with constant transmit powers and the reference approach	122
Figure 5.10	Comparing per vehicle throughput metric of AC3 with the default and reference approach	123
Figure 5.11	Adaptive transmit power behaviour of a vehicle with four normal beacons followed by a high priority beacon over a period of time	125
Figure 5.12	Comparing reliability over increasing distances for MPC and constant use of transmit powers	126
Figure 5.13	Comparing reliability over increasing distances for MPC and the reference approach	127
Figure 5.14	Comparison of overall message reception with respect to vehicular density	128
Figure 5.15	Comparison of average number of collisions for varying levels of vehicular densities	129
Figure 5.16	Run-time selection probability of minimum contention window w.r.t CBT for the first few seconds of simulation	130
Figure 5.17	Jain's fairness index of the proposed approach with standard 802.11p	131
Figure 5.18	Awareness quality measured as the number of received beacons and compared with the standard 802.11p	132
Figure 5.19	Comparison of average number of collisions for varying levels of vehicular densities and window sizes	132
Figure 5.20	Comparison of throughput variation of the proposed approach with the standard 802.11p	133
Figure 5.21	Comparing the number of back-off slots experienced by each vehicle in a 50 vehicles/lane/km scenario for the 802.11p and the PBS design	134
Figure 5.22	Comparing the average number of beacon reception from a specified node using 802.11p and the proposed approach with 20 dBm transmit power	135

Figure 5.23	Comparing the average per-vehicle reliability achieved by PBS and 802.11p in different vehicular densities	136
Figure 5.24	Comparing the number of messages received from a source vehicle over increasing distance when using 802.11p and the PBS by using 20 dBm transmit power	137
Figure 5.25	Comparing the number of messages received from a source vehicle over increasing distance when using 802.11p and PBS with 32 dBm transmit power	138
Figure 5.26	Comparing the overall average number of collisions in a network using 802.11p and the proposed approach with 20 dBm transmit power	139
Figure 5.27	Comparing the overall average number of collisions in a network	

using 802.11p and the proposed approach with 32 dBm transmit power 140

LIST OF TABLES

Impact of gathered information from different information sources	16
Key observations about surveyed beaconing approaches	35
Evaluation of adaptive beaconing approaches	40
Comparison of beaconing approaches with respect to the architectural characteristics	46
Notations	61
Comparison of transmit power levels in dBm for a unique transmission range under different levels of the channel quality and the application priority levels	82
Contention window sizes defined by the Enhanced Distributed Channel Access.	88
Simulation parameters in Veins for AC3 performance evaluation	117
Simulation parameters in Veins for MPC performance evaluation	124
List of figures in the appendix along with a brief description	156
	Impact of gathered information from different information sources Key observations about surveyed beaconing approaches Evaluation of adaptive beaconing approaches Comparison of beaconing approaches with respect to the architectural characteristics Notations Comparison of transmit power levels in dBm for a unique transmission range under different levels of the channel quality and the application priority levels Contention window sizes defined by the Enhanced Distributed Channel Access. Simulation parameters in Veins for AC3 performance evaluation Simulation parameters in Veins for MPC performance evaluation

university

university

university

LIST OF APPENDICES

Itinerary of Appendices	156
APPENDIX B: AC3 Initialization	157
APPENDIX C: AC3 coalition finder	158
APPENDIX D: AC3 Permutations	159
APPENDIX E: AC3 Player Contributions	160
APPENDIX F: AC3 Payoff Calculation	161
APPENDIX G: AC3 Fair Power Calculation	162
APPENDIX H: AC3 Message Preparation & Distribution	163
APPENDIX I: Multi-metric Power Control	164
APPENDIX J: Post-transmit Phase in Weighted Contention Window Adaptation	165
APPENDIX K: Post-transmit Phase of the PBS Design	166

CHAPTER 1: INTRODUCTION

Vehicular ad hoc Networks (VANETs) consists of moving vehicles as mobile nodes and communicate wirelessly with other vehicles and road side units (RSUs). The mobile nodes in VANETs are autonomous and have the capability to sense road conditions (e.g., icy road surface, reduced traction etc) and traffic situations (e.g., vehicles approaching intersections, presence of disabled vehicles on road etc) (Consortium et al., 2005). The ability of vehicles to sense and communicate forms the basis of the Intelligent Transportation Systems (ITSs) that provide various applications for the passenger safety and comfort.

The key feature of ITS applications is the public interest in the sensed information by any vehicle. For instance, a vehicle sensing reduced traction on one part of the road may be of significance to the approaching vehicles on some other part of the road. It follows that the sensed information must be frequently communicated to all vehicles. Therefore, ITS applications mandate periodic and network-wide transmission of the sensed information to establish awareness among vehicles. The periodic transmission of information allows the vehicles to maintain a topological view of the neighbours and it is used by the driver's assistance system to generate alarms/warnings to facilitate a timely reaction during a hazardous condition.

The periodic transmission of information is made possible through the exchange of small messages called beacons, which provide actual services for the ITS applications. The beacon transmission requirements are defined by the IEEE Wireless Access for Vehicular Environments (WAVE) and the European Telecommunications Standards Institute (ETSI) ITS ("IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services", 2010), (E. ETSI, n.d.). This includes the use of the wireless spec-

trum as well as the application requirements for desired performance. The Federal Communications Commission (FCC) has allocated a 75MHz spectrum for the exchange of beacons using a Dedicated Short Range Communications (DSRC) capability. Among the defined list of safety applications, most require a high message frequency for high level of awareness about the traffic situation. Similarly, the desirable range of transmission for different message types is also specified which translates into the proper use of transmitting power. For safety applications, these requirements are critical to avoid accidents and to prolong the reaction time for the drivers during a hazardous condition.

However, several constraints contribute to the loss and erroneous transmission of periodic beacons. One category of constraints relates to the inherent characteristics of the vehicular networks such as constant mobility, sparse and dense VANETs and the physical infrastructure. The second category of constraints are the technological limitations such as relatively bandwidth constrained wireless medium, which imposes restriction on the proper use of message frequency and transmission power. For instance, a bandwidth constraint wireless medium minimizes the chances of successful beacon reception if a high message frequency or transmit power is used in a dense VANET. Therefore, to meet the application requirements of safety applications, these constraints must be tackled. While the inherent VANET characteristics cannot be controlled, the technological limitations can be reduced to a certain extent using delivery mechanisms for periodic beacons.

The focus of this thesis is to propose new adaptive beaconing designs to overcome the technological limitations of the DSRC specifications. Primarily, two types of parameters are considered for adaptive beaconing designs i.e., the transmit power and the contention window size.



Figure 1.1: Some example applications of Vehicular ad hoc Networks

1.1 Motivation and Significance

Safety while traveling has always been a concern and the statistics about road casualties around the world are alarming. The UK's department of transport has recorded 22,830 people seriously injured or killed in just the second quarter of 2015 (of Transport, 5.11.2015/n.d.). Across all the states in the US, the most recent figures show an average fatality rate of 11.39 in road accidents per 100,000 population (IIHSHLDI, 2013/n.d.). Improving upon these statistics requires significant efforts such as: improving the automobile safety, improving the road infrastructure and imposing strict rules against the use of drugs during driving etc. Besides, various other factors have also contributed to the increasing rate of casualties over the years that includes a substantial growth of vehicles on roads, fatigue while driving, over speeding and distractions.

A study has shown that approximately 60 percent of the accidents could be avoided provided that drivers receive warnings earlier by a fraction as low as half a second (C. D. Wang

& Thompson, 1997). Therefore, the research industry and academia have recognised the use of technology as a co-pilot for the drivers. That is, technology can help facilitate a responsible reaction of a driver in response to a hazardous traffic scenario.

This perspective is corroborated by several initiatives taken up by the US and Europe. As a result, it has encouraged the motor industry to equip vehicles with the DSRC technology and on-board sensing units. According to a survey conducted by the Center for Automotive Research (CAR), all the public and private sector motor industries feel that by the year 2022-2025 DSRC will be the standard equipment in the new vehicles (Valerie Sathe et al., 2013). To achieve sustainable mobility by the year 2020, Europe has set the European ITS action plan called Horizon 2020 (European Commission & Innovation, 2011/n.d.). Among various objectives of this vision, reduction in the number of fatalities and reduction in the number of seriously injured passengers by 30% are considered most significant. Besides, the major focus of research in these initiatives for safe commuting is the Information and Communications Technology (ICT).

Considering the world-wide initiatives for safety on roads, finding solutions for the limitations of proposed technologies (such as DSRC) are critical for effective ITS. Therefore, by reducing the effects of technological limitations, we may soon experience services of a sustainable ITS with an aim to make traveling safer, comfortable and environmental friendly. This notion has motivated the work done in this thesis, which contributes by proposing adaptive beaconing designs to overcome technological limitations to achieve reliable communication for the ITS applications.

1.2 Problem Statement

As aforementioned, ITS application performance can be characterised by the transmission requirements of beacons such as a predefined periodic message frequency and a certain transmit power for the desired coverage. The rationale for carrying out this research lies in the recent findings of the difficulties in achieving the desired awareness quality and coverage of beacons. These difficulties are associated with the effects of beacon transmission on the shared wireless channel and the inflexibility of the DSRC standards for beaconing.

It is critical for the vehicles to transmit beacons using a high messages frequency to ensure high level of mutual awareness ("IEEE Standard for Information technology–Part 11 Wireless Access in Vehicular Environments", 2010). The shared wireless medium for beacon transmission is limited in bandwidth, and in large-scale ITS deployment, the amount of broadcast information (i.e., beacons) saturates the channel. As a result, vehicles experience high contention for the channel access, which causes erroneous transmissions and inappropriate coverage of beacon messages due to interferences (R. K. Schmidt, Kloiber, et al., 2011). Therefore, given a high message frequency requirement, it is a challenge to maintain an acceptable level of channel saturation and minimize erroneous transmissions without reducing the message frequency.

Another difficultly comes from the DSRC channel access mechanisms, which defines how vehicles contend for the access of a shared wireless channel and avoid collisions. It includes a random selection of waiting time from within a specified window before each vehicle can attempt to transmit. The DSRC standard only allows a collision free domain for a handful of vehicles due to its small contention window size. In addition, due to the inflexibility in the window size adaptation, synchronous collisions become inevitable even in a network of few vehicles.

These difficulties indicate that although the DSRC standard provides the foundations for communication for vehicular networks, the standard is not fully compliant with the communication requirements of vehicular applications. This perspective brings the ITS away from its design objectives in which reliable beacon delivery during due to channel saturation and synchronous collisions cannot be guaranteed.

1.3 Objectives

As aforementioned, the objective is to design new adaptive beaconing designs to control the high level of channel saturation and minimize beacon collisions among vehicles. In existing literature several beaconing approaches are proposed with a focus on the message frequency adaptation, transmit power and contention window adaptation, to name but a few (detailed survey of all the different techniques is given in Chapter 2). While the message frequency control techniques are disputed given the strict message frequency requirements of safety applications (Consortium et al., 2005), the transmit power adaptation and contention window size adaptation are considered sustainable parameters to adapt for beaconing. However, there are some challenges in the design of power control and contention window adaptation.

In the following, we list the objectives of this thesis in light of these challenges.

- 1. To review the advancements in beaconing approaches for VANETs.
- To design power control approaches for controlling congestion, wherein this is achieved;
 - a) By proposing fair power decrease mechanism for vehicles. Note that, for a power control design, it is critical to make adaptive decisions with the minimal use of feedbacks from neighbours and yet be able to effectively control congestion. Besides, the power adaptation should be fair among the vehicles, which is defined as a strategy of transmit power adaptation during the congestion control phase. We address this challenge through an adaptive power control design which requires minimal feedbacks during congestion. The proposed design achieves fairness in power adaptation through a game-theoretic approach in which the power decrease is based on the vehicle's marginal contribution towards congestion.

- b) By satisfying coverage requirement of applications. In large-scale ITS deployment, the 802.11p only allocates a 10 MHz channel for shared broadcast of beacons. It means that achieving transmission to the desired range is dependent on the channel state which changes according to the vehicular density. Therefore, rather than using a constant transmit power, the objective is to propose a power control strategy which takes into account multiple metrics to determine a transmit power for every beacon. The metrics include the quality of channel as depicted from the local information in recent past and in future. In addition, to ensure that the event-driven messages are transmitted reliably to a longer range than the periodic beacons, the design also distinguishes between message types to provide coverage differentiation. The objective is to constantly determine a suitable transmit power for beacons under varying levels of channel conditions for periodic beacons as well as for event-driven beacons.
- 3. To design contention window adaptation design in order to control overall beacon collisions in vehicular networks. A key challenge in beaconing design arises from the aggressive nature of the Binary Exponential Back-off (BEB) together with the minimum contention window size for the beacons as specified by the 802.11p. The 802.11p standard overlooks the channel conditions in order to adapt the window size after a successful beacon transmission. Therefore, given the minimum size of the contention window, synchronous collisions become inevitable among vehicles. The objective is to replace the BEB with a weighted contention window adaptation scheme, which is less aggressive in choosing the minimum contention window size to increase the contention window size as specified by the standard. Note that, increase in the



Figure 1.2: Traffic scenario requiring a highly reliable delivery of messages from the RSU to the vehicles approaching an intersection

default window size for beaconing may cause loss of beacons at the source. Thus, a provision to address the packet drops at the source is also included in the design.

- 4. To design a back-off selection mechanism in order to reduce collisions of beacons transmitted by a particular node/vehicle. Traffic scenarios are bound to change in a vehicular network. Accordingly, in most safety-critical scenarios (if not all) beacons from certain vehicles are considered more crucial than others. For instance in Figure 1.2, the vehicles require highly reliable message delivery from the RSU for accurate awareness about vehicles approaching the same intersection. Under these conditions providing reliable reception of beacons transmitted by a specific node cannot be guaranteed using 802.11p standard. Therefore, we propose a simple yet intuitive back-off selection design using the concept of pseudo-random number generator that provides reliable reception of beacons transmitted from a particular node.
- 5. To implement and evaluate the proposed beaconing designs using discrete-event simulations.

1.4 Research Methodology

The research methodology for the proposed beaconing designs consists of the following phases.

Review of Literature: This phase includes a comprehensive review of the developments in the field of adaptive beaconing from its initiation to the most recent proposals. The review qualitatively analyzes the problems addressed by different types of beaconing proposals. For instance, controlling congestion, minimizing beacon collisions and determining adequate message frequency, transmit power and contention window sizes to name but a few. Besides, the qualitative review includes a design based beaconing taxonomy, qualitative capability evaluation and comparison of beaconing approaches. As part of a comprehensive literature review, we analyse the design challenges for the proposed beaconing approaches in this thesis.

Design Modeling: The next phase includes design modeling of the beaconing approaches in Chapter 3 and Chapter 4. The Chapter 3 includes the design of two power control approaches. The design of the first beaconing approach is based on a game-theoretic approach with a focus on fair power adaptation during congestion. The second beaconing approach is designed with a localized approach to adapt transmit power for periodic beacons and event-driven beacons. Chapter 4 includes the design of beaconing approaches by taking into account the standard contention window size and the back-off selection mechanism. The design methodology discusses all the details of the proposed beaconing approaches which include assumptions, system models and algorithms.

Implementation: Due to the cost associated with the real VANET testbeds, the popular choice for preliminary deployment and testing of various proposals is to use simulation tools. The proposed beaconing approaches are implemented in OMNeT++ 4.2.2 and the mobility traces are generated using SUMO 0.17.1. The implementation includes modifications at the application layer and the MAC layer while some information is also used from the Physical Layer. Due to the nature of the beaconing designs, a cross-layer interaction at different layers is used during the implementation.

Performance Evaluation: Initially, during the performance evaluation the behavior of the proposed beaconing approaches is verified according to their design methodology using simulation traces. Afterwards, different simulation scenarios are used to evaluate the performance of beaconing designs along the axes of metrics such as message reception rates, collision rates and reliability etc.

CHAPTER Background This chapter proposes the design of two HAPTER power control approaches. It includes the An introduction to the anatomy of beaconing system model, formulation and functional strategies is provided. The design based details of the proposed algorithms, Fransmit Power Control taxonomy and key observations about each Designs for Periodic Beacons category of beaconing are discussed. Capability evaluations of the beaconing approaches are CHAPTER Adapting Contention given. Finally, challenges and requirements for This chapter includes performance Windows and Predicting the proposed beaconing designs in this thesis are evaluation of the proposed beaconing **Back-offs for Reliable** discussed. designs. OMNeT++ simulation plattform Beaconing is used for design implementation and the results are analysed. rformance Evaluation CHAPTER 4 This chapter proposes modifications in MAC CHAPTER 6 layer of the DSRC with an aim to enhance This thesis concludes with review of reliability by reducing beacon collisions. It proposed adaptive beaconing designs and includes the functional details of the proposed contributions. Also, possible extension of designs algorithms the work presented in this thesis is explained.

Figure 1.3: Thesis Layout Representation

1.5 Thesis Layout

This thesis is organised as follows: first, necessary background information on beaconing techniques is provided and the thesis scope is defined; in the following two chapters adaptive beaconing designs are proposed, each chapter focusing on a separate set of strategies. Performance evaluation is conducted using simulations and the acquired results are analysed in the next chapter. The thesis ends with the conclusion by highlighting main results, contributions and possible extension to the work presented in this thesis. The Figure 1.3 details this organisation:

2.1 Introduction

Recent analysis on beacon transmission indicates that existing standards in beaconing restrict the performance of vehicular applications (He et al., 2010), (W. Guan et al., 2011). Essentially, for constant message frequency, the limited wireless bandwidth causes loss and erroneous beacon reception under high-density networks. As aforementioned, the standards for periodic beaconing are designed to be inline with the spontaneous mobile ad hoc communication requirements, which do not necessarily conform to the communication requirements of vehicular safety applications. That is, during high message frequency transmissions by safety applications, channel saturation and loss of messages cannot be addressed by the beaconing standards alone (Jabbarpour et al., 2014). This situation calls for adaptive beaconing approaches that can efficiently utilize the wireless channel and provide reliable vehicular communications.

Despite the vast number of proposals, only a few surveys exist on beaconing approaches (Sepulcre et al., 2011), (Willke et al., 2009), (Ghafoor et al., 2013). The study in (Sepulcre et al., 2011) classified adaptive beaconing as means for controlling congestion and improving neighbor awareness by surveying a few beaconing approaches. Another study in (Willke et al., 2009), classified safety and non-safety applications to discuss inter-vehicle communication protocols, which also included multicast and broadcast. A recent survey also summarized salient features of beaconing approaches (Ghafoor et al., 2013) along with some simulation results. The background in this chapter aims to provide a comprehensive survey of the developments in the area of adaptive beaconing from its initiation to the most recent proposals. Moreover, the chapter is designed to be comprehensible for the readers even outside the specialty of the topic. Therefore, we have

used a qualitative approach to conduct a survey on adaptive beaconing approaches, which provides discussions on the important concepts without putting complicated results into the context. The key contributions are listed as follows.

2.2 Contributions

- We describe the anatomy of beaconing through a schematic layered illustration and multi-channel communication perspective.
- We list the key performance requirements of beaconing and elaborate the beaconing design with respect to the information required by the beaconing approaches.
- With the aim of classifying beaconing approaches, we introduce a design-based taxonomy.
- We survey the salient features of a number of beaconing approaches and highlight the key observations about each category of the beaconing approach.
- We qualitatively evaluate the capabilities of beaconing approaches using important parameters.
- We explore the architectural characteristics to further classify and compare the beaconing approaches.
- Finally, we briefly analyze the problems addressed in the subsequent thesis.

2.3 Anatomy of Beaconing

Here, we describe the layered illustration and multi-channel communication perspective of the IEEE 802.11p for beaconing ("IEEE Standard for Information technology–Part 11 Wireless Access in Vehicular Environments", 2010).



Figure 2.1: (a) Schematic layered Illustration of Beaconing in Vehicular ad hoc Networks, (b) Transmitter and Receiver perspective of information flow

2.3.1 Schematic Layered Illustration of Beaconing

The European Telecommunications Standards Institute (ETSI) (E. ETSI, n.d.) and IEEE Wireless Access for Vehicular Environments (WAVE) (Uzcategui & Acosta-Marum, 2009), ("IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services", 2010) have conceived the necessary layered architecture for vehicular application communication. In Figure 2.1(a), we show a schematic illustration of this layered architecture, which does not necessarily correspond to the actual standard; rather, it highlights only the noteworthy aspects involved in beaconing. The flow of beacons is also illustrated with respect to the transmitter and the receiver in Figure 2.1(b).

The beacons in VANETs provide the actual services for the safety and non-safety applications. However, upon close examination, it can be observed that the scope of the required information for vehicular applications is limited to sensor inputs, vehicular speeds and longitudinal and lateral dynamics, to name but a few. Accordingly, there exists an additional facilities layer/Message sub-layer. The role of this layer is to maintain a local topology image encompassing neighbor vehicles and to communicate with the application layer, which in-turn informs the driver assistance system to generate warnings
and message alerts. Two types of messages are used for this purpose: 1) periodic beacons for neighbor localization, and 2) event-driven messages to inform neighbors about a potential hazard. It should be noticed that beacon transmission is broadcast and vehicles may receive messages not intended for them. Therefore, this layer is also responsible for dropping irrelevant messages through message filtration. The inconsistency estimator is critical in identifying variations in the desired accuracy of the local topology image and in the longitudinal and lateral dynamics of the vehicle itself. The other type of messages is the Wireless Service Advertisements (WSAs), which are used to advertise non-safety application services by the service providers.

Regardless of the type of message, the efficient periodic beacon dissemination is governed by the choice of certain parameters, such as message frequency and transmission power along with several MAC/PHY layer parameters. Indeed, the choice for adapting these parameters can be based upon the traffic context and application-specific context. As such, the Dedicated Short Range Communication (DSRC) control block specifies how message frequencies and transmission powers are adapted, while the MAC/PHY control block allows the adaptation of contention windows, and data-rates to name but a few. Also, in order to avoid channel saturation in the wireless medium, the distributed congestion control block specifies congestion control strategies based on the open-loop and close-loop control theory approaches. After fine-tuning of the transmission parameters at the DSRC control block, the beacons are then disseminated on the shared wireless medium. Next, we examine the details involved in multi-channel beacon transmissions.

2.3.2 Multichannel Communications

To avoid the complexities of channel association and to provide spontaneous wireless access, IEEE 802.11p is specified as a multi-channel access mechanism for VANETs. It is based on 802.11x Wireless Local Area Network (WLAN) standard. Unlike WLAN, the



Figure 2.2: Single and dual radio configurations for beaconing: (a) IEEE WAVE radio configuration options (b) ETSI radio configuration options

802.11p distributes its services across two types of channels ("IEEE Standard for Wireless Access in Vehicular Environments (WAVE)–Multi-channel Operation", 2011): 1) control channel (CCH) and 2) service channel (SCH). The periodic beacons are transmitted with a high frequency on the CCH. In addition, providers also advertise the non-safety applications on the CCH. In response to the non-safety advertisements, users can switch to a SCH to access a service. It implies that vehicles are bound to tune their radios to a desired channel for a particular service.

Figure 2.2 illustrates radio configurations for channel switching using single and dual radios (Campolo & Molinaro, 2013). The IEEE WAVE has one CCH and six SCHs with four different configurations as shown in Figure 2.2(a). The W1 configuration requires a radio to permanently tune to the CCH. The W2 configuration requires the radio to switch between the CCH and SCH. In W3, the radio can switch between the available SCH but cannot access the CCH. In W4, the radio is permanently tuned to the CCH and cannot access any SCH. It should be noted that W3 and W4 configurations require dual radio setup to access both safety and non-safety services. A single radio tuned in W4 requires the second radio in W2 configuration. A radio tuned in W3 can have another radio which is tuned in configuration W1 or W2. Figure 2.2(b) shows the radio configurations in the ETSI standard for one CCH and four SCHs. The T1 configuration permanently tunes

Information category	Beaconing load	Application diversity	Fairness	Reliability
App. Requirement	_	_	Direct	Direct
Network state	Direct	-	Direct	Indirect
Traffic scenario	Direct	-	_	_
Mixed	Co	ombination of above		

Table 2.1: Impact of gathered information from different information sources

the radio to the CCH. The configurations in T2 and T3 are used to access any SCH with mandatory tuning to the CCH. During congestion, the ETSI also allows service advertisements on the SCH1.

To provide service differentiation, these standards allow classification of messages by using Enhanced Distributed Coordinated Access (EDCA) of 802.11e ("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", 2012). According to EDCA, contention window sizes are assigned to different traffic categories. High-priority data gets lower contention windows and vice verse. In addition, the default data rate for beaconing is defined as 6 Mbps (Jiang et al., 2008).

2.4 Performance Requirements and Beaconing Design

This section discusses the desired performance requirements and the subsequent design of adaptive beaconing approaches.

2.4.1 Performances Requirements

The following performance requirements are desirable for beaconing approaches: 1) reduced beaconing load, 2) application diversity, 3) fairness in beacon transmission, and 4) reliable beacon delivery.

2.4.1.1 Reduced Beaconing Load

Beaconing load on the control channel indicates the state of channel occupancy. During the state of high occupancy, otherwise known as congestion, the vehicular applications scale poorly. For instance, beaconing load for dense networks can affect application performance due to higher latency in acquiring neighbor awareness. To manage the state of channel occupancy, beaconing approaches must adapt according to the vehicular density, channel states and Bit Error Rates (BERs) etc. Possible mechanisms to reduce load includes 1) the use of position prediction algorithms, and 2) reduction in transmission power. The former avoids unnecessary beacons by predicting the vehicle positions based on their previously received positions, while the latter restricts the transmission range to minimize beaconing load. It should be noted that it is undesirable to use feedbacks for beacons which have marginal temporal validity.

2.4.1.2 Application Diversity

Vehicular networks have the capability to host safety applications (T. ETSI, 2009a), (Gabbard et al., 2014), (Sepulcre et al., 2013) as well as non-safety applications (Céspedes et al., 2013). These applications have diverse requirements for beacon dissemination and awareness levels. For instance, beacon dissemination for safety applications are delay-sensitive, while non-safety applications (Liu et al., 2013), (Ota et al., 2015), (Ota et al., 2014), (Zhang et al., 2011), (K. Yang et al., 2007) can tolerate a certain level of delay. Therefore, application diversity of a beaconing approach indicates the ability to satisfy different application requirements.

2.4.1.3 Fairness in Beacon Transmission

The consistency in mobility and communication patterns are pertinent to vehicular networks. Consequently, vehicles have different views about their respective topologies and the state of channel occupancy. Under these conditions, for a beaconing approach to be fair, it must perceive the views of neighbors before adapting a transmission behavior. In other words, the adaptive transmissions from one vehicle should not affect transmissions from its neighbors. As an example, consider a vehicle experiencing low channel occupancy, which subsequently increase its message frequency. However, beaconing approach with fairness criterion demands that frequency increase should not cause a state of congestion in neighbors and force them to use a lower message frequency. Similarly, an increase in transmission power is known to decrease the message reception probability of nearby neighbors (Schmidt-Eisenlohr et al., 2007). Therefore, power adaption must be fair across vehicles within a transmission range. Implementing fairness requires information sharing among vehicles about their views of the topology and network states.

2.4.1.4 Reliable Beacon delivery

A critical objective of adaptive beaconing for safety applications is the reliable delivery of beacons in a timely manner. Note that, the beaconing approaches do not use acknowledgments to indicate beacon reception. Therefore, reliability must be provided through different adaptive approaches such as message prioritization, increasing message frequency and transmission power etc. Providing reliable delivery of safety-critical data may violate fairness criterion at some vehicles, therefore an appropriate choice for measuring reliability is to use application-centric metrics such as Time-Window Reliability (T-WR) and driver's reaction time to name but a few.

2.4.2 Design of Adaptive Beaconing Approaches

Two aspects govern the design of beaconing approaches: 1) the information used as input by the adaptive beaconing approach, and 2) the subsequent choice of the control mechanism for beacon transmission. Here, we restrict our discussion to the concepts and categories of the information used as input for the adaptive beaconing. Table 1 lists the impact of the type of information on the system performance requirements.

2.4.2.1 Application Requirements

Application requirements indicates the transmission requirements of beacons for correct operation of vehicular applications. Based on these requirements, the MAC layer can adapt the beacon transmission accordingly. For instance, in ETSI, the facilities layer can specify strict temporal requirement for the MAC to transmit beacons with prioritized access using 802.11e. The application requirement has a direct impact on the fairness and reliability. Reliability results in improved reaction time for the drivers in a hazardous road condition e.g., through prioritized delivery of a collision avoidance message.

2.4.2.2 Network State

Network state specifies the locally computed performance metrics of the wireless channels. It includes Channel Busy Ratios (CBR), bit error rates (BER) and interference levels, to name but a few. Most of the approaches depend on these metrics to cope with the scarce channel resources. It follows that, using network state has a direct impact on the beaconing load and fairness. With the capability of sharing the network states with neighbors, the secondary impact can be specified in terms of improved reliability.

2.4.2.3 Traffic Scenario

Traffic situation corresponds to the one of the defined safety scenarios in (T. ETSI, 2009a). To detect a traffic scenario, a vehicle constantly monitors the status of neighbors and road conditions (R. Schmidt et al., 2010). Specifically, the vehicle yaw rates, intersection crossings, overtaking maneuvers and roads with merging locations etc. Variations in a traffic situation directly impacts the beaconing load required for a certain level of awareness. For instance, a high speed vehicle approaching an intersection needs a higher message frequency and hence a high beaconing load (Gozalvez & Sepulcre, 2007).



Figure 2.3: Design-based Taxonomy of adaptive beaconing approaches

2.4.2.4 Mixed

The discussed information categories can be used in different combinations for a multi-objective beaconing approach. As an example, reduced beaconing load and reliability requires network state as well as application information in order to maintain CCH saturation and to provide timely delivery of beacons (R. Schmidt et al., 2010).

2.5 Design-based Taxonomy

The design of beaconing approaches can be classified into 1) Beaconing category, 2) Information dependency and 3) Objective function as shown in Figure 2.3. Each design element is discussed in the following.

2.5.1 Beaconing Category

Beaconing category classifies the response by a beaconing approach to the acquired information. The four beaconing categories include: 1) Message frequency control (MFC), 2) transmit power control (TPC), 3) Miscellaneous and 4) hybrid.

With message frequency control, vehicles adapt the frequency for beacon transmission. The aim is to improve CCH utilization for a variety of objective functions. For instance, lower frequency reduces CCH load and helps achieve a higher probability of beacon reception. Similarly, a higher frequency can be used to guarantee message delivery in an intersection collision warning system (Gozalvez & Sepulcre, 2007).

Transmit power control is primarily used as a topology control mechanism. The TPC approaches share similar objective functions with the MFC. Additionally, efficient TPC increases the throughput, coverage area of the transmitter (Narayanaswamy et al., 2002) and the reception probability for specific regions (Gupta & Kumar, 2000).

More recently, researchers have started focusing on the multi-channel switching aspects of 802.11p for adaptive beaconing. We refer to these aspects as Miscellaneous, which includes adaptation of contention window size, physical data rates and de-synchronization of transmission intervals etc.

Hybrid control specifies the combination of MFC, TPC, and miscellaneous approaches. The aim is to exploit the strengths offered by different approaches. For instance, given the fundamental bounds of wireless networks, transmission rate and power must be adapted to efficiently utilize shared channels. In VANETs, this notion is relevant and may be utilized according to the context and desired objectives. Such as, transmit rate can be adapted according to the traffic context while power can be adjusted for higher informationpenetration.

2.5.2 Information Dependency

The beaconing approaches can also be classified by examining the information required by a beaconing approach for decision making. This information represents 1) situation, 2) communication feature and 3) hybrid.

The first category indicates the traffic situation. That is, at a particular time, the

vehicular network represents a unique traffic situation. It further implies that, the traffic information is diverse and can be classified as microscopic, macroscopic and selfsituation. Microscopic information refers to the exact traffic scenarios as specified by ETSI (T. ETSI, 2009a). On the other hand, macroscopic information describes an overall traffic situation such as vehicular density i.e., high or low. Finally, self-situation represents the variations in the movement of a vehicle itself.

Communication feature specifies the transmission characteristics. For example, CBR, clear channel assessment reports, interference levels and packet collision etc. It follows that this information can be differentiated as: 1) localized and, 2) generalized. The former specifies local computations of transmission characteristics, while the latter specifies local as well as acquired statistics from the neighbors.

The hybrid category is more diverse and uses a combination of traffic related information and communication information.

2.5.3 Objective Functions

The objectives of beaconing can be system-specific or application-specific. Systemspecific objectives include performance improvement in the quality of transmission. For instance, reducing the channel load on CCH, managing packet drops and controlling collisions during transmission. System-specific objectives require localized or generalized communication information.

On the other hand, application-specific objectives aim at enhancing safety application performance. For instance, rapid event detection, fairness in channel access, higher degree of awareness, prioritization of critical event-driven messages and message delivery within strict time constraints.

2.6 Survey of Adaptive Beaconing Approaches

Here, we survey the most important beaconing approaches in existing literature. Subsequent to the survey of each beaconing category, we provide a discussion on the advantages and disadvantages and summarize it in Table 2.2.

2.6.1 Message Frequency Control Approaches

With message frequency control (MFC), vehicles adapt the frequency for beacon dissemination. In this section, we survey the most noteworthy MFC proposals in literature.

2.6.1.1 MFC based on traffic situation

The most common criterion for adapting message frequency is the surrounding traffic situation. As such, the MFC approach in (R. Schmidt et al., 2010), studied the vehicular density and speed for message frequency adaption. The authors proposed to adapt message frequency based on a vehicle's own movement or based on the surrounding situation. A vehicle's own movement includes speed and yaw rates along with special vehicles that need prioritized access to the road lane. Any of these conditions require a higher message frequency. By contrast, congestion is deemed more significant than awareness in high-density networks because of the high probability of beacon collisions. Therefore, the study proposed to reduce the frequency based on vehicular density to reduce congestion and maintain an acceptable level of awareness.

2.6.1.2 MFC based on position prediction

The MFC approaches in (Boukerche et al., 2009) and (Rezaei et al., 2007) proposed to use a vehicle position prediction model for adapting the message frequency. The basic motivation is to reduce congestion by minimizing unnecessary beacon transmissions.

The MFC approach in (Boukerche et al., 2009) models position prediction by exploiting the information in the received beacon. That is, after receiving a beacon from the neighbor, the receiving vehicle starts predicting the neighbor's position for a specified time. In the meantime, beacons are sent to the predicted neighbor position. The position is updated upon the reception of a new beacon from the same neighbor.

Similarly, the position prediction in (Rezaei et al., 2007), is based on the Kalman filter for distributed position estimation logic. It means that after advertising a beacon, the vehicle calculates its own position in the near future that replicates the estimated position at the neighbor vehicle. Therefore, using the errors in position, the vehicles adjust their message frequency.

2.6.1.3 MFC based on fairness

Fairness in adapting message frequency is critical and requires cooperation among vehicles. The approaches proposed in (Tielert et al., 2011) and (He et al., 2010) provide fairness with respect to the periodic beacons and the event-driven messages.

The approach in (He et al., 2010), and (W. Guan et al., 2011) uses high channel occupancy as an indicator for high congestion. Therefore, during congestion, a vehicle informs the neighbors about its state. Upon reception of this message, all vehicles co-operate by blocking the transmission of periodic beacons to allow the transmission of potential event-driven messages. Moreover, in response to the message, vehicles adapt the message frequency by using the concept of additive increase and multiplicative decrease. This approach implies that the message frequency is initially increased by one message per second and reduced by half if congestion occurs.

Similarly, periodically updated load-sensitive adaptive rate control (PULSAR) (Tielert et al., 2011) adapts message frequency by considering the vehicles that cause congestion within the carrier sense range. For a specified time interval, a vehicle monitors the CBR and listens to the CBR advertised by the neighbors. Thus, the adapted message frequency maintains an acceptable CBR level to provide highly probable transmission of eventdriven messages. Moreover, the feedback helps in identifying vehicles that contribute more to the congestion. As a result, the transmission rate of such vehicles is reduced.

2.6.1.4 MFC for overtaking assistance

An important consideration in adaptive MFC is the performance of safety applications. The approach in (Bohm et al., 2011) defines two types of vehicles: leading and regular vehicles. Unlike regular vehicles, the leading vehicle has no neighbors in front. Therefore, to enable safe overtaking maneuver by regular vehicles, the leading vehicle monitors and reports the presence of oncoming traffic. For reliable reporting, this information is transmitted by using event-driven messages at a higher message frequency than the normal vehicles.

2.6.2 MFC for non-safety applications

Non-safety applications may also benefit from message frequency adaptation. The approach in (Sommer et al., 2011) uses beacons to transmit Traffic Information Systems (TIS) data (Ota et al., 2011). The main objective is to provide high event-penetration ratio without using flooding. To reduce the channel load, message frequency is adapted based on two pieces of information: 1) the distance of the vehicle that generates the TIS data to the event and 2) the age of the disseminated message that specifies the information freshness. It also uses communication-driven information that includes 1) the number of collisions, 2) the signal-to-noise ratio, and 3) the number of received beacons. To ensure that rate adaption is inclined toward congested channels and collisions, communication-driven parameters are weighted more than the distance to the event and message age parameters. This situation implies that the highest transmission rate is selected if the TIS data is fresh and the channel usage is minimal. Otherwise, the transmission rate is optimized to meet the dissemination requirement of the data while keeping the channel load at a minimum.

The beaconing approach in (Schwartz et al., 2014) controls the frequency of beacons for efficient bandwidth utilization. In addition, the approach introduces a fair data selection mechanism such that the most significant messages receive high priority for transmission. This condition is achieved by identifying vehicle interests in the data and then distributing that interest among the neighbors. Moreover, to efficiently utilize the channel, message frequency is controlled by considering parameters such as data age, distance to the destination/roadside unit, history of message reception, and vehicular interest in data.

Discussion The literature surveyed in this section showed that message frequency adaptation improves channel utilization, awareness levels, and application performance. A key observation on MFC for safety applications originates from the strict message frequency requirements as specified in (Consortium et al., 2005), wherein most safety applications require at least 10 Hz and up to 50 Hz message frequency for transmitting beacons. On the downside, the use of communication parameters for message frequency adaptation is disputed, particularly when message frequency adaptation depends on position prediction (Rezaei et al., 2007), (Rezaei et al., 2008). Therefore, a significant challenge in the evaluation of MFC approaches is to report the extent up to which a safety application can tolerate the reduction in message frequency if used for safety applications.

2.6.3 Transmit Power Control Approaches

Transmit Power Control (TPC) defines variation in the transmission power for beacon dissemination. In this section, we survey the TPC approaches proposed in (Torrent-Moreno et al., 2009), (Mittag et al., 2009), (Kloiber et al., 2012), (X. Guan et al., 2007) for VANETs.

2.6.3.1 TPC based on fairness

For constant message frequency, the authors in (Torrent-Moreno et al., 2009) defined the congested region as the one with the maximum number of interfering interference ranges. The motivation of the proposed TPC is to provide strict fairness in the transmit power through cooperation. The approach works in two phases. In the first phase, a vehicle collects information about the power levels of the neighbors. The vehicle then calculates a power value, which is the maximum common value among the received power values. In the second phase, the calculated power value is advertised. This step ensures that the locally computed power level does not violate the congestion requirement of the neighbors. Finally, upon reception of the calculated power values, the vehicle selects the minimum power level to transmit.

2.6.3.2 TPC with random power level

In highways, vehicles have a tendency to form clusters because of minimum relative speed variations. Under this scenario, beacon collisions are recurring. As such, the approach in (Kloiber et al., 2012) proposes random transmit powers to reduce recurring collisions to increase neighbor awareness. To ensure fairness in power selection, all vehicles randomly select transmit powers by using a common mean and variance. The mean power level enables the vehicles to maintain a higher awareness of close-by neighbors. Furthermore, it reduces the overall congestion by transmitting less at longer distances.

2.6.3.3 TPC for spatial reuse

Power adaption can be used to optimize the spatial reuse and to provide transmission over long distances. The TPC in (Mittag et al., 2009) provides spatial reuse by reducing the transmit power for beaconing. Initially, a beacon is transmitted by using a low power level. It is followed by the retransmission phase, which also provides a simple form of information aggregation, that is, along with the received beacon, the relay also transmits self-information. To retain information freshness and to avoid delays in the multihop transmission, the retransmission is scheduled on selected relays.

2.6.3.4 TPC based on feedback

The authors in (X. Guan et al., 2007) proposed an application-based power control using feedback. The motivation was to transmit safety messages with enough power level to cover a desired range with no excessive coverage. The initial transmit power for beacons is assigned with respect to the coverage required by an application. Each vehicle then maintains a speaker list, which contains neighbors whose power level exceeds the desired coverage. A feedback message is used to notify the speaker list about their high transmit power levels. Therefore, neighbors whose addresses are included in the feedback reduce their transmit power.

Discussion The performance gains of adapting the transmit power depend on the vehicular scenario. That is, number of vehicles on the road (sparse or dense), and the safety application requirements. A higher transmit power enables communication with distant vehicles in the sparse networks. However, transmitting beacons at high power produces congestion in the dense networks, which indicates that fairness in power adaptation is crucial. However, a trade-off between the extra beaconing load and fairness in the assigned power levels exists through cooperation (Torrent-Moreno et al., 2009) or feedback (X. Guan et al., 2007). The propagation effects on the choice of power levels are also crucial, especially when selecting a lower transmit power. A lower transmit power is susceptible to shadowing or fast fading. Moreover, the reduction in transmit power also causes synchronous collisions (mainly due to the same back-off selection at the MAC layer) closer to the vehicle (Stanica et al., 2012).



Figure 2.4: Illustration of the access mechanism using contentions and back-offs

2.6.4 Miscellaneous Approaches

Miscellaneous approaches use a variety of parameters for the adaptation of beaconing as shown in Figure 2.4. These parameters specify intricate details of the MAC layer transmission. Therefore, we briefly study these parameters before proceeding with the survey.

The distributed inter-frame space (DIFS) is a time interval for a vehicle to wait before transmission. Note that, the Short Inter-frame Space (SIFS) precedes the DIFS and it represents the collective time required to process a received frame and a subsequent response frame. Before transmission, if the medium is sensed idle for the duration of DIFS, the vehicle starts transmitting. Otherwise, the vehicle enters a contention period by choosing a back-off. Upon the expiry of the contention period, the vehicle can start transmitting if other vehicles have selected higher back-off values. If a vehicle still finds the channel busy then as part of Binary Exponential Back-off (BEB), the contention window size is increased for the next transmission attempt. The rate of beacon transmission is specified through the data rate to effectively utilize link throughput. Another parameter is the guard interval, which is a 4 msec timer between the CCH and SCH interval. During this interval, the channel is advertised as busy to restrict transmission. In the following, we survey some of the important beaconing approaches in this category.

2.6.4.1 Desynchronized beacon transmissions

A stochastic model for non-deterministic channel switching and its effect are introduced in (Settawatcharawanit et al., 2012) with an aim of reducing collisions. The approach monitors the beacon firing intervals used by the neighbors. Then, a vehicle selects a distinct firing interval for beacon transmission. In addition, to minimize the probability of converging at the same firing interval, it uses random back-off before transmitting at the selected firing interval. It also has a provision for a network having different periodic transmission intervals, that is, vehicles can report their transmission time periods to each other. In this way, any vehicle that receives a beacon sets its own time period, which is in multiples of the received time period. This approach allows adaptability for vehicles having shorter transmission intervals with those having longer transmission intervals.

More recently in (Park & Kim, 2013), the authors proposed an application-based mechanism to reduce MAC layer collisions. At the application layer, they proposed the intuition of replicating the CCH interval with consecutive 1 ms epochs. Vehicles keep track of the epochs used by the neighbors in the previous time interval. To avoid possible collisions, a vehicle uses an underutilized epoch. In situations where all the epochs are utilized, a random epoch is selected for beacon transmission.

2.6.4.2 Adapting physical data rate

In VANETs, the link quality changes due to fading and mobility. Therefore, an accurate estimate of bit rate adaptation is required to effectively utilize the link throughput with respect to the link quality.

To gain maximum utilization of the link, the approach in (Shankar et al., 2008) proposes an estimation of the data rate for transmission. It exploits the local information for rate adaption without constant probing of the link. As a result, this approach induces minimum delays in rate adaption. With the ability to exploit local information, faulty data rate selection at the beginning of the bursty traffic could be avoided. Data rate estimation is based on two types of functions. The first uses the current context, that is, the local topology, current data rate, and the packet size to estimate packet error. The second function uses previous statistics on the bit rates as exponentially weighted moving averages. The estimation of packet error in the first function for beacon dissemination is based on an empirical model, which uses multivariate linear regression on the measurements obtained from real test beds. For high-speed vehicular networks, data rate estimation using the context is given higher preference over the estimates of previous statistics on the bit rate.

The objective of beaconing approach in (Campolo et al., 2012) is to avoid synchronized collisions at the beginning of the channel interval and to minimize packet drops before the end of the control channel interval. The solution is based on two observations: 1) the beacons can collide due to same back-off selection by different vehicles at the start of a channel interval and 2) a packet may be dropped if the required transmission time for the packet exceeds the available transmission time of the channel interval. To handle the first observation, a longer contention window is proposed, which brings diversity in the slot selection and higher variation in the selection of waiting times before transmission. Nevertheless, this approach reduces the interval for the transmission of beacons and a higher probability of packet drops before transmission. Therefore, the approach introduces a higher data rate. Before transmitting at higher data rates, the delivery probability is calculated for an assured reception.

2.6.4.3 Adapting contention window

In the 802.11p standard, beacons are transmitted with the access category (AC) IV. Due to short temporal validity of beacons the minimum contention window size of AC-VI is kept small. Recent studies have shown that the minimum window size of AC-VI is the main cause of beacon collisions. Here, we discuss recent solutions in handling collisions through contention window adaptation.

The approach in (Di Felice et al., 2012) avoids synchronous CCH collisions and addresses packet drops before transmission. The beaconing approach augments the exponential random back-off with slot utilization estimation. Slot utilization is based on the 1) current slot utilization, which is the average of busy slots to the number of available slots, and 2) previous values of slot utilization. After expiry of the back-off, the beacon transmission proceeds if the probability of successful transmission based on the available slot is sufficient. Otherwise, the beacon is dropped. Deferring beacon transmission due to increased contention window can compromise certain vehicles. Therefore, to enable fairness in packet drops across vehicles, a weighted probability of beacon transmission is calculated, which is based on the number of un-transmitted beacons and the number of transmission attempts for a beacon.

A related problem with the adaptation of contention window is the aggressive selection of back-off under normal conditions. In (Stanica et al., 2014), the authors investigated the effect of contention window under various vehicular densities. Their contribution can be divided into two parts: 1) An analytical framework, which models the behavior of IEEE 802.11p MAC protocol, where the authors show that the broadcast nature of the safety messages affect the optimal value of the contention window. That is, a larger contention window is desired for high-density networks. Moreover, the contention window adaptation should aim to balance out the collisions and expired messages at the source. 2) A unique reverse back-off proposal, in which the initial contention window is set to a higher value. Then, based on the expired message, the window is reduced to half and vice versa for successful transmission.

2.6.4.4 Beaconing based on carrier sense Threthold

In multi-channel access, before transmission, the carrier is sensed to conclude a free or occupied channel. A high threshold suggests that the radio is less sensitive to transmission from the neighbors and vice versa.

R. K. Schmidt et al. (R. K. Schmidt, Brakemeier, et al., 2011), presented a stepwise clear channel assignment threshold adaptation for beaconing. The adaptation mechanism is based on the current waiting time of a beacon in a queue. That is, when a beacon arrives at t0, the default value is assigned to the clear channel assessment threshold. If the beacon stays in the queue after time t1, the threshold is incremented with an offset. After increasing the threshold, the clear channel assessment is carried out immediately. If the channel is found busy at time t2, the threshold is increased again. Finally, the procedure ends if the message is dropped or sent. Furthermore, the approach is capable of assigning priority to different types of messages. It also proposes the use of a traffic-shaping mechanism by employing a mechanism similar to the token bucket scheme to regulate bursty traffic.

The authors in (Yoo, 2013) proposed a receiver-initiated MAC protocol (RIMAC) for efficient spatial reuse. Unlike sender-oriented approaches, RIMAC allows the receiver to initiate transmission from the sender. The intuition follows from the fact that a sender cannot accurately sense the channel states of the receiver. Therefore, the effectiveness of both physical and virtual carrier sensing is employed in RIMAC. The receiver initiates the transmission by sending a short message that serves two purposes: 1) initiate transmission at the sender and 2) serve as a virtual carrier sense for vehicles besides the sender. To avoid collision, physical carrier sense is used before transmitting the request to the sender. On the contrary, virtual carrier sensing allows the receiver to identify any existing request made by other vehicles. If detected, the transmission is delayed until the channel becomes free.

Discussion We draw significant observations about the beaconing approaches in this category. Several studies have analyzed data rate adaptation beyond 6 Mbps by using simulations (Jiang et al., 2008) and real testbeds (Bai et al., 2010), (Camp & Knightly, 2010). In the context of achieving higher packet delivery ratio, 6 Mbps is the optimum choice according to (Jiang et al., 2008) and (Bai et al., 2010). The intuition for this differentiation is the difference between the modulation schemes (Bai et al., 2010). Therefore, quadrature amplitude modulation (16 QAM) used for 18 Mbps has a higher sensitivity to noise than the quadrature phase-shift keying used for 12 Mbps. As for the contention window adaptation, previous studies (Reinders et al., 2011) concluded that an increase in the contention window has no effect on the beaconing performance. However, recent studies (Di Felice et al., 2012) and (Stanica et al., 2014) have shown that during high contention, the size of the contention window could be modified for performance gains. However, the trade-offs of the contention window adaptation design must be considered based on the objectives of adaptive beaconing. As an example, the choice of higher contention window increases the probability of dropped beacons at the source. On the contrary, an increased contention window may also help to reduce synchronous collisions that occur because of the same back-off selection. Note that, the carrier sense threshold is a hardware-specific parameter. Therefore, only a few proposals have been presented for beaconing that exploits carrier sense threshold.

2.6.5 Hybrid Control Approaches

Hybrid control approaches specify the combination of MFC, TPC and miscellaneous approaches. This section surveys hybrid approaches in (Lasowski & Linnhoff-Popien, 2012), (Huang et al., 2010), (Huang et al., 2011), (Sepulcre et al., 2010), and(Gozalvez & Sepulcre, 2007).

	Table 2.2: Key ob	servations about surveyed beaconing approaches
Approach	Idea/Parameters for Adaption	Key observations
Message Frequency Control (MFC)	-Message frequency -Situation prediction -Fairness -Safety application specific -Non-safety applica- tion specific	-Message frequency adaption is disputed in context of stringent frequency requirements of safety applications -Control mechanisms for position prediction lack timely predic- tion of potential hazardous situations -Evaluation of tolerable extent up-to which frequency could be adapted for safety applications is a challenge
Transmissio Power Control (TPC)	-Fairness in power allocation -Random transmit powers -Spatial reuse -Exact transmission range	-A trade-off exists between fair power allocation and high bea- coning load -Power reduction requires consideration for propagation effects i.e., shadowing/fading -Reduced transmit power brings synchronous collision close to the critical safety range specified by the application -Unfair power allocation may cause low reception probabilities for vehicles at close range
Miscellanec (Misc)	-Desynchronized transmissions -Physical data-rate adaption -Contention window adaption -Carrier-sense thresh- olds based beaconing	-For higher PDR, data-rates beyond 6 Mbps is not beneficial due to sensitivity of modulation schemes to noise -Increase in contention window increases the probability of bea- cons being dropped at the source -Increase in contention window also helps in selection of different back-offs, hence reduced probability of collisions -Being hardware-specific parameter, the carrier-sense threshold has very few proposals
Hybrid	-Combination of above	-Useful for highly specialized vehicular scenarios with hard QoS requirements -Allows flexibility in choice of adaption parameters

eaconing approaches
ã,
ă
Ň
é.
5
\mathbf{v}
Ħ
б
ã,
ч
observations
N
°.
\mathbf{X}
•••
Ч.
N
e
Ë

Vehicular movements can be represented as a tracking problem (Huang et al., 2009), which is used for the adaptation of message frequency and power in (Huang et al., 2010), (Huang et al., 2011). The objective is to keep a free channel for high-priority data. Message frequency is regulated by using the error in the predicted neighbor position. As for power adaptation, vehicles monitor CBR. For a higher estimate of CBR, a vehicle assumes similar values for neighbors. This assumption helps in adapting the transmission power to reduce congestion on channel.

A novel concept of beaconing as a service (BaaS) is proposed in (Lasowski & Linnhoff-Popien, 2012). BaaS uses vehicular distance to adapt message frequency and transmit power. It specifies the 100 m distance as critical for safety applications with a higher message frequency. A 2 Hz message frequency is used in excess of 100 m. Within the 100 m range, a collision partner is defined as a vehicle that has excessive longitudinal and lateral dynamics. Therefore, to avoid possible collision, BaaS requests for a higher transmission rate from the collision partner. The request includes specifications of a desired transmission rate and the transmission duration. This approach uses a dual radio setup. Therefore, to handle adjacent channel interferences (ACI), transmission power is reduced in one of the channels during parallel transmissions.

To satisfy the requirements of safety applications, a hybrid beaconing approach is introduced in (Sepulcre et al., 2010). In this approach, rate and power control regulates the CCH load to address the requirements of safety applications. Specifically, a lane changing scenario is considered for which the proposed approach detects an oncoming vehicle to avoid potential collision. In this situation, the requirement of lane change application is reliable beacon delivery. To implement adaptive control, the beaconing approach uses critical distance between vehicles for which a beacon must be shared to avoid collision. This critical distance is considered between two types of vehicles: a) a vehicle initiating a lane change maneuver, and b) a vehicle representing potential collision during lane change. To provide sufficient time for the driver to react, adaptive transmission emphasizes the reliable delivery of at least one warning message for vehicles entering the critical distance. Authors have proposed to use a higher transmission power with low transmission rate. This concept is due to the fact that increasing the transmission rate reduces the transmission range in comparison to the increase in transmission power.

Another beaconing approach in (Gozalvez & Sepulcre, 2007) is designed for intersection crossings in urban scenarios. The main objective is to avoid vehicle collision at the intersection. The adaptation uses message frequency and transmit power. The algorithm becomes active when two vehicles from two different road segments reach a critical distance. Just like in (Sepulcre et al., 2010), reliability is considered for a critical distance between vehicles in which they must receive one beacon to avoid collision. Upon arriving at the critical distance, vehicles increase the transmit power, such that the probability of successful reception could be guaranteed for a given message frequency. The approach is more reliable than a similar evaluation conducted in (Sepulcre et al., 2010).

A transmit power and contention window adaptation is proposed in (Rawat et al., 2011). The idea of power adaptation is based on an accurate estimation of vehicular density, whereas contention window adaptation is used in case of high-priority beacons. After estimating the vehicular density, the beaconing approach uses a static look-up table to select a power level, which is sufficient to cover a desired range. The number of collisions indicate the level of congestion on the channel. As a result, the contention window size is constantly adapted in direct proportions for all the access categories.

Discussion Hybrid beaconing approaches are application-dependent and may be the only applicable choice for certain conditions such as overtaking assistance and intersection collision avoidance. Such applications have hard QoS requirements. Therefore, these techniques pose a challenge in order to identify an optimal combination of adaptive parameters to fine tune the performance of an application. Nevertheless, the choice for

parameter selection is flexible, which helps in addressing the requirements of specialized safety applications.

2.7 Capability Evaluation

Here, we evaluate the capabilities of the beaconing approaches by using parameters such as beaconing load (BL), congestion control strategy (CCS), fairness, reliability, data utility distribution (DUD) and co-existing message dissemination evaluation (CMDE). Table 2.3 summarises our evaluation.

The given parameter values are not absolute by any means. Instead, we use qualitative values to evaluate beaconing approaches. The aim is to qualify the evaluation parameters by describing the notion for the choice of a value for each parameter as discussed below.

2.7.1 Beaconing Load

Beaconing load is significant in indicating the expected channel occupancy of a beaconing approach by evaluating their respective message frequency requirements. We measure beaconing load on a qualitative scale with values of low, application-dependent, and high. The beaconing approaches that restrict or defer beacon transmissions are most effective in reducing the beaconing load. The beacon transmission can be restricted based on criteria such as predicting the neighbor positions or low successful transmission probability of beacons. The application-dependent value implies that the beaconing approaches have no mechanisms to restrict or defer transmissions, rather the beaconing load is defined by the application requirements such as pre-crash sensing application that requires 50 Hz message frequency. Finally, a high beaconing load is associated with: 1) beaconing approaches with multi-hop transmissions, 2) beacons that carry information as extra payload, and 3) beaconing approaches using feedbacks.

2.7.2 Congestion Control Strategy

Congestion control strategy has a profound effect on the desired performance of vehicular applications. Therefore, the key objective of each beaconing approach is to minimize the state of channel occupancy. Beaconing approaches employ either an open-loop or a closed-loop approach to tackle high channel occupancy. The open-loop strategy is proactive, which requires an efficient design to stop congestion from occurring in the first place. As an example, adapting transmission power based on a predefined maximum beaconing load is a proactive congestion control strategy (Torrent-Moreno et al., 2009), which has a tendency to maintain channel occupancy at a certain level. As a result, unforeseen safety events can be transmitted with a higher probability of reception on a less congested channel. On the other hand, closed-loop strategy is reactive, which allows the congestion to occur. Therefore, it requires feedback and continuous channel sensing mechanism to adapt transmission behavior. For instance, the approach in (He et al., 2010) uses channel busy time as an indicator for congestion and only then triggers reduction in message transmission frequency. For spontaneous communication requirements of vehicular safety applications, an open-loop congestion control strategy is more desirable.

2.7.3 Fairness

As discussed previously, the safety of each vehicle in a network is critical, therefore beaconing approach must ensure that transmissions from one vehicle do not interrupt transmission from other vehicles. Providing fairness can be considered from two perspectives: a) fairness during transmission, and b) fairness in congestion control. The former approves fairness through a mutual agreement among vehicles to use certain adaptive behavior for general purpose periodic beacons. While the latter, is applicable upon reception of congestion events from neighbors. Fairness in congestion control demands that the reduction in the frequency/power is relative to the vehicle's marginal contribution towards

Approach	S - NS	BL	CCS	Fairness	Reliability	DU	CMDE
(R. Schmidt et al., 2010)	I	app. Dependent	y/CL	tx-fairness	probable	NA	NA
(Boukerche et al., 2009)	ı	low	y/OL	NA	best-effort	NA	NA
(Rezaei et al., 2007)	ı	low	y/OL	NA	best-effort	NA	NA
(He et al., 2010),(W. Guan et al., 2011)	ı	app. Dependent	y/CL	FCC	best-effort	NA	NA
(Tielert et al., 2011)	ı	high	y/CL	FCC	best-effort	NA	NA
(Bohm et al., 2011)	ī	app. Dependent	NA	tx-fairness	deterministic	NA	NA
(Sommer et al., 2011),(Sommer et al., 2010)	н	high	y/CL	NA	best-effort	NA	NA
(Schwartz et al., 2014)	T	low	y/CL	NA	best-effort	yes	NA
(Torrent-Moreno et al., 2009)	1	high	y/OL	tx-fairness	probable	NA	NA
(Kloiber et al., 2012)		app. Dependent	y/OL	NA	best-effort	NA	NA
(Mittag et al., 2009)	ī	high	NA	NA	best-effort	NA	NA
(X. Guan et al., 2007)	-	high	NA	NA	best-effort	NA	NA
(Settawatcharawanit et al., 2012)		app. Dependent	NA	NA	best-effort	NA	NA
(Park & Kim, 2013)	ı	app. Dependent	NA	NA	best-effort	NA	NA
(Shankar et al., 2008)	ı	app. Dependent	y/CL	NA	best-effort	NA	NA
(Campolo et al., 2012),(Campolo et al., 2011)	ı	app. Dependent	y/CL	NA	probable	NA	NA
(Di Felice et al., 2012)	ı	app. Dependent	y/CL	NA	probable	NA	NA
(Stanica et al., 2014)	ı	app. Dependent	y/CL	NA	probable	NA	NA
(R. K. Schmidt, Brakemeier, et al., 2011)	ı	app. Dependent	y/CL	NA	best-effort	NA	NA
(Yoo, 2013)	ı	app. Dependent	NA	NA	best-effort	NA	NA
(Huang et al., 2010),(Huang et al., 2011)	ı	app. Dependent	y/CL	NA	probable	NA	NA
(Lasowski & Linnhoff-Popien, 2012),(Lasowski & Schmidt, 2011)	ı	app. Dependent	NA	NA	deterministic	NA	NA
(Sepulcre et al., 2010)	ı	app. Dependent	NA	NA	deterministic	NA	NA
(Gozalvez & Sepulcre, 2007)	ı	app. Dependent	NA	NA	deterministic	NA	NA
(Rawat et al., 2011)	ı	app. Dependent	NA	tx-fairness	probable	NA	NA
S-NS: safety non-safety, BL: beaconing load, CCS: congestion contro application, y: yes, CL: closed-loop, OP: open-loop, FCC: fair congestic	l strategy, n control,	DU: data utility, CN tx: transmission, NA	MDE: cc v: not apj	existing mess plicable	age dissemination	ı evalu	ation, app:

 Table 2.3: Evaluation of adaptive beaconing approaches

congestion. Note that, transmission of event-driven messages may violate fairness under certain conditions. For example, fairness criterion does not hold true for beaconing approaches that are designed to fulfill application-specific transmission requirements such as prioritized delivery and timely reception of messages (i.e., fairness is conditional). Under such conditions, the safety events are transmitted with the highest message frequency or transmission power, which may interrupt transmissions at certain vehicles within the transmission range.

2.7.4 Reliability

In the absence of acknowledgments and because of the short temporal validity of beacons, reliability is treated as a critical performance measure for safety applications. We evaluate the reliability of beaconing approaches by using three scales: 1) deterministic, 2) probable, and 3) best-effort. The deterministic reliability is a guaranteed delivery of messages within strict time constraints, such as for lane change warnings approaches presented in (Gozalvez & Sepulcre, 2007), (Lasowski & Linnhoff-Popien, 2012), (Sepulcre et al., 2010) and (Yoo, 2013). Nevertheless, deterministic reliability has hard QoS requirements to fulfill. Therefore, such beaconing approaches cannot be generalized for a wide range of safety applications. Another most commonly used beaconing approach is to provide highly probable reliability by relying on the prioritization mechanism of 802.11p without strict time constraints. For example, contention periods for messages could be reduced by assigning a higher priority to beacons, such as in (Torrent-Moreno et al., 2009), (R. K. Schmidt, Brakemeier, et al., 2011), (Stanica et al., 2014). The rest of the approaches are considered best effort, which support only general purpose neighbor localization. These approaches are not suitable for safety applications.

2.7.5 Data Utility

Data utility specifies the benefit of a received beacon for a vehicle. Enhancing data utility requires effective distribution of vehicles' interest in the data, which also specifies the conflict of interest among vehicles. As an example, in a two-way highway, vehicles in one direction may hold data relevant to vehicles in the other direction. Considering the available capacity for the exchange of only two beacons, the focus of a data utility-based approach is to select and forward messages that maximizes the utility for receiving vehicles and not necessarily to improve the total utility of all vehicles (Schwartz et al., 2012). The classification of vehicles based on their interests is crucial in saving bandwidth by transmitting data with the highest utility. The approaches in (Schwartz et al., 2012), (Schwartz et al., 2014) utilize data utility for the distribution of TIS.

2.7.6 Co-existing Message Dissemination Evaluation

The notion of co-existing message dissemination evaluation originates from the conditional fairness property. As discussed previously, the fairness condition for periodic beacons is subject to violation during the transmission of high priority event-driven messages. This concept applies particularly in situations where periodic beacons, eventdriven messages, and wireless service advertisements co-exist in a network. Therefore, the idea of evaluating the effect of adapting transmission behavior for one type of periodic message on the other is subject to the empirical evaluation. To the best of our knowledge, (Böhm et al., 2013) is the only study that explored co-existing periodic beacons and event-driven messages. In the study, the effects of varying priority levels and message frequency were evaluated. Its findings indicated that keeping periodic beacons at a lower priority enhances beacon up-to-dateness (metric for measuring awareness quality). By contrast, while event-driven messages transmitted at a higher frequency, the temporal effects, that is, low up-to-dateness can be monitored for the low-priority beacons. In light of this study, similar evaluations can be performed to analyze the periodic communication performance when parameters such as transmit power, contention windows, and physical data rates are adapted.

Based on the safety application requirements, beacon dissemination beyond a certain specified range is of least interest to the safety applications and is unreliable. By contrast, non-safety applications require periodic transmission of WSAs to a longer range for maximum advertisement coverage. In addition, the standards specify the use of local information for a provider to maintain an accurate view of SCH utilization in nearby providers. This context requires evaluations of different beaconing approaches on the performance of infotainment service providers and users alike. That is, significant insights could be gained by considering evaluation aspects, such as false channel selections by the users and suboptimal SCH utilization views by providers because of increased/decreased frequency, transmission power, contention window, and so on.

2.8 Comparison

Based on the architectural and implementation aspects, this section presents a classification for beaconing approaches and conducts a comparison.

2.8.1 Classification Approach

Upon close examination, several variations can be identified among beaconing approaches such as coordination mechanisms, resource utilization and implementation logic as shown in Figure 2.5.

The coordination mechanism characterizes the interaction of a vehicle with its neighbors. It is specified using three parameters: 1) communication scope, 2) execution definition and 3) information acquisition. Communication scope specifies the area for which beaconing is considered applicable. It implies that the 1-hop range can be further classified based on the region of interest. Execution definition specifies the time of action for the beaconing approach such as a) reactive, b) proactive, and c) on-demand. The information acquisition definition shows the type of information i.e., active or passive.

The underlying assumptions of the available architecture include number of radios and channel access definition. The beaconing standards allow for one radio for multichannel access. However, in some cases, dual radio setup is also possible in order to increase the system capacity. Depending upon the number of radios, the control channels can be accessed in different ways. We represent this aspect by using channel access definition.

Implementation of beaconing at a system level can be characterized by studying the local implementation details. We classify implementation details by using three parameters: 1) evaluation approach, 2) metric type, and 3) platform.

2.8.2 Comparison Among Beaconing Approaches

This section compares the beaconing approaches by analysing the strengths and weaknesses of different parameters as specified in Figure 2.5. Table 2.4 summarizes the comparison.

2.8.2.1 Communication Scope

Communication scope (CS) defines the applicability of beaconing to a logical organization of vehicles in a transmission range. It includes 1) 1-hop broadcast, which specifies all the vehicles in a transmission range. 2) 1-hop cluster, which is a dynamic organization consisting of group/s of vehicles. For instance, in (Lasowski & Linnhoff-Popien, 2012), two distinct ranges are specified that require different transmit rate control. That is, vehicles within 100 meter range form a logical inner cluster with higher awareness requirement whereas, vehicles within 300 meter range form an outer cluster. 3) The 1-hop peer communication scope is restricted to unique vehicles within the 1-hop range. For instance, to identify a potential collision partner during mobility (Sepulcre et al., 2010),



Figure 2.5: Classification of Beaconing with respect to the Architectural Components including coordination mechanisms, implementation logic and available resources

and lane change applications (Bohm et al., 2011) etc. The 1-hop cluster and 1-hop peer scope are suitable for specific safety situations. 4) Multi-hop CS has the ability to extend communication to the carrier sense range using multi-hop transmission (Mittag et al., 2009). The aim is to reduce network beaconing load while increasing transmission range without the need of increasing transmission power.

2.8.2.2 Execution Definition

Execution definition (ED) refers to the type of beaconing. It can take three values: a) reactive, b) proactive, and b) on-demand. Reactive defines beaconing after event detection. Reactive approaches can be classified as instances of event-driven mechanisms, in which events relate to a particular communication problem, application demand or safety

	0		-				
Approach	CS	ED	IAD	Radio/s	CAD	EA	Metric type
(R. Schmidt et al., 2010)	1-hop broadcast	Reactive	Passive	Single (W2)	Synch intervals	Simulation	Rx centric
(Boukerche et al., 2009)	1-hop peer	Reactive	Passive	Single (W2)	Synch intervals	Simulation	Rx centric
(Rezaei et al., 2007)	1-hop broadcast	Reactive	Passive	Single (W2)	Synch intervals	Simulation	Rx-Tx centric
(He et al., 2010),(W. Guan et al., 2011)	1-hop broadcast	Reactive	Act(1-hop)	Single (W2)	Synch intervals	Simulation	Rx centric
(Tielert et al., 2011)	1-hop broadcast	Reactive	Act(Multihop)	Single (W2)	Synch intervals	Simulation	Offered Load
(Bohm et al., 2011)	1-hop peer	Proactive	Passive	Single (W2)	Synch intervals	Simulation	Rx centric
(Sommer et al., 2011),(Sommer et al., 2010)	1-hop broadcast	Reactive	Passive	Single (W2)	Synch intervals	Simulation	Rx-Tx centric
(Schwartz et al., 2014)	1-hop broadcast	reactive	act(1-hop)	Single (W2)	Synch intervals	Simulation	Rx-Tx centric
(Torrent-Moreno et al., 2009)	1-hop broadcast	Reactive	Act(multihop)	Single (W2)	Synch intervals	Simulation	Rx centric
(Kloiber et al., 2012)	1-hop broadcast	Reactive	Passive	Single (W2)	Synch intervals	Simulation	Rx centric
(Mittag et al., 2009)	Multi-hop	Reactive	Act(Multihop)	Single (W2)	Synch intervals	Simulation	Rx-Tx centric
(X. Guan et al., 2007)	1-hop broadcast	Reactive	Act(1-hop)	Single (W2)	Synch intervals	Simulation	Rx-Tx centric
(Settawatcharawanit et al., 2012)	1-hop broadcast	Reactive	Act(1-hop)	Single (W2)	Interval hopping	Simulation	Rx-Tx centric
(Park & Kim, 2013)	1-hop broadcast	reactive	Act(1-hop)	Single (W2)	Interval hopping	Simulation	Rx-Tx centric
(Shankar et al., 2008)	1-hop broadcast	reactive	Passive	Single (W2)	Synch intervals	Simulation	Rx centric
(Campolo et al., 2012),(Campolo et al., 2011)	1-hop broadcast	proactive	Passive	Single (W2)	Window tuning	Analy. model	Rx-Tx centric
(Di Felice et al., 2012)	1-hop broadcast	reactive	Act(1-hop)	Single (W2)	Window tuning	Simulation	Rx centric
(Stanica et al., 2014)	1-hop broadcast	proactive	Passive	Single (W2)	Window tuning	analy./sim.	Rx-Tx centric
(R. K. Schmidt, Brakemeier, et al., 2011)	1-hop broadcast	reactive	Passive	Single (W2)	Synch intervals	Simulation	Rx-Tx centric
(Yoo, 2013)	1-hop broadcast	pro/reace	Act(1-hop)	Single (W2)	Synch intervals	Simulation	Rx-Tx centric
(Huang et al., 2010),(Huang et al., 2011)	1-hop broadcast	Reac/pro	Passive	Single (W2)	Synch intervals	Real	Rx centric
(Lasowski & Linnhoff-Popien, 2012),(Lasowski & Schmidt, 2011)	1-hop cluster	Reac/on-dem	Act(1-hop)	Dual (T2)	Dedicated Access	Simulation	Rx centric
(Sepulcre et al., 2010)	1-hop peer	Reac /reac	Passive	Single (W2)	Synch intervals	Simulation	Reliability
(Gozalvez & Sepulcre, 2007)	1-hop peer	Pro/pro	Passive	Single (W2)	Synch intervals	Simulation	Rx centric
(Rawat et al., 2011)	1-hop broadcast	Reactive	Passive	Single (W2)	Synch intervals	Simulation	Rx-Tx centric
CS: communication scope, ED: execution definition,	IAD:information	acquisition c	lefinition, CAD	: channel acc	ess definition, E/	A: evaluation a	pproach, Act:

Table 2.4: Comparison of beaconing approaches with respect to the architectural characteristics

نټ | active, pro: proactive, reac: reactive, on-dem: on-demand, Synch: synchronization, Analy: analytical, Rx: receiver, Rx-Tx: receiver-transmitter condition. Reactive execution is easy to implement and produces deterministic results because the adaptive behavior is based on currently acquired information. Proactive execution is based on future estimates or models to prevent a communication problem or safety situation. For instance, saving the useful amount of CCH by preventing congestion and predicting a collision partner before the collision happens. However, the estimations and models are non-deterministic and involve certain assumptions, which might not reflect the actual state. Finally, on-demand execution defines the request mechanism for a particular adaptive behavior from neighbors (Lasowski & Linnhoff-Popien, 2012). Specifically, a high message frequency could be requested from a vehicle having highly variable longitudinal and lateral dynamics. On-demand beaconing execution has more implementation complexity with an additional request and response mechanism.

2.8.2.3 Information Acquisition Definition

Information acquisition definition (IAD) is the scope of information used for decision making. That is, it can be active or passive. Active IAD requires information sharing and has a wide scope indicative of neighbor vehicle information. It is based on a closedloop control theory. Approaches with active IAD are capable of solving issues such as fairness (Tielert et al., 2011), (He et al., 2010), (W. Guan et al., 2011), prioritization -(Torrent-Moreno et al., 2009) and preventing potential hazardous situations (Lasowski & Linnhoff-Popien, 2012), (Kloiber et al., 2012). The granularity of IAD varies as a) 1-hop, and b) multi-hop. Approaches with 1-hop IAD restricts the scope of acquired information to the 1-hop range. The 1-hop range specifies the standard range ("IEEE Standard for Information technology–Part 11 Wireless Access in Vehicular Environments", 2010) or can be explicitly defined by the beaconing approach (Lasowski & Linnhoff-Popien, 2012). Multi-hop IAD (Mittag et al., 2009) extends the information scope to the CS range. In the context of safety applications, multi-hop IAD affects information freshness that is critical for safety scenarios. Contrastingly, passive IAD depends on the local information. Its implementation is relatively simple, and it assumes a uniform view of the network. Therefore, it is not suitable for addressing dissemination problems such as fairness. However, it can be used effectively to address issues of general interest such as CCH load reduction and safety applications such as collision warning scenarios.

2.8.2.4 Number of Radios

Multi-channel operation for VANETS is designed for single and dual radio setups ("IEEE Standard for Wireless Access in Vehicular Environments (WAVE)–Multi-channel Operation", 2011), (T. ETSI, 2009b). Most of the approaches follow the standard single radio setup. Single radio setups are suitable for decentralized spectrum sharing. How-ever, as described in previous sections, switching between CCH and SCH is time syn-chronized. It implies that during communication the available channel capacity decreases to half (Campolo & Molinaro, 2013). All approaches in this study use single radio except for BaaS (Lasowski & Linnhoff-Popien, 2012). Dual radio setup requires permanent tuning of one radio to the CCH while channel switching is allowed on the second radio. Use of dual radios increases the CCH capacity. Nonetheless, using dual radio for multi-channel access with no centralized scheduler introduces adjacent ACI (Hu & Mao, 2013). In addition, system complexity also increases with the need of dual radio management services. One of the counter measures used in BaaS (Lasowski & Linnhoff-Popien, 2012) against ACI is to reduce the transmission power in one of the radios, as a trade-off between reduced ACI and increased transmission range.

2.8.2.5 Channel Access Definition

Channel access definition (CAD) specifies the use of synchronization (sync) intervals and contention windows. There are different ways to access the CCH besides the synchronization interval defined in the standards ("IEEE Standard for Information technology–Part 11 Wireless Access in Vehicular Environments", 2010), ("IEEE Standard for Wireless Access in Vehicular Environments (WAVE)–Multi-channel Operation", 2011). Most beaconing approaches use the default synch intervals. However, dedicated access (Lasowski & Linnhoff-Popien, 2012), interval hopping (Settawatcharawanit et al., 2012), (Park & Kim, 2013) and window tuning (Campolo et al., 2012) are also proposed in literature. The main aim of different CAD is to improve neighbor awareness by minimizing collisions. Dedicated access replaces channel switching with a permanent CCH access to increase neighbor awareness of only one neighbor. Interval hopping (Settawatcharawanit et al., 2012) uses a heuristic of hoping to distinct firings interval to avoid synchronized collisions. However, it requires a steady state of vehicles for which firing intervals are evenly distributed in time space. Finally, window tuning (Campolo et al., 2012), (Di Felice et al., 2012), (Stanica et al., 2014) the increases the contention window for beaconing in order to provide time diversity in accessing a channel and hence minimizing collisions.

2.8.2.6 Evaluation Approach

Evaluation approaches (EA) are the mechanisms to evaluate the performance of beaconing i.e., 1) analytical models, 2) simulation and 3) real implementation. Analytical models provide an abstract view of the system. It is a cost effective mechanism and provides a prompt evaluation. However, it does not represent dynamic properties of a real system. Analytical models lack randomness and heavily depend upon the underlying assumptions. In order to validate an analytical model, the concepts need to be field-tested or simulated. For instance, in (Stanica et al., 2014), the authors prove the suitability of higher contention windows during high-density networks. However, the extent of limits for contention window adaptation requires evaluation in a realistic network. Therefore, it is recommended to use analytical models alongside simulations and field-tests. On
the other hand, simulations are used to prove the validity of a proposed analytical model (Campolo et al., 2012). Simulations provide randomness in the environment and produce accurate results with less abstraction of underlying assumptions. However, too many details may lead to an unmanageable simulation environment. Finally, evaluations using test-beds are rare in VANETs (Huang et al., 2011). Such evaluation is more costly and has minimal assumptions for a distinct test case. However, for large systems, designing a test-bed is not feasible and it must be accompanied by simulation results to make evaluation more dynamic.

2.8.2.7 Metric Type

Metric type classifies metrics to indicate the performance gains of a proposed beaconing approach. That is, a traditional receiver-transmitter (Rx-Tx) centric metric is used to show the overall system performance such as throughput, packet delivery ratio and latency etc. On the other hand, receiver (Rx) centric metrics for beaconing are used to evaluate the application-level performance of beaconing approaches. For the evaluation of safety applications, Rx centric metrics are more desirable, which can capture specific effects such as driver's reaction time and update delays to name but a few. In Figure 2.5, some example metrics under each category are shown. Note that, penetration rate/ratio and data utility are the metrics used for non-safety TIS. The former specifies the speed and coverage of TIS data while the later indicates the benefit of selected data for other vehicles upon reception.

2.9 Challenges and Design Considerations

We observe that certain aspects in adaptive beaconing can be improved in order to control the channel congestion problem and poor reliability due to beacon collisions. We simulate a highway with varying levels of vehicular densities to demonstrate the effect of beacon transmissions with respect to the channel busy ratio, average channel busy time, reliability and beacon collisions.

2.9.1 Power Control Design

The most important consideration for a beaconing design is to provide adequate opportunities for vehicles to transmit as and when desired. The beaconing approach can provide these adequate opportunities only if it has provisions to control channel saturation or channel busy ratios.

As shown in Figure 2.6 (on the right), a vehicle experiences varying levels of channel saturation with respect to time, which is representative of increasing densities. Note that, channel saturation in different parts of the road may vary significantly. Similarly, in Figure 2.6(on the left), the average busy time (in percentage) increases for the entire network as the network density increases. The phenomenon of the channel congestion is critical for the power control designs proposed in Chapter 3. In particular, we consider the following factors in the design:

Use of transmit power is dependent upon the channel saturation. That is, if a vehicle experiences high channel saturation, it decreases its transmit power (Torrent-Moreno et al., 2006). Therefore, knowing that vehicles have different levels of channel saturation, the transmit power levels vary as well. This may lead to certain vehicles in high-density road sections with less transmit power and vice versa. More importantly, the vehicles contributing to congestion can further increase congestion, if a proper adaptive design in not followed. It follows that the design of a power control approach should be based on a congestion control policy that considers the marginal contributions of the vehicles towards congestion. In other words, during congestion, a transmit control approach should fairly determine a transmit power value for all vehicles based on their current power levels. The challenge

of determining fair power decrease during congestion forms the basis of our first



power control approach in Chapter 3.

Figure 2.6: Illustration of the evolving channel busy ratio for one vehicle in a network (on the left), and average busy time of all the nodes with respect to densities (on the right)

• Another important factor in transmit power adaptation is the appropriate coverage of beacons. ITS applications specify the desirable coverage of beacons. Again, channel saturation plays a significant role in reliable transmission up to the desired range. The effect of using different transmit power levels for beacon transmissions is shown in Figure 2.7. The x-axis represents vehicle ids that are arranged with respect to the increasing distances from a source vehicle. The y-axis shows the reliable delivery (ratio of a total number of received beacons to the total number of sent beacons). It can be observed that use of lowest transmit power (8dBm) produces 100 percent reliability up to a very short range. Whereas, use of highest transmit power (32dBm) increases the coverage of beacons, however, the reliability of reception decreases significantly. Similar trends can be seen for various transmit power levels if a constant transmit power is used without considering channel saturation. Note that, the Figure 2.7 shows the reliability of periodic beacons as well as the event-driven messages. This marks an important observation in the design

of our next power control design. Initially, the power control design should make the best effort in reducing congestion and to maximize the reliability of beacons to longer ranges. The design should also make provisions to provide a form of coverage differentiation for the event-driven messages or the high priority messages to maximize their coverage even further. Ideally, such a design requires adaptive decisions made locally without the use of any feedback. In Chapter 3, we propose a multi-metric power control design by considering the challenge of controlling congestion and at the same time providing coverage differentiation for different kinds of beacons.



Figure 2.7: Comparing reliability of beacon reception from a source vehicle on different vehicles with respect to increasing distances

2.9.2 Contention Window Design

It could be argued that controlling congestion can reduce collisions on the CCH, however, synchronous collisions can still occur in a reasonably small VANET. This is due to the random back-off selection of 802.11p from within a small contention window size (Reinders et al., 2011). The effect of using the standard contention window size in 802.11p can be analysed through simulations. In Figure 2.8, the overall number of synchronous collisions is shown that increases proportionally with respect to the vehicular densities. From the ITS application's perspective, increasing synchronous collisions can reduce awareness, which is a critical performance metric for safety applications. We consider two important factors to reduce synchronous collisions that involve modifications in the contention window mechanism and the back-off selection mechanism. In particular, we are interested in reducing the overall collisions in a network and collisions from a particular vehicle under a hazardous road condition. The following challenges are addressed:

- The adaptive beaconing design should minimize synchronous collisions by adapting the contention window size. Since the synchronous collisions are bound to increase in high-density networks, the adaptation logic must incorporate channel states in order to increase the window size. Note that, the contention window size cannot be increased beyond a certain limit because it causes delays in beacon transmission and even packet drops at the source. Therefore, the design should be capable of reducing delays and packet drops at the source. The contention window adaptation proposed in Chapter 4 is to address the problem of overall reduction in synchronous collisions in the network.
- Note that the use of standard contention window size and back-off selection mechanism has no provision for reducing collisions from a particular vehicle. That is, all the vehicles are bound to select a random back-off with uniform probability from the current window size without any differentiation of their current traffic scenario (i.e., high variation in movement pattern on road etc). This can be crucial in a hazardous road condition where transmission from a particular vehicle is deemed more important for the neighbouring vehicles. Instead, the standard provides a pri-

oritized access to the channel that can not enhance reliable delivery of a beacon from a certain vehicle. Therefore, we look at the challenging aspect of modifying the back-off selection mechanism in 802.11p with an aim to reduce collisions from a specific vehicle and yet be compliant with the existing DSRC standards. This notion forms the basis of our proposed back-off selection design in Chapter 4.



Figure 2.8: Total synchronous collisions recorded for different vehicular densities

2.9.3 Layered View of the Proposed Approaches

The protocol stack view of the proposed beaconing designs is shown in Figure 2.9. The ITS applications provide message specification to the facilities layer. Upon reception, the facilities layer examines the variations in the local topology and subsequently decides to transmit/defer messages to the lower layers. The proposed beaconing designs are then placed in the DSRC communication control block in order to facilitate cooperative congestion control and contention window size adaptation.



Figure 2.9: The protocol stack view of proposed awareness and congestion control schemes

2.10 Conclusion

Intelligent transportation systems have strict beacon dissemination requirements, which are typically addressed through various beaconing approaches. This chapter has contributed by conducting a survey of the adaptive beaconing approaches designed for effective ITS. Specifically, it first identified the performance requirements of vehicular applications. Then, the information used as input by the beaconing approaches and the subsequent choice of a control mechanism is explored to propose a design-based beaconing taxonomy. The salient features of a number of beaconing approaches under each category of MFC, TPC, Miscellaneous and Hybrid are surveyed and key observations about each category are listed. We further evaluated the capabilities of beaconing approaches on a qualitative scale by considering parameters including beaconing load, congestion control strategy, fairness, reliability, data utility distribution and co-existing message dis-

semination evaluation. In addition, the variations in the architectural and implementation aspects among the beaconing approaches are used to highlight similarities and variations among them. In the subsequent chapters, we propose adaptive designs for periodic beacons.

CHAPTER 3 : TRANSMIT POWER CONTROL DESIGNS FOR PERIODIC BEACONS

3.1 Introduction

The previous chapter has surveyed beaconing approaches aiming to improve vehicular communications with respect to a variety of objective functions. Accordingly, one possible solution for reducing CCH occupancy is to reduce message frequency. Due to strict message frequency requirements of safety applications (Consortium et al., 2005), transmit power adaptation approaches are generally regarded as one of the most suitable congestion controls (Torrent-Moreno et al., 2009).

In this chapter, we motivate two distinct beaconing approaches based on transmit power: 1) Adaptive transmit power Cooperative Congestion Control (AC3) design and 2) Multi-metric Tx-Power Control (MPC) design.

The key objective of AC3 is to facilitate fair power reduction by enabling cooperation among vehicles during congestion. The AC3 design assumes the transmit power levels for beacon transmission as an indicator of a vehicle's marginal contribution towards congestion. In order to minimize congestion on the CCH, the AC3 monitors channel states to generate congestion events. Subsequently, a game-theoretic model is proposed that allows vehicles to reduce transmit power fairly. The power reduction is applicable within the carrier sense (CS) range and it uses information acquired through the periodic beacons.

The second beaconing approach attempts to provide sufficient transmission coverage for beacons with respect to the channel states as well as providing coverage differentiation for different kinds of beacons (such as general periodic beacons and event-driven beacons). The MPC design exploits local information and does not involve any feedback to correct the transmission adaptation made in the past. The main objective is to provide a strategy that can 1) satisfy the transmission range requirement with coverage differentiation for periodic messages, and 2) to maintain low channel utilization. The first objective is crucial with regards to the appropriate coverage of beacons and safety events as specified by the standards (Consortium et al., 2005). Whereas, the second objective is more relevant to the transmit power adaptation in response to the varying levels of vehicular densities.

The organization of this chapter is as follows: In Section 3.2, we present the motivation and problem statement for AC3. In Section 3.3, a detailed description of AC3 is provided. Initially, a cooperative game-theoretic system model is given in Section 3.3.1 followed by its implications on the system in Section 3.3.2. In Section 3.3.3, some rules are provided to enable spontaneous response to the proposed shapely-value-based power decrease mechanism. The work flow of AC3 is provided in Section 3.3.4 followed by the analysis of proposed fairness in power decrease in Section 3.3.5. The mechanism for information distribution in AC3 is given in Section 3.3.6 with a detailed algorithm in Section 3.3.7. Section 3.4 describes the MPC protocol. Its metric composition is given in Section 3.4.1 which includes quality of channel and the application range requirements. The MPC activity diagram is given is Section 3.4.2 and the chapter concludes in Section 3.5.

3.2 Motivation and Problem Statement of AC3

We assume all vehicles determine the initial transmit power with respect to their respective channel congestion. That is, the higher the congestion level, the lower the transmit power (and vice versa). Maximum congestion is experienced on road sections with the maximum number of intersecting interference ranges (Torrent-Moreno et al., 2005). In Figure 3.1, *zone* – 3 has a maximum number of intersecting interference ranges



Figure 3.1: Illustration of congested zone on a highway

as a result of wireless receptions from zone - 1 and zone - 2. This may result in vehicles in zone - 3 decreasing their transmit power due to their channel congestion. In other words, vehicles in zone - 1 and zone - 2 contribute towards congestion in zone - 3.

In this paper, we consider the level of transmit power of a vehicle as the marginal contribution towards congestion. One possible way of reducing congestion would be to decrease the transmit power of all vehicles by a certain factor such as the Additive Increase and Multiplicative Decrease (AIMD) (Y. R. Yang & Lam, 2000). However, in the context of Figure 3.1, vehicles in *zone* -1 and *zone* -2 transmit with higher power than vehicles in *zone* -3. Moreover, based on the number of neighbours, vehicles are bound to have varying levels of transmit power. Therefore, the use of AIMD will cause vehicles in *zone* -3 to reduce their transmit power in equal proportions to that of the vehicles in the other two zones, which is unfair power decrease. It follows that during congestion, the significant requirement for a transmit power adaptation approach is the fair power decrease which is based on the vehicles' marginal contribution.

We model the cooperative congestion control approach on the principles of the cooperative game theory (Harsanyi et al., 1988), which allow us to construct models of conflict and cooperation among players (i.e., vehicles) in order to maximize individual payoffs. In particular, the use of cooperative game theory allows us to study coalition formation among players consistent with their preferences and derive the conditions optimal for the players in payoff distribution. Given a cooperative game, shapely value (Winter, 2001) defines the notion of fair distribution of gains and expenses among players within a coalition. In other words, shapely value allows coalition formation among players with unequal contributions. The proposed Adaptive transmit power Cooperative Congestion Control (AC3) design controls congestion by considering the vehicles' marginal contribution towards congestion, where marginal contribution is equivalent to the level of transmit power used by different vehicles.

3.3 AC3: Adaptive transmit power Cooperative Congestion Control (AC3) Design

In the proposed Adaptive transmit power Cooperative Congestion Control (AC3) approach, fairness in transmit power reduction is achieved through the shapely values. However, the shapely value concept cannot be readily applied to beaconing and must be adapted for cooperative congestion control in VANETs. Table 3.1 presents the notations used in the system model for AC3.

Notations	Meaning Set of vehicles	
N		
S	Coalition of set N	
ν	A function to map <i>S</i> to real number	
G(N, v)	Cooperative congestion control game	
v(S)	Payoff of coalition S	
mci	Marginal contribution of vehicle <i>i</i>	
t^{σ}	Set of all permutation of vehicles in <i>N</i>	
σ	Permutations	
in_{v_i}	Index of a vehicle v_i	
n	Total number of neigh- bours in the sorted list	
<u>n'</u>	Equivalent to $n-1$	

Table	3.1:	Notations
LUDIC	···	1 totallono

3.3.1 System Model

The congestion control scheme of AC3 consists of a set of vehicles N = |N|, where |N| = 1, 2, 3, ..., n is the number of vehicles in this set (i.e., |N| corresponds to vehicles within the transmission range). The coalition of N is denoted by $S \subseteq N$, where $S \neq \emptyset$. This coalition is formed subsequent to a congestion event generation/reception. Then, a cooperative congestion control game is given by G(N, v), where $v : 2^N \rightarrow R$ is a function that maps a coalition $S \subseteq N$ to a real number, and v(S) refers to the payoff of the coalition and $v(S) \neq 0$. The payoff distribution among the members of S is based on the marginal contribution mc_i , where $i \in N$ for every $S \in 2^N$. In AC3, the mc_i shows the contribution of a coalition in terms of the current transmit power of $i \in S$. For AC3, the mc_i for a given payoff v in every $i \in N$ is given by:

$$mc_i^{\sigma}(v) = v(t^{\sigma}(i) \cup i) - v(t^{\sigma}(i))$$
(3.1)

where σ specifies the permutations, and t^{σ} is the set of all permutation of $i \in N$. Thus, fair distribution of payoffs among all $i \in N$ within (N, v) is given by:

$$\boldsymbol{\theta}_{i}\left(N,\boldsymbol{v}\right) = \frac{1}{n!} \sum_{\boldsymbol{\sigma}} m c_{i}^{\boldsymbol{\sigma}}(\boldsymbol{v}) \tag{3.2}$$

Eq. 3.2 is the average of the marginal contributions for each player considering all possible permutations of the players' transmit powers. Unlike conventional payoff distribution in cooperative games where a higher marginal contribution results in higher payoff; in AC3, a higher marginal contribution is seen as a higher contribution towards congestion. Therefore, fairness in power decreases with respect to the payoff in AC3 is defined as:

Definition: Given a set of vehicles $v = v_1, v_2, ..., v_n$, fairness in power decrease $fair_{(pr)}$ is a function that assigns to each vehicle in the Carrier Sense (CS) range, a re-

duced transmit power value which is reduced in proportion to its payoff:

$$fair_{pr} = txp_{current} - \theta_i(N, v) \tag{3.3}$$

where $\theta_i(N, v)$ is the marginal contribution of vehicle *i*, and $txp_{current}$ is the current transmit power used by vehicle *i*.

Thus, AC3 provides a fair approach for the coalition to reduce transmit powers based on individual payoffs, where we define payoffs as a value in dBm that a vehicle is required to reduce its transmission power upon detecting a congestion event.

3.3.2 Implications of Fairness using Shapely value

Ideally, to achieve fairness in congestion control game, each vehicle should consider joining a coalition comprising the complete neighbourhood in the CS range. While distribution of congestion event to CS range can be achieved through multi-hop beacon transmission (as described in Section 3.3.6), the payoff calculation for all vehicles in the CS range can be computationally expensive. The difficulty of applying Eq. 3.2 for dense networks comes from the calculation of permutations for all neighbour vehicles. It is widely known that calculating permutations has an exponential time complexity. For instance, there are 1.30767436e + 12 possible permutations for 15 players and it takes approximately 30 seconds to calculate using a personal computer with standard configurations. It implies that given the computational capacity of the DSRC equipment, a spontaneous response to a congestion event cannot be guaranteed even in a network of few vehicles. A spontaneous response to a congestion event is crucial in order to minimize congestion in real-time and avoid loss of further beacons.

3.3.3 Player Specification Rules

To reduce the time complexity in calculating permutations while maintaining fairness in power decrease, we define the rules for a vehicle to join a selected set of players for cooperative congestion control game. We assume that vehicles have accurate information about the current transmit power used by neighbours in the CS range, which is a realistic assumption since vehicles can easily "broadcast" in a small field of transmitted beacons. In Figure 3.8, a beacon frame format is shown with the extra 8bits of tx – power used in AC3. Another 1 bit field is also depicted, which acts as flag for the congestion event distribution (described in Section 3.3.6).

With the given transmit power information of neighbours in the CS range, the rules to minimize the number of permutations are applied to the list of neighbour information. Note that the neighbour information is sorted with respect to the level of transmit power values. The following steps are performed for coalition formation.

- In the first step, a vehicle selects an appropriate index from the sorted list of neighbours to start the player selection process.
- In the second step, the selected index is used as a reference point to specify a group of four players for the cooperative congestion control game.

As an example (see Figure 3.2), let *n* be the number of neighbours in a list sorted based on the level of transmit power values, and v_i specifies a vehicle identifier, and $f(in)_{v_i}$ corresponds to a function for selecting an index (*in*) for a vehicle (v_i) from the list



Figure 3.2: Illustration of coalition formation with reduced size using the specified rules in AC3.

of neighbours according to the rules in Eq. 3.4 as part of step 1.

$$f(in)_{v_i} = \begin{cases} in(v_i) < n - (\frac{n}{2} + 1), & retain \\ in(v_i) = \frac{n}{2} | n - (\frac{n}{2} + 1), in(v_i) = n - (\frac{n}{2} + 2) \\ else, in(v_i) = n - (i + 1) \end{cases}$$
(3.4)

The initial value of *in* corresponds to a vehicle's own index in the sorted list shown in Figure 3.2 (*SelfID*). In step 2, a set of vehicles, N = |N|, along with their transmission powers is selected. After selecting the index, Eq. 3.5 is used by a vehicle to specify a coalition of four vehicles using its own index *in* as depicted in Figure 3.2.

$$f|N| = \{in(v_i), in(v_i+1), in(n'-i), in[n'-i-1]\}$$
(3.5)

where n' represents n - 1. This selection of players by each vehicle ensures that vehicles with maximum transmit power join other vehicles with a minimum transmit power (see Figure 3.2). Note that we only consider a group of four vehicles for cooperative con-



Figure 3.3: Work flow of AC3, which includes seven steps from congestion event distribution to the transmit power convergence after power decrease.

gestion control game and the sorted list of neighbours is always maintained even for the proper selection of index using Eq. 3.4. In the event that the number of neighbours in the CS range is odd, we remove the vehicle with the least transmit power from the list. This decision is taken individually by every vehicle, and we found that such an action has no significant effect on the fair power reduction.

3.3.4 Work flow of AC3

As aforementioned, AC3 focuses on congestion control with fair power reduction for all vehicles in the CS range, and we assume that methods for disseminating congestion events and gathering neighbour information about CS range are already in place (as detailed in Section 3.3.6). The complete work flow of AC3 is given in Figure 3.3.

- 1. When a vehicle monitors high level of congestion on the channel, it generates a congestion event which is then relayed by vehicles up to the CS range using the mechanism described in Section 3.3.6.
- 2. The receiving vehicles, including the vehicle generating the congestion event, sort their neighbour list (i.e., list includes all neighbours within the CS-range) with respect to the transmission powers.



Figure 3.4: Schematic illustration of the fair power decrease in a coalition of four vehicles

- 3. Each vehicle then joins a coalition of only four vehicles in order to reduce the computational complexity in finding the payoff.
- 4. Then, the payoff for a given coalition is calculated as specified by the AC3 system model.
- 5. Given the coalition and the corresponding payoff, each vehicle calculates the marginal contribution to determine the level of transmit power reduction.
- 6. This is followed by the power decrease of every vehicle equivalent to the marginal contribution of each vehicle.
- 7. Finally, the power decrease is followed by gradual increase of transmit power until the next congestion event is generated/received.



Figure 3.5: Player selection for the 16 player example

3.3.5 Analysing Fairness in Power Reduction

The effect of fair power decrease achieved through AC3 can be illustrated using a schematic example in Figure 3.4. Four vehicles are shown along the x-axis with their respective transmit power values along the y-axis. The difference in the transmit powers could easily be noticed wherein vehicles 1 and 2 have minimum transmit powers for beacon transmission and vehicles 3 and 4 have maximum transmit powers. The marginal contribution of each vehicle with respect to their transmit power is also depicted. Clearly, as proposed by AC3, the higher the transmit power in use, the higher the associated marginal contribution towards congestion. Therefore, Eq. 3.3 forces the vehicles with a higher marginal contribution to reduce their transmission powers the most.

The Figure 3.5 shows an extended example of 16 vehicles which are sorted based on their transmit powers as shown in the table (depicted at the top of the figure). The first row in the table is the index for every vehicle, the second row contains the vehicle id and the last row is the current transmit power of the corresponding vehicle. The figure also shows the selected groups of players according to the rules specified in Eq. 3.4 and 3.5. We use this example to further analyse the fairness in power reduction with reference to the Additive Increase and Multiplicative Decrease (AIMD) approach (Hurley et al.,



Figure 3.6: Comparison in the power decrease between proposed AC3 and the AIMD approach

1998) employed in wired networks. In VANETs, the AIMD has also been used as means for message frequency control to reduce congestion (He et al., 2010). For the sake of comparative analysis, we consider the example of AIMD when adopted for the transmit power control, and compare it with AC3 to demonstrate the ability of AC3 in providing fair power decrease.

Initially, in Figure 3.6 it could be seen that the initial transmit powers represent a steep curve. After applying AC3, the steep trend-line has been normalized especially towards the end for higher transmit powers. This shows the ability of AC3 to employ relative power decrease with respect to the marginal contribution by each vehicle. In order to further understand the behaviour of AC3, the comparison of power decrease for the same scenario using AC3 and AIMD can be used. Observe that AIMD reduces the transmit power equally for all the vehicles. While this approach reduces congestion effectively, it does not consider marginal contributions. Thus, vehicles in the highly congested zone

(these vehicles have low transmit power) are forced to reduce their transmit power even further. Contrastingly, towards the beginning of the graph, AC3 gives consideration to the vehicles in highly the congested zones (vehicles with low transmit power). This effect can be seen in relatively lesser decrease in transmit power for vehicles at the bottom of the sorted list of neighbors with respect to the transmit powers. Also, the difference between the relative reduced power for AC3 and AIMD is minimal towards the end of the graph. It implies that, AC3 works similar to the AIMD approach for high transmit power levels. However unlike AIMD, the AC3 design demonstrates a more intelligent approach in figuring out marginal contributions and relative power decrease for controlling congestion.

The key benefit of AC3 comes from the behaviour of the cooperative congestion control scheme, which is similar to a self-organizing system in which vehicles determine the transmission power decrease independently. As a result, it enables the vehicles to reduce congestion on the CCH. Hence, provision of proper local rules leads to the desired congestion control at the global level.

3.3.6 Mechanism for Information Distribution

We have discussed the employed mechanism in AC3 to enable fair power reduction for congestion control. However, an important prerequisite for AC3 is the distribution of the congestion event up to the CS range and the acquisition of transmit power values from the neighbours in the CS range. In AC3, the design of this information distribution revolves around two main objectives, namely: 1) congestion event distribution should not affect the vehicles too often and 2) the acquired neighbour transmits power information that is accurate and the mechanism should incur a low overhead. In Figure 3.7, the flow diagram illustrates how AC3 distributes the congestion event and shares transmit power information with the neighbours.

It is important for vehicles to identify local congestion as well as having the ability



Figure 3.7: Flow diagram demonstrating the transmit power sharing and congestion event distribution mechanism

In Danialate Denginate Speed Direction Informet Ing

8-bits 1-bit

Figure 3.8: Information in the beacon frame append with an extra 8-bit tx - power field and 1-bit *flag* field.

to determine whether congestion has been reported by a neighbour within the one hop or from within the CS range. While local congestion can be easily identified using the *cbt* value, the congestion event reporting is employed using a one bit field called *flag* (refer to Figure 3.8) in every beacon and a local variable called *RcvdEvent*. By default the *flag* has a value of 0, which specifies a normal beacon. A value of 1 is only used to report congestion for the first time. Therefore, a receiving vehicle knows that the message has been transmitted by its one hop neighbor. Since, the congestion event needs to be transmitted up to the CS range, the receiving vehicle increments the *flag* value for the next scheduled beacon. The received *flag* value of 2 specifies that the congestion event has been distributed up to the CS range. Therefore, the transmission of congestion event is not required any more. The *RcvdEvent* is a local variable which records the value of the received *flag*. By default, it has a value of 0, which either denotes that congestion is not reported by any neighbor or the congestion event has already been sent with the *flag* value of 2. To ensure that the congestion event distribution does not affect its neighbors too often, AC3 restricts frequent transmission of congestion event. This is achieved by recording the time of last congestion event transmission (i.e., specified here as 4 messages or 400 msec for 10 Hz frequency). Hence, a vehicle is not allowed to transmit a congestion event if a previous congestion event has already been sent before the expiry of specified time.

A beacon in AC3 uses a small field which contains the transmit power value used by the vehicle. Each receiving vehicle records this information in a table. However, the fair power decrease in AC3 requires neighbor transmit power information of all vehicles in the CS range. Therefore, vehicles are configured to share their local information periodically with neighbours. As a result, each vehicle will have transmit power information of all vehicles in the two-hop range. It turns out that achieving the second objective is somewhat intuitive and only involves specification of the message transmission frequency. Therefore, as a design choice, for a 10 Hz message frequency, we configure vehicles to share neighbour information twice in a second, which gives accuracy in neighbour information and incurs low overhead. While a higher frequency provides more accuracy, it incurs a higher channel load. This mechanism can easily be observed in Figure 3.7.

3.3.7 Algorithm:AC3

This section describes the algorithms for the congestion event distribution and the subsequent transmit power reduction for congestion control.

The algorithm for application-based congestion control is given in Algorithm 1. The inputs to this algorithm are the transmit power information about all the neighbours (n_{txp}) , the message frequency (f) used by all neighbours (s_{pkt}) , size of the beacons and clear channel assessment (*CCA*). The algorithm gives beaconing load (bl), marginal contribution (θ) and the transmit power (txp) for beacons as an output.

Initially, a vehicle checks the level of congestion locally or at another neighbour vehicle through the received beacon event. From line 2 to line 5 a vehicle checks local congestion by monitoring the clear channel assessment (*CCA*) report and if *CCA* is beyond a threshold, it transmits a congestion event (E_{cong}) with a value of 1. The retransmission is necessary in order to provide coverage of the congestion event up to the CS range. In line 7 and 9 the receiver of E_{cong} with the value of 1 and 2, retransmits the beacon. Subsequently, in line 4, 8 and 10, the vehicle generating E_{cong} event, the vehicles retransmitting the E_{cong} and the vehicles receiving the E_{cong} with a value of 2 enter into the congestion control phase.

The lines 11 through 16 indicate the congestion control phase where vehicles are required to reduce their transmission power. As mentioned before, the vehicles go through a routine of sorting the neighbour list, joining a coalition of players, specifying the worth of the coalition, calculating the marginal contribution towards congestion in terms of

Alg	orithm 1 AC3: Cooperative Congestion Con	trol
inp	uts: n_{txp} , f , s_{pkt} , CCA	
out	puts: bl, θ_i, txp	
1:	procedure CONGESTION NOTIFICATION	
2:	if $CCA >= \tau$ then	
3:	set $cong_{flag} \leftarrow 1$	
4:	enter congestion control	
5:	transmit	
6:	if b_{rec} and $E_{cong}=1$ then	
7:	retransmit	
8:	enter congestion control	
9:	else if b_{rec} and $E_{cong}=2$ then	
10:	enter congestion control	
11:	procedure Congestion Control	
12:	sort <i>neighbor</i> – <i>list</i> \leftarrow <i>n</i> _{<i>txp</i>}	
13:	set $F(N) \leftarrow equation(4.5)$	⊳ form coalition
14:	set $v(S)$	▷ specify worth of the coalition
15:	calculate $\theta_i(N, v) \leftarrow equation(4.2)$	
16:	set $fair_{pr} \leftarrow equation(4.3)$	
17:	procedure BEACON TRANSMISSION	
18:	for each beacon from above do	
19:	calculate $txp = bl \leftarrow \sum_{i=1}^{n} (f * s_{pk})$	$r_t > txp$ equivalent to the <i>bl</i>
20:	if $\theta_i = null$ then	
21:	if $\theta_i < txp$ then	▷ allows to converge to a higher power
22:	increment θ_i	
23:	$txp = \theta_i$	
24:	else if $\theta_i \ge txp$ then	▷ end of congestion control cycle
25:	set $\theta_i = null$	
26:	transmit with <i>txp</i>	

transmit power and finally reducing the transmit power equivalent to their marginal contributions in lines 12, 13, 14, 15 and 16, respectively.

The beacon transmission phase starting from line 18 specifies the transmit power adaptation in normal condition (i.e., when there is no congestion) and during congestion phase. In line 19 each vehicle calculates the beaconing load for every beacon generated by the application layer, using the already known message frequency (f), the packet size (s_{pkt}) and the number of neighbours and sets the transmit power such that it does not violate the maximum beaconing load requirement on the CCH. During normal condition, this step is followed by the beacon transmission in line 26, using the calculated transmit power. On the other hand, in line 20, the value θ is used as a flag to check whether AC3 is in congestion. If the condition is satisfied at line 20, then it is important for AC3 to keep on increasing the transmit power with the transmission of every beacon. Therefore, at line 21 if the θ_i is less than the current transmit power as specified by the beaconing load, the θ_i is incremented and the transmit power is set equal to the θ_i . Otherwise for conditions where the value for θ_i has equalled or increased (line 24) than the current transmit power, i.e., the value for θ_i is set to null. This indicates that AC3 has completed one cycle of power decrease (as part of congestion control) followed by the incremental power increase. Therefore, until the generation/reception of next E_{cong} with the value 1 or 2, the beacons can now be sent using the calculated transmit power.

This concludes the design of the Adaptive transmit power Cooperative Congestion Control (AC3). In the following section, we propose an alternative power control design to address CCH congestion and to satisfy the transmission range requirements of vehicular applications.

3.4 MPC: A Multi-metric Tx-Power Control Design

A key characteristic of ITSs is the common interest of all the vehicles in the sensed information by any vehicle. For instance, a vehicle sensing reduced traction on one part of the road may be of significance to the approaching vehicles on some other part of the road. Therefore, the sensed information must be frequently communicated to all the vehicles. Clearly, a higher frequency of distribution of such messages helps in establishing better traffic awareness among vehicles. This is particularly true for the safety applications in order to generate alarms/warnings and to facilitate a timely reaction during a hazardous condition (Fernandes et al., 2016). Besides, it is also critical for an application to transmit beacons up to the desired range as specified by the standards (E. ETSI, n.d.). For instance in Figure 3.9, a high speed ambulance seeks to transmit *emergency vehicle takeover* message up to a maximum range to clear the left lane for easy takeover. Similarly, a crash sensing application ideally requires transmission of the alert messages up to a 250 meter range (Dar et al., 2010) to enable timely lane change maneuver for approaching vehicles.



Figure 3.9: Example scenario of event-driven messages requiring adequate coverage.

Note that, the allocated 75 MHz band for network-wide transmission is relatively bandwidth constrained and transmissions at high frequencies up to the desired range are not without errors. This is particularly true in high density networks. Since a higher message frequency is critical for higher awareness (Dar et al., 2010), the techniques to reduce

message frequency for congestion control are disputed (Park & Kim, 2013). Therefore, finding the trade-off between providing sufficient coverage to different types of messages and maintaining low channel congestion remains the focus in the proposed amendments in safety message delivery approaches.

In this chapter, we handle this trade-off by proposing a Multi-metric Power Control (MPC) approach, which considers the application requirements and the channel states to determine a suitable transmit power for safety messages. Explicitly, the concept distinguishes between the types of safety messages to provide coverage differentiation. Therefore, considering the strict message frequency requirements, the MPC gives a best-effort approach to determine a transmit power for safety messages under different levels of channel congestion. Unlike the existing approaches that aim to enhance reliability for event-driven messages by using prioritized channel access (Rawat et al., 2011), MPC tries to maximize the coverage of event-driven messages in the context of Figure 3.9. This adaptivity is achieved by making local decisions such that the transmit power adaptation keeps low level of channel saturation and facilitates the use of higher transmit power for the event-driven safety messages.

A key challenge in designing such an approach comes from the contradictory requirements posed by the applications for the use of transmission power and the requirement to maintain an acceptable level of channel saturation. That is, a long range message transmission can be provided in a free channel, but using the same transmission power in a dense network can further saturate the channel. Based on this optimization problem, MPC gives a best-effort approach to satisfy the transmission range requirement with coverage differentiation while maintaining an acceptable level of channel saturation. In the following, we present an overview of the proposed metrics use to determine transmit power.

3.4.1 Metric Composition

MPC integrates multiple metrics into the transmit power calculation before every beacon transmission. These metrics include linear combinations of the quality of the control channel q_{cch} and the transmission range requirement specified by the applications app_r .

We introduce the q_{cch} and app_r metrics in the following subsections. At the end, we also show how these metrics are combined to determine the transmit power.

3.4.1.1 Quality of Channel q_{cch}

The key in transmit power selection is the available channel quality, which can be used as an indicator to determine the level of transmitting power. That is, use of high transmit power for maximum coverage is possible in a free channel while the same transmit power in a congested channel can increase the probability of collisions and cause further channel saturation. Therefore, it is important for a vehicle to be aware of the current channel quality as well as to predict to a certain extent the expected channel quality for future transmissions. In order to reflect the channel quality, we make use of the channel busy time *cbt* metric from the physical layer. To indicate the current state of the control channel, we only record the most recent *cbt* on the CCH i.e., *cbt* for the last 100 msec.

To predict the channel quality in future, the MPC uses the beaconing load metric. The idea is to predict the beaconing load for a particular transmit power level, which can provide coverage to the locally computed transmission range by a vehicle. However, accuracy in beaconing load prediction depends upon the estimate of the vehicular density. Therefore, MPC adopts the existing work in (Rawat et al., 2011), which gives a transmission range based on the estimated vehicular density. The formulation for acquiring density can be found in (Rawat et al., 2011). Given a vehicular density on road, the expected beaconing load is then calculated in Mb/sec and it is defined as follows:

Expected beaconing load (*expt_{bl}*): It indicates the expected load incurred on the CCH if a particular transmit power is used for beacon transmission such that the transmit power covers all the vehicles as specified by the vehicular density (as given in (Rawat et al., 2011)), Formally:

 $expt_{bl} = \{txp_i \in [(txp_{min} - txp_{max})] \mid txp_i \text{ covers all } n_i \text{ within vehicular density} \}$ (3.6)

Where, txp_i is the power used for beacon transmission, txp_{min} and txp_{max} are the minimum and maximum transmit powers, respectively. The beaconing load *bl* can be calculated using Eq. 3.7. Note that, the MPC protocol assumes a constant message frequency f_i and fixed size of packet S_{pkt} (i.e., 600 Bytes) to calculate *bl* for all vehicles within the vehicular density.

$$bl = \sum_{i=1}^{n} (f * S_{pkt})_i$$
(3.7)

Using the current *cbt* and the expected beaconing load, a vehicle can estimate the channel quality in recent past and in the future to a certain degree using Eq. 3.8

$$q_{cch} = w1 * (cbt) + w2 * (expt_{bl})$$
(3.8)

To derive q_{cch} , the values for *cbt* and the *expt_{bl}* are weighted (i.e., specified by *w*1 and *w*2, respectively) such that the implication of transmit power in the future (i.e., *expt_{bl}*) gets higher weight than the more immediate channel state specified by the *cbt*. The values are then integrated using a linear combination, which gives a value between the [0,1] interval. A lower value of q_{cch} specifies a better control channel whereas a higher q_{cch}

value specifies a more saturated channel.

3.4.1.2 The Application Requirements appreg

To reflect the application requirements in the transmit power adaptation, the MPC incorporates: 1) the desired transmission range as specified by the safety application, and 2) the priority of the message, which is used for differentiation in transmission coverage for different message types.

The safety applications specify the transmission range which can be mapped to the level of transmit power l_{txp} . We use the findings in (Rawat et al., 2011) to provide a mapping from the transmission range to a transmit power in *dBm*. We specify 1 *dBm* as the minimum transmit power and the highest as 32 *dBm* (i.e., from 120 meters up to 1000 meters, respectively). Ideally, during safety-specific scenarios a vehicle should be able to transmit to provide maximum coverage than the specified range. Therefore, MPC also differentiates between the general purpose applications (such as those for maintaining local topology) and applications for event-driven safety ITS by using a priority level ($l_{priority}$). The general purpose applications are given a priority level of '0' and the critical event-driven messages with higher priority are given a priority level of '1'. With the given transmission range and the priority level of the messages, the application requirement *app_r* is determined by using a linear combination of the aforementioned l_{txp} and $l_{priority}$ in Eq. 3.9.

$$app_r = 1 - [c1 * (l_{txp}) + c2 * (l_{priority})]$$
(3.9)

The specified transmission range of the application is given a higher weight (c1) so that a matching transmit power could be determined. A lower weight (c2) is given to the priority level. The presence of priority level gives a marginal increase in the transmit power for the high priority messages under all channel conditions. The absence of priority

level has no effect on the transmit power calculation as described in the next subsection.

Eq. 3.8 and 3.9 require all the values to be in the [0,1] interval. Note that, the *cbt* and $l_{priority}$ are in [0,1], while l_{txp} and $expt_{bl}$ require conversion into [0,1]. Therefore, Eq. 3.10 is used to map all the possible range of values in l_{txp} and $expt_{bl}$. The actual range of values that l_{txp} can take ranges from 1 to 32 *dBm*. The range of values considered for $expt_{bl}$ is from 0 to 2.9 Mbps, which is in line with the findings in (Torrent-Moreno et al., 2009).

$$f: a \to b = [value_{actual} - value_{min}] * \left[\frac{1}{value_{max} - value_{min}}\right]$$
(3.10)

Where, $value_{actual}$ specifies the value of l_{txp} and $expt_{bl}$ that needs to be converted. The $value_{min}$ and $value_{max}$ represents the minimum and maximum values that l_{txp} and $expt_{bl}$ can take.

3.4.1.3 Determining Transmit Power p_{tx}

The q_{cch} and app_r are used by MPC to continuously adapt the transmit power for every beacon. Each vehicle independently selects a transmit power to suit its transmission needs, and at the same time ensures efficient use of the control channel. The acquired values from the q_{cch} and app_r are integrated in such a way that the highest transmission power is used for a free channel for event-driven messages. The lowest transmit power is used for a congested channel for general purpose beacons. In all other cases, the MPC tries to adapt the transmission power to reduce channel utilization and to provide adequate coverage for the beacons. This also implies that under highly congested conditions, the MPC makes best-effort to give coverage differentiation by giving higher transmit power to the high priority messages. This is achieved by composing a metric from q_{cch} and app_r

app _r	Range	q_{cch}	$p_{tx}(dBm)$
l_{txp} +0	200	0.10	22
l_{txp} +1	200	0.10	25
$l_{txp} + 0$	200	0.50	13
$l_{txp} + 1$	200	0.50	16
$l_{txp} + 0$	200	0.75	7
$l_{txp} + 1$	200	0.75	10

Table 3.2: Comparison of transmit power levels in dBm for a unique transmission range under different levels of the channel quality and the application priority levels

and by further evaluating the weights for each as follows in Eq. 3.11

$$P_{tx} = P_{max} - [(P_{max} - P_{min}) * (\alpha 1(q_{cch}) + \alpha 2(app_r))]$$
(3.11)

The output of P_{tx} is always in the range between P_{min} and P_{max} , where $P_{min} = 1dBm$ and $P_{max} = 32dBm$. The weight $\alpha 1$ is set higher than the weight $\alpha 2$, which implies that quality of the channel is more influential in deciding the transmit power than the application range requirements. Accordingly, for a low level of channel saturation and presence of safety-specific scenario (i.e., for low values of q_{cch} and high value of app_r), the MPC uses maximum the transmission power. Similarly, for the highest level of channel saturation and absence of safety-specific scenario, MPC uses minimum transmit power.

In Table 3.2, the transmit power calculation can be observed (i.e., in *dBm*) by employing multi-metric power control. For the same application transmission range requirements of 200 meters, the Eq. 3.11 gives different transmit power levels for general purpose beacons with no priority level $l_{txp} + 0$ and for event-driven messages with a priority level $l_{txp} + 1$. It shows that a relatively low transmit power is used for general purpose beacons as compared to the event-driven messages for the same value of q_{cch} , which indicates the coverage differentiation effect among the different types of messages. Moreover, the effect of channel quality on the power calculation is also evident. That is, for higher values of the channel quality, the transmit power decreases by a certain value, which

indicates the influence of channel quality on the transmit power adaptation.

Algorithm 2 Multi-metric Tx-Power Control **inputs:** cbt, f, s_{pkt} , AN, l_{txp} , $l_{priority}$ output: txpower 1: procedure MAIN set $AN \leftarrow from neighbour table$ 2: calculate $TN \leftarrow adopted from (Rawat etal., 2011)$ 3: 4: set $t_{const} \leftarrow 0.25$ according to (Artimy etal., 2005) call *calcDensity*() 5: call *expLoad*() 6: 7: get $\leftarrow cbt$ calculate $q_{cch} \leftarrow \alpha(cbt) + \beta(exp_{load})$ 8: get $\leftarrow app_{req}$ from message header 9: calculate $app_{req} \leftarrow Eq. 3.9$ 10: 11: calculate $txp_{power} \leftarrow Eq. 3.11$ 12: send *beacon* procedure CALCDENSITY 13: calculate 14: $range = min \left\{ L(1-K), \sqrt{\frac{LlnL}{K} + \alpha L} \right.$ /*adopted from (Rawat et al., 2011)*/ return range 15: procedure EXPLOAD 16: $\sum_{i=1}^{n} (freq * s_{pkt})_i$ 17: $\exp_{bl} =$ 19: return *exp_{bl}* =0

3.4.2 MPC Algorithm and Organizational Processes

Here, we describe the computational and organizational processes involved in MPC using Algorithm 2 and a UML activity diagram in Figure 3.10. The relevant activity diagram of the implementation in OMNeT++ is also given in the Appendix I.

In Algorithm 2, the input data for the algorithm includes the channel busy time cbt, frequency f, packet size s_{pkt} , actual number of vehicles AN, a priority level $l_{priority}$ and the transmit power required for a priority level l_{txp} . The output of the algorithm is a transmit power txpower for transmitting a beacon. For completeness, we explain the steps in the Algorithm 1 through the activity diagram in Figure 3.10.



Figure 3.10: Illustration of computational and organizational processes in multi-metric power control approach

In Figure 3.10, the execution starts with a simple check to see if MPC is configured for execution. Four different functions i.e., densityRange(), computeLoad(), intervalConversion(), mmetricTxPower() are specified to compute the range of vehicles, calculating beaconing load, to convert the transmit power and beaconing load into [0,1] interval and to compute the transmit power, respectively.

Initially, MPC requires actual number and a total number of vehicles to calculate the

vehicular density as specified by (Rawat et al., 2011). That is, first a C++ map *ndi* is used to get the actual number (*AN*) of neighbour vehicles, whereas the total number of vehicles (*TN*) is calculated through the existing road topology. For instance, considering a 2 lane highway in which each vehicle maintains a safety distance of 20 meters from the neighbors in the same lane and the theoretical transmit power for each vehicle is 750 meters, the *TN* can be calculated as (750/20) * 2 * 2 (Rawat et al., 2011). The density *K* is calculated as AN/TN. With the given vehicular density, an iterator searches the *ndi* to find the range of the farthest vehicle. Subsequently, the expected beaconing load is calculated for the vehicular density as specified in Eq. 3.7. The message frequency is set constant at 10 Hz and the size of a beacon is specified as 600 bytes. To calculate the channel quality, the current *cbt* value is captured from the MAC layer and weighted using α and β .

Each vehicle is configured to specify the application range requirement using a small field which is extracted at the MAC layer and the corresponding transmit power is determined using the look-up table. After converting the transmit power values into [0,1] interval the range is the calculate using Eq. 3.9. Finally, the transmit power is calculated using 3.11.

3.5 Conclusion

As reported in Chapter 2, the most promising solutions for congestion control are based on adapting the transmit power for periodic beacons. Accordingly, we have proposed two transmit power adaptation approaches i.e., a) Adaptive transmit power Cooperative Congestion Control (AC3) design, and b) Multi-metric Tx-power Control (MPC) design. This chapter focused on the descriptions of the proposed beaconing designs including system models, assumptions, schematic illustrations and algorithm specifications. The design verification and performance evaluation of these approaches are presented in
Chapter 5.

Typically, during congestion (i.e., locally computed or reported by remote vehicles), vehicles are required to reduce the transmission power for periodic beacons. The proposed AC3 is designed to improve the fairness in the transmit power reduction through a cooperative game theoretic approach. A congestion event distribution mechanism has been designed, which is a typical requirement to enable fairness within the CS-range. Subsequently, a shapely-value-based approach has been adapted to calculate the marginal contribution of a vehicle towards congestion.

Unlike AC3, the MPC integrates application requirements and channel states to specify a transmit power metric. The MPC metric is locally computed and it is adaptable with respect to the channel congestion as well as the transmission range requirements of an application. The efficient use of CCH is enabled by the best effort approach in MPC, which determines highest transmit power for event-driven messages under a free channel. Whereas, the general purpose messages under congested channel are transmitted with the lowest transmit power. In all other cases, the MPC tries to avoid congestion and provides adequate coverage for periodic beacons.

CHAPTER 4 : ADAPTING CONTENTION WINDOWS AND PREDICTING BACK-OFFS FOR RELIABLE BEACONING

4.1 Introduction

The objective of this chapter is to provide reliable beacon transmission by minimizing synchronous beacon collisions. It could be argued that controlling congestion through the power control techniques can actually result in reduced collisions. This argument is partially correct because the actual reason for synchronous collisions is the unscheduled channel access mechanism of the DSRC (Stanica et al., 2012). In an ad hoc communication setting such as VANETs, the harmonized channel access becomes difficult due to the limited size of the contention window and the aggressive Binary Exponential Back-off (BEB) mechanism. Here, we propose modifications at the 802.11p MAC layer that can potentially minimize beacon collisions to improve reliability. A weighted contention window selection is proposed, which replaces the standard BEB with a weighted contention window selection. Later in the chapter, we also consider a more specific vehicular scenario in which reliable reception of beacons transmitted by a subject vehicle is desired. In that case, we propose a simple yet intuitive PRNG-inspired back-off Selection (PBS) design, such that a group of vehicles tries to select a different back-off from the subject vehicle and hence avoid beacon collisions. The proposed modifications are aimed to be readily integrated into the DSRC standard.

The rest of the chapter is organized as follows: In Section 4.2 we analyze the reasons of beacon collision from the contention window size perspective and present contention window design considerations. Subsequently, Section 4.3 presents the weighted contention window adaptation design along with its behaviour and the algorithm. The preliminaries for the PBS design are given in Section 4.4. In Section 4.5, we analyze

Access category	<i>cwin_{min}</i>	<i>cwin_{max}</i>
Background	15	1023
Best-effort (AC_{BE})	15	1023
Video (AC_{VI})	7	15
Voice (AC_{VO})	3	7
Legacy DCF	15	1023

Table 4.1: Contention window sizes defined by the Enhanced Distributed Channel Access.

synchronous collisions from an illustrative space-time back-off selection perspective. In Section 4.6, we describe the PBS design and its functional specifications. The conclusion is given in Section 4.7.

4.2 Analysing Collisions from Contention Window Size Perspective

In order to enhance the reliability in beacon transmission, the transmit power adaptation is not sufficient. One of the main reasons for message loss is the synchronous collisions due to the simultaneous transmissions from multiple nodes on a shared medium. As a result, multiple wireless stations can collide if the same back-off is selected even in less saturated channels. While the design of the 802.11p brings randomness in back-off selection to avoid synchronous collisions, in reality, the small size of 802.11p contention window only allows collision free domain for a handful of vehicles. Therefore, reliability in beacon transmission cannot be guaranteed using the 802.11p standard and power adaptation alone. Before describing the proposed adaptation design for the contention window, we present some design considerations from the perspective of the contention window size defined in 802.11p.

4.2.1 Design Considerations

Periodic beacons are transmitted using the access category VI (see Table 4.1), which is based on the 802.11e standard (Mangold et al., 2002). This access category provides a class of service, which has a minimum contention window size of 8 with $cw_{min} = 7$ and $cw_{max} = 15$. The reason for having a small cw_{min} is to transmit beacons before they expire in order to achieve high mutual awareness. Note that, the binary exponential backoff increases the window size upon deferred transmissions and reduces it to the minimum upon a successful transmission. It implies that after a successful transmission, the cw_{min} provides a collision free domain for only 8 vehicles, which causes a high number of synchronous collisions at the start of the CCH.

It is worth mentioning that the BEB was designed to improve the reliability of retransmissions in case of collisions. However, retransmission for beacons in VANETs is not applicable due to 1) absence of acknowledgments, and 2) difficulty in judging collisions due to broadcast transmission of beacons. Based on this context, the proposed contention window adaptation aims to enhance reliability based on the following design considerations.

- In 802.11p, a high-level perspective of a transmission success or failure is indicative of the channel state, that is, a deferred transmission indicates a saturated channel and a successful transmission indicates a free channel. In VANETs, high channel saturation occurs in dense networks and the saturation is likely to persist as long as the vehicle remains a part of the dense network. Therefore, it is safe to say that the channel states are although highly variable in VANETs (defined by the vehicular density), the change in channel states is not abrupt, as depicted by the aggressive BEB in 802.11p. Therefore, assuming a constant message frequency, we argue that a contention window adaptation must be less aggressive (i.e., especially after the successful transmission) and adaptive towards channel states, in order to minimize synchronous collisions and to enhance reliable delivery of messages.
- Another observation originates from the effects of contention window size on the short temporal validity of beacons as discussed in Chapter 2. That is, the increase



Figure 4.1: Successful transmission probability with respect to the increasing contention window size

in contention window beyond a certain limit increases the probability of dropped beacons at the source, and hence, increasing the update delays at the receiver. An illustrative probability of beacon drop with respect to contention window sizes is shown in Figure 4.1. Also, the exact maximum window size for beaconing is difficult to determine, bacause contention window adaptation depends upon several dynamic and uncontrollable parameters such as transmission frequency, vehicular density, messages in the queue and channel conditions to name but a few. This notion is significant in adapting the size of the contention window up to an extent, which does not affect dropped beacons.

In the next section, we incorporate these considerations in the design of a weighted contention window adaptation for beaconing.

4.3 Weighted Contention Window Adaptation Design

Clearly, the weighted contention window adaptation introduces a less aggressive post-transmit (i.e., after successful transmission) contention window selection approach by making use of the local information while making sure that the increase in window size does not affect dropped beacons at the source.

To ensure that window adaptation is indicative of the evolving channel conditions (i.e., deteriorating or improving over time) and the contention window adaptation is not aggressive during the post-transmit stage, the design employs two main strategies: (a) a channel congestion state metric to predict the evolving channel condition, and (b) a weighted selection of a suitable post-transmit contention window size for the next beacon.

We use the channel busy time *cbt* at the physical layer to capture the evolving state of the CCH. According to *cbt*, the channel is considered busy if the received signal strength is above a certain threshold (i.e., a signal received or collision detected). We record *cbt* for the previous synchronization intervals (i.e., for 10 Hz message frequency we use 5 synch-intervals). Moreover, the *cbt* for each synch-I is weighted such that the most recent *cbt* is weighted higher than the older ones, as follows.

$$cbt(t) = w_1(cbt)_i + w_2(cbt)_{i+1} + \dots + w_n(cbt)_{i+(n-1)}$$
(4.1)

In order to map cbt(t) into meaningful weights for the contention window size selection, we introduce a middle contention window size (cw_{mid}) besides the default (cw_{min}) and (cw_{max}) such that $(cw_{min}) < (cw_{mid}) < (cw_{max})$. Then for every successful beacon transmission, the cbt(t) is mapped to a selection probability associated with a contention window size in the post transmit phase as follows:

$$P_{cwin(mid)} = |1 - [\sigma_t * \tau]| \tag{4.2}$$

$$P_{cwin(min)} = 1 - [P_{cwin(mid)}]$$
(4.3)

The, $P_{cwin(mid)}$ and $P_{cwin(min)}$ are the probabilities of selecting the middle size contention window and the minimum windows for some value of cbt(t). The σ_t is the inverse of cbt(t) and τ is the threshold of the cbt(t) beyond which weighted contention window selection is considered applicable. As cbt(t) increases beyond a threshold, the probability of selecting back-off from $cwin_{mid}$ for the next beacon increases. The default 802.11p BEB is used as long as the channel conditions remain suitable for transmission. That is, upon a successful transmission, the minimum contention window is selected. Moreover, the dropped beacon at the source also ensures the selection of the minimum contention window.

$$cwin_{post-tx} = \begin{cases} cbt > \tau, cwin(mid) \\ cbt < \tau | beacondropped, cwin(min) \end{cases}$$
(4.4)

The following section further illustrates the behaviour of the proposed approach.

4.3.1 Behaviour at a Microscopic Level

Figure 4.2 illustrates the weighted contention window adaptation design during different possible stages of beacon transmission: a) shows the view of the normal contention window with the minimum and maximum window size as defined in 802.11p standard and the middle contention window size as set by the proposed design, b) shows the probability of selecting the minimum window or the middle size upon successful transmission at *cwin_{min}*, defined by the weights *w*1, and *w*2, respectively, c) shows the increase in window size by $2 * cwin_{current}$ upon a deferred transmission (the increase in window size is similar to the 802.11p standard), d) in case of successful transmission at a contention



Figure 4.2: Behaviour of contention window adaptation for different transmission

window size, which is higher than the $cwin_{mid}$, the $cwin_{mid}$ is reset to the current window size and then the weights w1 and w2 are applicable as in Figure 4.2(a), finally in e) upon dropped beacon at the source, the window size is set to the minimum window size with the probability 1.

Note that, the selection of back-off from cwin(mid) for a subsequent beacon after successful transmission has implications on dropped beacons at the source. That is, continuous transmissions at a higher contention window may result in longer waiting times for the beacons in the queue and hence, resulting in dropped beacons before transmission. Under such conditions, as soon as a vehicle detects a dropped beacon, the back-off is immediately initialized to $cwin_{min}$ to reconcile for the delay incurred due to the loss of the dropped beacon.

For the sake of logical argument and to highlight the usefulness of the proposed approach, we consider the following example:

Without loss of generality, let's assume that two vehicles v_i and v_j have similar *cbt* values, then the probability of simultaneous transmission by selecting same back-off is given by $P(v_i = v_j)$. Where $v_i = s$ for $s \in [all \ slots \ in \ cw_{min} \land cw_{mid}]$ containing initial

and maximum contention windows sizes of c_{min} and c_{mid} , respectively, then selecting s_i and s_j by v_i and v_j , respectively are independent events. So, we have Eq. 4.5.

$$P(v_i = v_j) = \sum_{x=c_{def}}^{c_{mid}} P(v_i = s \mid v_j = s)$$
(4.5)

Since, $P(v_i = s) = P(v_j = s)$ for every slot in the contention window, therefore it is sufficient to calculate $P(v_i = s)$. Hence, for $s \in [cw_{min} : cw_{mid}]$, we have the law of total probability:

$$P(v_{i} = s) = P(v_{i} = s \mid cw_{min}) \cdot P(cw_{min}) + P(v_{i} = s \mid cw_{min}) \cdot P(cw_{mid}) = \begin{cases} \frac{1}{\mid cw_{min} \mid} \cdot w_{cw_{mid}} + \frac{1}{\mid cw_{mid} \mid} \cdot w_{def}, & s \in cw_{min} \\ 0 \cdot w_{cw_{mid}} + \frac{1}{\mid cw_{mid} \mid} \cdot cw_{mid}, & s > cw_{min} \end{cases}$$
(4.6)

Thus, the probability of synchronous collision due to same back-off selection between two vehicles $P(v_i = v_j)$ with the same $cwin_{min}$ and $cwin_{mid}$ is given by:

$$P(v_i = s) = \sum_{x} P(v_i = x, v_j = x) = \sum_{a} P(v_i = x)^2$$
(4.7)

The benefit offered by the weighted contention window selection is the probabilistic post-transmit selection of $cwin_{min}$, which is a less aggressive approach that minimizes collisions at the start of the CCH. In addition, vehicles experiencing high slot utilization can also select back-off from $cwin_{min}$ with certain reduced probability. It means that high slot utilization does not always allocate a large window size and presents an opportunity for vehicles to transmit using small window size. In addition, to avoid vehicles from continuous transmissions using a higher window size, the proposed approach uses a dropped beacon as an indication for very long waiting times at the source. Therefore, to

provide prioritized channel access to account for the dropped beacon, the window size is

initialized to *cwin_{min}* for the next beacon transmission.

Alg	orithm 3 Contention Window Adaptation		
inputs: beacons, transmission status, $cbt(t)$			
out	puts: $cwin_{post-tx}$ > probability of selecting minimum window size		
1:	set $(cwin_{mid}) (cwin_{min}) < (cwin_{mid}) < (cwin_{max})$		
2:	for beacons from above do		
3:	procedure BACKOFF($P_{cwin(mid)}, P_{cwin(min)}$)		
4:	pick $backoff \leftarrow [cwin_{min} - cwin_{mid}]$		
5:	while backoff do		
6:	record $cbt(t) \leftarrow equation 4.1$		
7:	transmit		
8:	if $(cwin_{current} > cwin_{mid})$ then		
9:	$cwin_{mid} = cwin_{current}$		
10:	switch transmit status do		
11:	case transmitted		
12:	calculate $cwin_{post-tx} \leftarrow equation 4.4$		
13:	call Backoff()		
14:	case deferred		
15:	set $cwin_{current} \leftarrow ((cwin_{current}(v_i) + 1) * 2) - 1$		
16:	calculate $cwin_{post-tx} \leftarrow equation 4.4$		
17:	call Backof()		
18:	case Dropped		
19:	set $P_{cwin(min)} = 1$		
20:	$P_{cwin(mid)} = 0$		
21:	call Backoff()		

4.3.2 Algorithm: Contention Window Adaptation

The algorithm for contention window adaptation is given in Algorithm 1. The inputs to this algorithm are the beacons from the application layer, transmission status and the value of *cbt*. The algorithm gives the probabilities for selecting a contention window size upon each transmission attempt $(cwin_{(post-tx)})$. Initially, the algorithm demarcates the contention window sizes i.e., $cwin_{min}$, $cwin_{mid}$ and $cwin_{max}$ in line 1. Then the back-off for all beacons arriving from the application layer is selected using the function Backoff() at line 3. The arguments of this function are $P_{(cwin(mid))}$ and $P_{(cwin(min))}$, which specify the probability of selecting a post transmit back-off from $cwin_{mid}$ and from $cwin_{min}$, respectively. The line 5 through line 6 records the *cbt* during the back-off interval and in line

7 the beacon is transmitted. The algorithm from line 8 through line 21 is significant in order to record the transmission status and to convert the slot utilization into meaningful weights that can be used to determine the contention window size for the next beacon transmission. First of all in line 8, the current contention window size is checked and if it is greater than the *cwin_{mid}*, then the *cwin_{mid}* is reset to *cwin_{current}* in line 9, otherwise the contention window size demarcation remains the same as in line 1. The transmission at line 7 may result in a successful transmission, a deferred transmission or a dropped beacon during the back-off. Therefore, for a successful transmission, the *cwin_(post-tx)* is calculated using Eq. 4.4. For deferred transmission, the contention window is increased as specified in 802.11p and then *cwin_(post-tx)* is calculated. In either case, the calculated values for $P_{(cwin(min))}$ and $P_{(cwin(mid))}$ are used to call the Backoff() function at line 13 and line 17. Finally, if the beacon is dropped during the back-off, the value of $P_{(cwin(min))}$ is set to 0 in lines 19 and 20, respectively. It indicates that for the next beacon transmission the back-off at line 4, will be selected from the *cwin_{min}*.

This concludes the specification of the weighted contention window adaptation design, which aims to reduce the overall synchronous collisions in the network. In the next section, we describe a back-off selection design in order to provide reliable reception of beacons transmitted by a specific vehicles.



Figure 4.3: Example of an influential vehicle with a high longitudinal and lateral dynamics

4.4 Preliminaries for Proposed Back-off Selection Design

Most safety-critical scenarios (if not all) require reliable reception of beacons transmitted by a subject vehicle e.g., during vehicle collision avoidance. As an example, in Figure 4.3, reliable beacon reception from the vehicle (in blue) with high longitudinal and lateral dynamics is more important for the neighbours because it presents a greater risk of causing an accident. It follows that reliable reception of beacons from subject nodes, in safety-critical scenarios such as Figure 4.3, is a critical requirement for vehicular safety applications based on the IEEE 802.11p specifications.

However, according to the specifications in IEEE 802.11p, beacons are transmitted with a small contention window size. As a result, multiple vehicles contend for the shared channel access by selecting a same back-off slot. This is a perfect recipe for synchronous collisions wherein reliable beacon delivery cannot be guaranteed for any vehicle. We consider the problem of selecting the back-off slots from the current contention window to provide reliable delivery of beacons transmitted by a subject vehicle to its neighbors. Given a safety scenario, we propose a Pseudo-Random Number Generator (PRNG)-inspired Back-off Selection (PBS) technique. The proposed technique works on the hypothesis that synchronous collisions of beacons transmitted by a subject vehicle can be reduced if all its neighbors select different back-off slots (i.e., not the back-off slot selected by the subject vehicle). However, the PBS technique presents a tradeoff between



Figure 4.4: Example illustration of hidden node and exposed node problem

the overall collisions in a network and high message reception from a subject vehicle.

Before addressing the synchronous collisions of beacons transmitted from a specific vehicle, we analyze collisions using an illustrative space-time perspective.

4.5 Analysing Collisions in 802.11p

Besides contention among vehicles, hidden node and the exposed node phenomena can also cause collisions (see Figure 4.4). The hidden nodes, A and B in Fig 4.4(a), are not able to sense each other; consequently, they transmit simultaneously and cause a collision at node B. In Figure 4.4(b), node C is exposed to node B's transmission and cannot transmit messages to node D. We remark that reducing the effect of hidden node and exposed node is out of the scope of the proposed PBS technique, as this would typically require some sort of request/response mechanism prior to communication (Koubâa et al., 2009), (Hwang et al., 2005), (Tseng et al., 2011). Rather, in PBS, we only consider the synchronous collisions due to the random probability selection of back-off from the current contention window.

In the following, we seek to explain synchronous collisions using a space-time backoff selection perspective. The outcomes will then be used to improve reliable delivery of beacons transmitted by a specific vehicle using a PRNG-inspired back-off selection design.

The system model is given in Figures 4.5 and 4.6. The space-time schematic illustration shows multiple vehicles transmitting on the CCH. In Figure 4.5, three vehicles select random back-offs before trying to transmit a beacon. A black oval in the time-line denotes the time of back-off selection and a black rectangle denotes the time of back-off expiry. Upon close examination, the details for synchronous collisions due to back-off selection can be identified.



Figure 4.5: Space-time illustration of synchronous collision due to same back-off selection time and back-off value

In Figure 4.5, it can be seen that vehicles *A* and *C* select the back-off at the same time and their back-offs expire at the same time as well, which results in a synchronous collision. Similarly at a later time, the transmission from vehicles *A* and *B* also collide due to the same phenomenon. On the other hand, in Figure 4.6, the back-off selection time for vehicles *A* and *B* are different but their respective back-offs expire at the same time resulting in a synchronous collision. Clearly, the main reason of a synchronous collision is the expiry of back-off at the same time for multiple nodes. Note that, in 802.11p MAC layer, a uniform random probability is used to select back-off from the current window size. Since the number of available back-off slots is significantly smaller than the number of vehicles, the uniform random probability selection does not guarantee a unique back-off value for every vehicle.

Given the space-time back-off selection perspective, our objective is to propose a back-off selection technique for reliable beacon reception of beacons transmitted from



Figure 4.6: Space-time illustration of synchronous collision due to back-off expiry at the same time

a subject vehicle. The proposed technique considers explicit hazardous road scenarios (e.g., forward collision avoidance, and intersection collision warnings), which demand a highly reliable message delivery from a subject vehicle to avoid accidents. Therefore, given a subject vehicle whose beacons must be delivered reliably, we design a simple yet intuitive PRNG-inspired Back-off Selection (PBS) technique. Not only does the PBS preserves the randomness in the slot selection within the current contention window, but it also allows vehicles to avoid the selection of the back-off slot used by any neighbor as and when desired. As a result, PBS improves reliable reception of beacons transmitted by the subject vehicle.

4.6 PRNG-inspired Back-off Selection

We now present our PRNG-inspired Back-off Selection technique, which works on the hypothesis that synchronous collisions of beacons transmitted by a subject vehicle can be reduced if a different back-off value is selected by all neighbors selecting a back-off at the same time (as depicted in Figure 4.5). This is a realistic assumption, as the short contention window results in a high probability of vehicles selecting the same back-off



Figure 4.7: Abstract view of the functional blocks of PRNG-inspired Back-off Selection technique

and that a high message frequency is used by the vehicles.

The scenario considered for reliable beacon delivery includes vehicles that are most crucial in avoiding an accident (e.g., the first or last car in a pileup or a vehicle with high longitudinal and lateral dynamics in a multiple-vehicle collision). We use the example scenario depicted in Figure 4.3, where a vehicle with high longitudinal and lateral dynamics (car in blue) is most likely to cause further accident (hereafter referred to as the subject vehicle). PBS focuses on the receivers of transmissions from this subject vehicle. That is, the beacons (transmitted by the subject vehicle) received by the nieghbors, which are then used to sense this danger. Then, using the proposed PBS technique, the neighbors select a back-off slot which is not used by the subject vehicle. However, it is widely known that 802.11p uses uniform random probability to select the back-off slots from the current contention window and this complicates effort to avoid selecting a back-off slot, which is also selected by the subject vehicle. In PBS, we solve this challenge by maintaining the effect of uniform random probability back-off slots.

At an abstract level, the proposed scheme is illustrated in Figure 4.7. Each vehicle contains active ITS applications, a local topology image, and the main logic of PBS. The local topology image is used to sense the abnormal longitudinal and lateral dynamics of vehicles through the received beacons. The PBS is then implemented in the post-



Figure 4.8: Flow diagram of PRNG-inspired Back-off Selection technique as implemented in the post-transmit phase

transmit phase, which includes the mechanism for back-off selection and back-off counter initialization. The post-transmit phase activates after beacon transmission, and it includes back-off selection to avoid internal and external contention.

4.6.1 Use of Pseudo Random Number Generator (PRNG) in Post-transmit Phase

Each time a beacon is transmitted, a new back-off is selected for the next beacon in the queue. This phase is known as the post-transmit phase. In Figure 4.8, the use of PRNG in the post-transmit phase is illustrated and explained as follows. The key tasks in the post-transmit phase are to pop the transmitted beacon from the queue, to select a back-off slot for the next beacon from the current contention window, and to push the beacon into the queue for transmission. In the proposed back-off selection technique, the uniform random probability selection of back-off is replaced with a PRNG. Similar to the uniform random probability selection, it is important for the PBS to avoid selection of a same back-off slot for every beacon. Therefore, the PRNG requires two different seeds as shown in stage 1, namely: the self MAC identifier, and the current time (i.e., SIM-time in our case). A vehicle can use the self MAC or the MAC of one of its neighbors. It implies that the MAC identifier plays a significant role in predicting the back-off slot of any subject vehicle.

Since the PRNG gives the same outputs if the seed is kept constant, a second seed is needed to create randomness in the back-off slot selection. Therefore, the evolving time (SIM-time) ensures that the seed continuously changes and produces different back-offs for every beacon (i.e., giving the effect of a uniform random probability selection). For every beacon, a back-off slot is selected using PRNG in stage 1. Then, the input from local topology image is used to check whether any subject vehicle exists. If it exists, then a vehicle considers a collision domain with the subject vehicle. That is, assuming that the back-off selection time for all the vehicles is the same (as shown in Figure 4.5), each vehicle tries to avoid the potential back-off value selected by the subject vehicle. Therefore, after selecting the back-off value in stage 1, a second round (i.e., stage 2) of back-off selection using PRNG is carried out. This time, the subject vehicle's MAC identifier is used instead of the self MAC. For identical back-off values in stage 1 and stage 2, a new back-off is selected and the back-off counter is initialized. After each time slot, the counter is decremented and the beacon is eventually transmitted when the counter hits zero. This process repeats as long as the subject vehicle exists in the neighborhood of a vehicle.

4.6.2 Artefact of Implementing PBS Using Discrete-event Simulation

Due to the use of seeds in PBS, the artefact of PBS implementation in getting a truly random back-off slot before every beacon transmission is detailed as follows.

In order to use multiple seeds, we take the product of a vehicle identifier veh_{mac} and the current simulation time η . Note that the random number selection of back-off slots depends upon the output of the PRNG. However, veh_{mac} remains constant for a vehicle and the variation in PRNG output of a vehicle completely depends on the current simulation time (which changes ever so slightly). As a result, a vehicle is more likely to select the same back-off for the consecutive beacon transmissions due to lack of variation in the PRNG output. Therefore, to get different values of back-off slots from a small contention window for every beacon, an exponential increase in the consecutive seeds is required. For this purpose, we utilize an exponential multiplier e^{η} . However, due to the exponential increase in e^{η} , the output from PRNG exceeds the maximum allowed limit of an unsigned integer value within a very short simulation run. Therefore, a limiter is needed to control the successive growth of the multiplier function (e^{η}) and for sustaining the randomness throughout the specified simulation time. For the limiter, we selected ζ such that $0 < \zeta < \eta$. Through multiple empirical tests, the value of ζ is set as 2.2. The equation for generating exponential increase for consecutive seeds using the PRNG is given in Eq. 4.8.

$$\beta_{prng} = \frac{veh_{id} * e^{\eta}}{\zeta \eta} \tag{4.8}$$

where *e* is the exponential constant, η is the simulation time and ζ is the limiter. Figure 4.9 gives a depiction of the corresponding values of *e*, ζ and their *ratio* with respect to the simulation time. Note that *ratio* increases much less in proportion to *e* and ζ over the simulation time. As a result, it allows the simulation to run for longer



Figure 4.9: Illustration of comparative values of e, ζ and their *ratio*

durations before converging to the maximum allowed limit of an unsigned integer. Note that ζ value can be adjusted as per the requirement of the simulation time.

4.6.3 Probability of Beacon Collision

The performance evaluation of the PBS design will be presented in Chapter 5. However, a few observation can already be made which validates the effectiveness of the back-off selection in reducing collisions. The logical explanation brings us back to the schematic illustrations in Figure 4.5 and Figure 4.6, which result in the question of "How can the proposed back-off selection reduce collisions by handling same back-off values selected at the same time as well as different back-off values selected at different times, which expire at the same time?". Thus, to answer this question, we make a few simplifying assumptions and formulate the probability of collision for a beacon that is transmitted by the subject vehicle.

4.6.3.1 System Model

We assume that all vehicles transmit beacons with the same message frequency, and the time instance for selecting back-off (i.e., at the first attempt and for the subsequent attempts when the medium is busy) is the same for all vehicles. For instance, assuming that each slot interval is 13μ sec, the time instance for selecting back-off can be specified at the beginning of every 13μ sec. With the given assumptions, the formulation can be done by finding the probability of a beacon collision transmitted by the subject vehicle. As aforementioned, prior to beacon transmission, each vehicle considers a collision domain that includes the subject vehicle. Therefore, subsequent use of the PRNG allows prediction of the back-off, to some extent, used by the subject vehicle. Upon close examination of this approach, a probabilistic evaluation of beacon collisions can be formulated by considering the following scenarios.

Before a beacon transmission, the influential vehicle v_i selects back-off slots from the current contention window *cwin_{current}*. If v_i selects a back-off *n*, then finding the probability that any other vehicle selects the same back-off is rather intuitive i.e:

$$P(v_i = v_x) = 1 - P(v^o)$$
(4.9)

$$P(v_i = v_x) = 1 - \left[\frac{cwin_{current} - 1}{cwin_{current}}\right]^{(v^0 - 1)}$$
(4.10)

where v_i is the subject vehicle, v_x is any other vehicle, and v^0 denotes all vehicles in the collision domain. Then, Eq. 4.10 is essentially equivalent to the inverse of the probability that no other vehicle selects the same back-off as selected by the subject vehicle. This scenario is relevant to Figure 4.5 in which the back-off selection time as well as the back-off expiry time is the same for two vehicles.

Scenario 2: The second scenario is more relevant to Figure 4.6, where back-off

selection time differs among vehicles but the back-offs expire at the same time that causes a synchronous collision among beacons. Therefore, we try to answer the following.

Consider that v_i selects a back-off *n* from the current contention window and waits until *n* hits zero by decrementing *n* after every slot time. Assuming that the time instance for selecting the back-off is the same for all vehicles, what is the probability that no other vehicle selects the remaining back-off value at the subject vehicle?

Since the probability of selecting any back-off *n* from the current contention window is $1/(cwin_{current})$, first we need to find the probability for the subject vehicle to select a sequence of back-off values in order (i.e., n, n - 1, n - 2, ..., 0), which is $(1/(cwin_{current}))^n$. Note that the selection of sequence depends upon the initial selected back-off; therefore, the expected value of the sequence of back-off values is given as follows.

$$P(n_{seq}) = \frac{1}{N} \sum_{\beta=0 \text{ to } n} (\frac{1}{N})^{\beta}$$
(4.11)

where β shows the sequence from 0 up to *n*. Assuming that the time instance for selecting the back-off is the same for all vehicles, the probability that v_i selects the same back-off while v_x is decrementing *n* such that *n* decrements in ordered sequence i.e., n, n-1, n-2, ..., 0 is given by:

$$P(v_x(n_i) = v_i(n_i)) = \sum_{i=0 \text{ to } n} [1 - \frac{i-1}{i}]^{v^0 - 1}$$
(4.12)

Therefore, total collision probability in scenario 1 and scenario 2 is given by

$$P(coll_{sync}) = 1 - \left[\frac{cwin_{current} - 1}{cwin_{current}}\right]^{(\nu^0 - 1)} * \frac{1}{N} \sum_{\beta = 0 \ to \ n} (\frac{1}{N})^{\beta} * \sum_{i=0 \ to \ n} [1 - \frac{i - 1}{i}]^{\nu^0 - 1}$$
(4.13)



Figure 4.10: Illustration of a complete collision and partial collision. The proposed approach only addresses the complete collision

The assumptions made to derive $P(coll_{sync})$ can be used to understand the type of collisions addressed by the proposed PBS technique. For instance, in Figure 4.10, a perfectly synchronized collision is shown, which is only possible if

- the back-offs for two vehicles are selected at the same time, which also expires at the same time; or
- 2. the back-off for two vehicles are selected at different times but the back-offs expire at the same time.

Therefore, assumption 2 in the system model implies that the proposed technique only addresses perfectly synchronized collisions in time. On the other hand, in Figure 4.10, a partial beacon collision is also shown which could occur using the proposed technique. It is also worth-mentioning that the PBS does not account for collisions caused due to the hidden and exposed nodes.

The key feature of the PBS design is its evolving behavior among receivers of an influential node (e.g., subject vehicle in our example), in which each receiver attempts to select a different back-off slots than the ones selected by the subject vehicle in order to minimize synchronous collisions. In addition, the use of PRNG for back-off selection in the post-transmit phase also maintains the effect of uniform random probability selection as in IEEE 802.11p.

4.7 Conclusion

Synchronous beacon transmission on the CCH continues to be the main concern in providing reliable vehicular communications. To minimize synchronous collisions, adaptive beaconing designs are required at the DSRC layer which can be readily incorporated in the standard. In this chapter we discussed the designs of two beaconing approaches i.e., a) a weighted contention window adaptation design, and b) a pseudo-random number generator (PRNG)-inspired back-off selection design. This chapter focused on the key features of the proposed designs, whereas the verification and performance evaluation, will be given in Chapter 5.

The limitations of the contention window size and aggressive BEB are identified as the main reasons for synchronous collisions. The proposed contention window adaptation approach translates the channel busy times into meaningful weights for selecting the window size in the post-transmit phase. After a successful transmission, the default aggressive behaviour of BEB is replaced such that a higher probability of selecting the minimum window is applicable only in situations of less channel saturation and vice verse.

The pseudo-random number generator (PRNG)-inspired back-off selection is designed to improve the reliability of reception for beacons transmitted from a subject vehicle during safety-specific scenarios. The key feature of the proposed approach is the use of PRNG for back-off selection. By carefully selecting the seed, the PRNG has the ability to randomly select back-offs from within the current contention window. More importantly, it can predict to a certain extent the back-off used by the influential vehicle and hence avoid synchronous collisions.

CHAPTER 5: PERFORMANCE EVALUATION

5.1 Introduction

In the previous chapters, we have been proposing adaptive beaconing strategies using transmit power, contention window size and the back-off selection mechanism. The AC3 makes use of the vehicle's marginal contribution to determine a proportional power decrease. The multi-metric power control approach focuses on controlling congestion and providing a form of coverage differentiation among periodic and the high priority beacons. The weighted contention window adaptation aims to reduce synchronous collisions to improve the reliability of the network as a whole. Finally, the PRNG-inspired back-off selection design aims to minimize collisions from a subject vehicle during a hazardous road condition.

In this chapter, we make use of a discrete event simulator to evaluate the performance of the proposed beaconing designs and demonstrate how the proposed approaches achieve their objectives.

The rest of the chapter is divided into two main sections. For completeness, in the first section, we give an overview of the available simulation tools followed by the description of the simulation environment used for evaluation. In the second section, a series of simulations are conducted to capture the performance of periodic beacons through some crucial metrics.

5.2 Simulators for Vehicular Network Simulations

Generally, for research in wired and wireless networks, an optimal choice of preliminary testing and deployment is carried out through Simulation software (Stanica et al., 2011). The choice of simulating a network originates from the fact that direct deployment of a solution in a network can cause unexpected results. Therefore, before deployment,



Figure 5.1: Basics components in VANET simulation

rigorous testing of a network solution requires simulations, which provide randomness in the vehicular scenarios and requires less abstraction in the underlying communication assumptions for analysis.

The complexity of simulating vehicular networks comes from two distinct simulation challenges. First is the simulation of vehicular mobility and the second is to model the communication behaviour during mobility. Usually, simulation of vehicular ad hoc network includes three main components as shown in Figure 5.1. In order to represent the topology of a vehicular network, a road structure is specified such as a highway, an urban road scenario or a particular vehicular safety scenario. Then, mobility models (Härri et al., 2009) are required to enable realistic vehicular movements on the road topology. Finally, packet-level simulation depicts the communication among vehicles which is based on the several communication models at different layers of the DSRC standard.

For quantitative evaluation of beaconing protocols in VANETs, numerous simulation platforms exist. To decide an appropriate simulator for designing new beaconing approaches, it is important to understand the features of different simulators. In the following, we briefly describe only the most widely used simulators for VANETs.

5.2.1 Network Simulators

Over the years network simulator-2 (Ns-2) (Issariyakul & Hossain, 2011) has been used as a de facto open-source standard for wired and wireless networks simulations. The Ns-2 is very complex due to the interaction between C/C++ and TCL languages. For vehicular simulations, there exists some limitations i.e., Ns-2 lacks provisions for channel switching and it needs to include patches during the synchronization interval, which adds to complexity in the simulation. Moreover, for large-scale ITS deployments, the memory usage and CPU consumption becomes unmanageable, which is a disadvantage. Ns-2 is not maintained anymore as an active project for network simulations.

Networks Simulator-3 (NS3) (Henderson et al., 2008) is the replacement of NS2 which is not backwards compatible with its predecessor. Unlike complex bindings among multiple languages in NS2, the NS3 is completely based on C++ and Python languages. This allows NS3 to be a lightweight network simulator, which is capable of simulating large-scale wireless networks. However, NS3 does not have a detailed framework as in some of the other simulators such as NS2, OMNeT++ and EstiNet (S.-Y. Wang et al., 2013).

Another open-source network simulator is the OMNeT++ (Varga et al., 2001), which has multiple frameworks for mobile ad hoc networks. The OMNeT is the modular and component-based simulation approach, therefore, it allows for ease of reusability. In addition, this approach enables OMNeT++ to simulate a wide variety of networks including wired, wireless, network-on-chip and queueing systems, to name but a few. The OM-Net++ also provides domain-specific functionality for VANETs using Vehicles in Networks Simulation (Veins) framework (Eckhoff & Sommer, 2012). It is highly recommended for the multichannel operation of 802.11p (Ros et al., 2014), and it has a strong integration with traffic simulators such as SUMO.

5.2.2 Vehicular Mobility Simulators

Simulation of Urban Mobility (SUMO) (Behrisch et al., 2011) is an open-source vehicular mobility simulator implemented in C++, which is developed by the Institute of Transportation Systems at German Aerospace center. SUMO supports microscopic simulations for vehicles and allows access to a traffic simulation through a TCP/IP-based interface called Traffic Control Interface (TraCI). Several tools are accompanied with SUMO, which enables tasks such as route finding, visualization, calculating CO2 emissions and importing networks generated by other supported vehicular mobility generators.

Corridor Simulation (CORSIM) (Halati et al., 1997) is one of the software tools in the Traffic Software Integrated Systems (TSIS) for microscopic mobility generation. CORSIM is a commercial tool maintained by the Federal Highway Authority (FHWA) of the US. CORSIM is an integration of NETSIM (used for urban vehicular networks) and FRESIM (used for highway vehicular networks). It is based on component-based architecture giving it more flexibility, which implies that users can modify the set of tools. However, CORSIM is a commercial product and can only be used on Windows platform, which makes it difficult to integrate with network simulators based on opensource platforms (e.g., linux, Ubuntu).

Mobility model generator for Vehicular Mobility (MOVE) (Karnadi et al., 2007) is developed in JAVA and it runs on top of SUMO. Two components enable vehicular simulations i.e., Map Editor and Movement Editor. The former allows for a manual map creation, automatic map generation or the import of real world maps using TIGER (Topographically Integrated Geographic encoding and Referencing) database. The movement editor allows manual trips specification for vehicles, automatically generated trips or trips based on real bus time table. MOVE provides a comprehensive and easy to use user-interface for quick vehicular mobility generation.

5.2.3 Simulation Framework used in Thesis

We choose to analyse and design beaconing approaches for VANETs using Veins. The main reason for this choice is the modular approach of the framework, which allows for ease of reusability. More importantly, amongst the available simulators, Veins



Figure 5.2: OMNet++ simulation anatomy of vehicular ad hoc networks

includes most comprehensive implementation of the MAC layer and a proven support for 802.11p. It is also the most recommended simulator for MAC layer modifications for VANETs according to (Ros et al., 2014). Note that, the proposed beaconing designs in this thesis are based on power and contention window adaptation mechanisms. For mobility, the Veins provides integration with the SUMO mobility generator with detailed mobility traces. SUMO supports large scale vehicle simulations only restricted by the computational ability of a PC. Moreover, the desired precision required in the microscopic mobility models, lane change scenarios and CO2 emission estimation (although not used in this thesis) are sufficiently enough for the scope of this thesis.

5.2.3.1 Veins Framework: An Overview

Veins integrates SUMO (for vehicular mobility) with OMNeT++ (for network simulation). This conceptual integration can be observed in Figure 5.2. To import a vehicular network scenario into OMNeT++ working environment, a TraCI server is connected to veins framework, which presents topology information and mobility traces to the MIXIM. The wireless communication behaviour is specified in MIXIM and executed on mobile vehicles obtained through veins framework. The behaviour of vehicular communication can be obtained in the form of simulation traces such as scalars or vectors for analysis.



Figure 5.3: OMNet++ simulation anatomy of vehicular ad hoc networks

The OMNeT++ has a modular approach in which a simulation is characterised by the network description (*.ned*) files, the C++ modules (simple or compound) that provide the functionality of a packet-level simulation and finally the messages (*.msgfiles*) used for communication among modules. The process of building a network simulation is illustrated in Figure 5.3. Initially the *.msg* files are translated into the C++ (*_*m.cc/h*) files by using the *opp_msgc* compiler. Then the modules in C++ and the simulation kernel libraries are compiled using conventional compilation and linking to generate a simulation program. Note that, the *.ned* files are dynamically loaded during the execution of the simulation program. The execution of the simulation program of a network description requires the initialization parameters from the *.ini* file.

They key compound module in Veins is the car module, which encompasses the DSRC layers as shown in Figure 5.4. The beacons are generated by the wave Application, which connects to the *nic* through *appl.lowerControlIn* \rightarrow *unicupperControlIn* gate. The wave application layer defines the format of safety and non-safety applications e.g., wave short message and the wireless service advertisement etc. The behaviour

of periodic messages can be made adaptive from the wave application such as the traffic generation pattern and the message frequency. The *nic* is also a compound module which extends *BaseMacLayer*. The *nic* includes the *mac*1609_4, which manages the channel switching behaviour and the timeslots in the CCH and SCH. Mechanisms such as contention window, EDCA queue management and transmit power assignment are also provided on the *mac*1609_4. The *mac*1609_4 connects to the *phy*80211*p* module using the gate *mac*1609_4.*lowerLayerOut* \rightarrow *phy*80211*p.upperLayerIn*. The *phy*80211*p* provides the modulation/propagation models for transmission as well as the mechanism to retrieve information about received signals.



Figure 5.4: The car compound module in Veins

5.3 Performance Evaluation

A pre-requisite of performance evaluation is to verify the correct implementation of the proposed beaconing designs with respect to the conceptual model (Carson et al., 2002), (Sargent, 2005). Therefore, the evaluation of each approach is preceded by verification of the beaconing design by observing its vector traces in a simulated scenario. After verification, the evaluation of the approach is presented using performance metrics to show how an approach achieves its objectives.

Parameter	Value
Carrier frequency	5.88, 5.89 GHz
CCH bandwidth	10 MHz
CS threshold	-95dBm
Propagation model	Freespace path loss
Bit rate	6 Mb/s
Msg. frequency	10 Hz
Beacon size	600 B
Highway lanes	2,4
Vehicle density	5 up to 50 veh/lane/km
Decider type	Decider80211p
Simulation time	Multiple runs of 200 seconds each

Table 5.1: Simulation parameters in Veins for AC3 performance evaluation

5.3.1 Evaluation of AC3

This section presents the verification and evaluation of the proposed applicationbased cooperative congestion control approach presented in Chapter 3.

5.3.1.1 Simulation Setup

The Veins framework – version 2.1, OMNeT++ – version 4.2.2 and sumo – version 0.17.0 is used for the evaluation of AC3. The implementation of AC3 is based on cross-layer information exchange of the DSRC layered architecture. The DSRC application layer is configured to generate beacons at 10 Hz. The neighbour tables for topology awareness are also maintained at the application layer. The MAC layer is responsible for acquiring channel states from the physical layer. Subsequently, this information is shared with the application layer to facilitate 1) generation of congestion event distribution messages and 2) enable fair tx-power calculation as defined in AC3. The simulation scenario consists of the 1 km 2 way and 4 way highways with varying number of vehicular densities ranging from 5 veh/lane/km up to 50 veh/lane/km at freeway speeds. The detailed simulation parameters are given in Table 5.1.

5.3.1.2 Verfication of the Approach

To validate AC3, we seek to answer two basic questions, namely: a) Do vehicles decrease their transmit power upon reception of a congestion event? and b) Do vehicles



Figure 5.5: An excerpt showing the transmit power adaptation in AC3 before and after a congestion event

with different congestion levels adapt transmit power differently? To verify the correct implementation of the design, we chose to observe the simulation traces.

Figure 5.5 shows an excerpt of transmit power adaption vector traces of a vehicle over a period of six seconds. Each vehicle in the network was configured to transmit beacons at 10 Hz frequency. We observed that the transmit power gradually increases (with every beacon transmission) before a congestion event is generated or detected. Upon reception of the congestion event, a sudden decrease in the transmit power was observed as proposed in the AC3 design.

We used the same scenario and captured the transmit power traces for two different vehicles as shown in Figure 5.6. Both vehicles have different levels of channel congestion which translates into varying levels of transmit power adaptation.



Figure 5.6: Run-time adaptive transmit power of two geographically apart vehicles

5.3.1.3 CBT for different values of α

The key objective of AC3 is to control congestion. In a two-lane scenario with 60 vehicles/lane/km, a Channel Busy Time (*cbt*) vector is shown in Figure 5.7. The threshold values (i.e. *al pha*) specifies the channel congestion level in percentage for a vehicle in broadcasting a congestion event, which is followed by the fair power reduction using AC3. The lower *cbt* values until 75 simulation seconds are due to the lack of vehicles which gradually increases when the road is fully congested. The value of *al pha* is purely a design choice and it can be observed that AC3 maintains the overall *cbt* in proportion to *al pha*. The findings suggests that AC3 can effectively control the overall *cbt*, which corresponds to the choice of threshold for congestion event distribution.

5.3.1.4 Channel Access Time

Besides controlling congestion, fair transmission opportunities are key to timely delivery of periodic beacons. This is illustrated in Figure 5.8, where the channel access



Figure 5.7: Comparison of the channel busy time (cbt) in case of different values of *alpha*

time of vehicles is shown. The gradual increase in the values is due to the increase in the network density. The lowest channel access time is achieved in (Torrent-Moreno et al., 2009), which is based on strict fairness in power adaptation to avoid congestion occurring in the first place. In contrast, the design of AC3 is based on fair power decrease during congestion. Still, AC3 produces acceptable level of transmission opportunities as compared to (Torrent-Moreno et al., 2009) (Reference 1) and better transmission opportunities as compared to (X. Guan et al., 2007) (Reference 2). Note that the increasing trend in the curves is due to the gradual increase in the vehicular densities over the simulation time.



Figure 5.8: Comparison of the channel access time with respect to the simulation time, which indicates the increasing channel load

5.3.1.5 Packet Delivery Ratio

To measure how reliable are the transmissions from the AC3, we used the packet delivery ratio (PDR). In Figure 5.9, PDR defines the ratio of overall successfully received beacons to the overall sent beacons with respect to different vehicular densities. The performance is compared against the constant transmit powers of 32 dBm and 20 dBm and also with the reference approach (Kloiber et al., 2012). The use of constant transmit power saturates the channel and the beacons suffer from very low reception rates for the given densities due to collisions. Since AC3 mandates transmit power adaptation through the distribution of E_{cong} , the beacon reception is significantly higher for the specified vehicular densities. The comparison of the AC3 with reference approach in (Kloiber et al., 2012) is also shown.


Figure 5.9: Comparison of overall packet delivery ratio (PDR) metric of AC3 with constant transmit powers and the reference approach

5.3.1.6 Average per-vehicle throughput

We then used per-vehicle throughput metric to analyse the rate of successful message delivery in AC3. The comparison of per-vehicle throughput can be observed in Figure 5.10, where throughput is represented in bits per second (bps) for various vehicular densities. Each vehicle in all vehicular densities is configured to transmit at 10 Hz frequency. The comparison of throughput is performed with a constant transmit power (AC3 OFF), the reference approach (Kloiber et al., 2012) and with different values of *alpha* (at 50% and 65%). It can be observed that similar values of throughput were recorded until the 20 vehicle density scenario. This is due to the lower congestion values in the network, which results in similar throughput values. For α value of 50%, AC3 shows maximum throughput. This is because the threshold ensures that congestion events are generated as soon as a vehicle records *cbt* value greater the 50%. As a result, the network maintains lower congestion levels and higher throughput values. On the other hand, for higher values of



Figure 5.10: Comparing per vehicle throughput metric of AC3 with the default and reference approach

 α (i.e. 65%), relatively lower throughput can be observed. This is because higher α values allow higher congestion in the network, which causes more erroneous transmissions. Similarly, the lowest throughput value is observed for the constant transmit power, which does not implement any congestion control policy.

5.3.2 Evaluation of MPC

This section evaluates the multi-metric power control technique proposed in Chapter 3. First, we verify the correct functioning of the proposed MPC design followed by a comparison with the most relevant beaconing approach.

5.3.2.1 Simulation Setup

The simulation platform is still the Veins framework – version 2.1, OMNeT++ – version 4.2.2 and sumo – version 0.17.0 for the evaluation of MPC. The implementation of MPC is also based on the cross-layer information exchange of the DSRC layered architecture. Two types of messages are generated by the application layer: a) general

Parameter	Value
Carrier frequency	5.88, 5.89 GHz
CCH bandwidth	10 MHz
CS threshold	-95dBm
Propagation model	Freespace path loss
Bit rate	6 Mb/s
Frequency	10 Hz
Beacon size	600 B
Highway lanes	2,4
Vehicle density	5 up to 50 veh/lane/km
Decider type	Decider80211p
Tx-power range	1 – 32 dBm
w1	0.25
w2	0.75
<i>c</i> 1	0.65
c2	0.35
α1	0.75
α2	0.25
Simulation time	Multiple runs of 200 seconds each

Table 5.2: Simulation parameters in Veins for MPC performance evaluation

purpose beacons for topology awareness, and b) periodic event-driven messages $l_{priority}$. The default value of 0 for $l_{priority}$ represents a normal beacon and a value of 1 represents event-driven beacon. The MAC layer uses the $l_{priority}$ value from the application layer and the *cbt* from the physical layer to adapt transmit power for every beacon. The simulation scenario consists of the 1 km 2 way and 4 way highways with varying number of vehicular densities ranging from 5 up to 50 veh/lane/km at freeway speeds. The detailed simulation parameters are given in Table 5.2.

5.3.2.2 Verfication of the Approach

The idea of MPC verification is to: a) observe the power adaptation with respect to the increasing channel saturation or vehicular density and b) to observe the coverage differentiation effect. Accordingly, we use a two lane highway with 30 vehicles in each direction and collect vector traces for the power adaptation of a vehicle over time. We configure the vehicles to transmit beacons at 10 Hz frequency. Besides, each vehicle is configured to transmit five periodic beacons followed by one event-driven message. This is to observe the evolving effect of coverage differentiation of event-driven messages



Figure 5.11: Adaptive transmit power behaviour of a vehicle with four normal beacons followed by a high priority beacon over a period of time

with respect to the periodic beacons. For the first 20 simulation seconds, the road has less number of vehicles. Therefore, the transmit power of event-driven message and periodic beacons stay at approximately 22dBm and 13dBm, respectively as shown in Figure 5.11 (figure on the left). At a later time between 115 to 135 simulation seconds, the number of vehicles on road increase and the change in the relative transmit power can be observed. The transmit power for event-driven messages and periodic beacons becomes 19dBm and 10.5dBm, respectively. This behaviour is inline with proposed MPC design that requires vehicles to adapt transmit power for beacons under varying levels of channel saturation.

5.3.2.3 Reliability

Reliability is measured as a ratio of the number of received packets to the number of sent packets. We use reliability to demonstrate the effect of controlling congestion and providing coverage differentiation in MPC. In Figure 5.12, the x-axis shows the vehicle ids arranged with respect to the increasing distances from a source vehicle. The y-axis shows the reliability of message reception from the source vehicle to the neighbour vehicles over a period of time. It can be observed that the use of highest transmit power (32dBm) gives best reliability of approximately 0.8 for very short distance due to high



Figure 5.12: Comparing reliability over increasing distances for MPC and constant use of transmit powers

interferences. On the other hand, lowest transmit power gives a 100 percent reliability for short distances and it drops abruptly to 0 due to signal attenuation. Other similar trends can also be observed in the figure. The reliability of normal beacons and event-driven beacons in MPC can also be observed. For high priority beacons, approximately 95% re-liability is achieved over longer distances and approximately 70% reliability is achieved for periodic beacons over longer distances. This is due to the ability of MPC to maintain transmit power according to channel states, as a result, use of higher transmit power for event-driven messages gives better reliability than the constant transmit power.

Similarly, in Figure 5.13 the same scenario is used to compare reliability of beacons with the reference approach in (X. Guan et al., 2007). Clearly, the MPC performs better than the reference approach. The reliability of the reference approach represents both the periodic beacons and the high priority beacons. The adaptive mechanism according to channel congestion enables MPC to achieve higher reliability. Whereas, in the reference



Figure 5.13: Comparing reliability over increasing distances for MPC and the reference approach

approach lower reliability can be attributed to an instability problem, which arises due to lack of mechanisms to control congestion.

5.3.2.4 Per-vehicle Message Reception Rates

Another way to represent the successful beacon reception is to analyse the average per-vehicle message reception with respect to vehicular densities (see Figure 5.14). For the same number of overall sent messages, the MPC shows much better message reception rates. Note that, we use the message reception only for the periodic beacons and not the event-driven messages. Again, the better results are due to the provisions in MPC to adapt the transmit power with respect to the varying levels of channel saturation.

5.3.2.5 Collision Rates

In Figure 5.15, average number of collisions is depicted for the MPC and the reference approach (X. Guan et al., 2007) with respect to vehicular densities. Clearly, the reference approach, which suffers from the instability problem during higher levels of



Figure 5.14: Comparison of overall message reception with respect to vehicular density

channel saturation, experiences more collisions than the MPC.

5.3.3 Evaluation of Contention Window Adaptation

This section evaluates the weighted contention window approach proposed in Chapter 4. First, we verify the correct functioning of the proposed design followed by a comparison with the de facto standard i.e., 802.11p.

5.3.3.1 Simulation Setup

As aforementioned, when a vehicle transmits a beacon, the proposed approach monitors the channel states in order to associate a meaningful weight for contention window size selection. Therefore, the implementation of weighted contention window requires modifications at the MAC layer during the post-transmit phase.

5.3.3.2 Verfication of the Approach

The logic behind weighted contention window is to associate probabilities with minimum and middle contention window sizes with respect to the increasing channel sat-



Figure 5.15: Comparison of average number of collisions for varying levels of vehicular densities

uration. Therefore, it is important to verify this behaviour for vehicles in a simulated scenario. We configure a two lane highway which is heavily populated with vehicles that transmit beacons at a high frequency. In Figure 5.16, for increasing vehicular densities, we record the window selection probabilities for minimum and middle window sizes in the post-transmit phase. It could be observed that as the channel becomes saturated (here increase in time is representative of the increasing number of vehicles or otherwise more congestion), the probability of selecting the middle contention window approaches to 1. Accordingly, with the exact same proportions, the minimum window selection probability approaches to 0. This behaviour verifies the evolution of weights for window sizes according to the design.

5.3.3.3 Fairness Index

An important feature of the contention-based channel access approach is to provide equal opportunities for the vehicles to transmit on the CCH. Therefore, we use the Jain's



Figure 5.16: Run-time selection probability of minimum contention window w.r.t CBT for the first few seconds of simulation

Fairness index (FI) (Jain et al., 1999) to analyse the level of fairness in the channel access provided by the proposed approach. The Eq. 5.1 represents the *FI* used for evaluation.

$$FI = \frac{\left(\sum_{i} G_{i}\right)^{2}}{n * \sum_{i} \left(G_{i}\right)^{2}}$$
(5.1)

where G_i represents the throughput, which is defined as the number of bytes sent in a unit time by a vehicle *i*. The *n* represents the total number of vehicles. Clearly, the Eq. 5.1 gives a value between [0, 1], where 1 shows perfect fairness and 0 shows no fairness. Accordingly, the Figure 5.17 shows the comparison between the proposed contention window adaptation and the standard 802.11p. It can be observed that the fairness index is comparable in both contention window mechanisms. However, for larger values of *cwin_{mid}*, the fairness slightly deteriorates in the proposed approach. This is mainly due the diversity in back-off slot selection when window size increases.



Figure 5.17: Jain's fairness index of the proposed approach with standard 802.11p

5.3.3.4 Awareness quality

One way of measuring awareness is to measure the number of received beacons in a network. Clearly, high message reception means a high level of awareness of the local local topology. In Figure 5.18, the number of received beacons from a source vehicle is recorded on different vehicles. The receiving vehicles are arranged on the x-axis with respect to their increasing distances from the source. By controlling the synchronous collisions, the awareness quality in terms of the proposed approach increases as compared with the 802.11p.

High message reception is achieved due to the less aggressive behaviour in selecting the $cwin_{min}$ and larger window sizes in the post-transmit phase. The Figure 5.19 shows the average number of collisions. Observe that, significantly fewer collisions are recorded



Figure 5.18: Awareness quality measured as the number of received beacons and compared with the standard 802.11p

for the proposed approach as compared with the 802.11p. Besides, for higher values of $cwin_{mid}$, the collisions are further reduced.



Figure 5.19: Comparison of average number of collisions for varying levels of vehicular densities and window sizes

5.3.3.5 Overall Throughput

In a highway scenario of 50 vehicles/lane/km in a two lane road, we show the performance of the proposed approach using overall throughput. In Figure 5.20, the results are compared with the standard 802.11p. It can be observed that initially for few seconds



Figure 5.20: Comparison of throughput variation of the proposed approach with the standard 802.11p

the throughput values remain similar. This is because initially the network has limited vehicles and the probability of selecting the minimum contention window remains very high. However, as the number of vehicles increase, the proposed approach starts to select $cwin_{mid}$ in the post-transmit phase for new beacons. Therefore, as a result of reduced collisions, a higher throughput can be observed.

5.3.4 Evaluation of the PBS

This section evaluates the pseudo-random inspired back-off selection design proposed in Chapter 4. First, we verify the correct functioning of the proposed design, which is then followed by a comparison with the standard IEEE 802.11p using relevant metrics.

5.3.4.1 Verification of the Approach

To verify the correctness of random back-off selection using PRNG, we use a scenario with 50 vehicles/lane/km where vehicles are configured to transmit at 10Hz. We do not consider any influential node / subject vehicle. The idea is to analyze the effect of



Figure 5.21: Comparing the number of back-off slots experienced by each vehicle in a 50 vehicles/lane/km scenario for the 802.11p and the PBS design

using PRNG in selecting back-offs using per-vehicle number of selected back-off slots. In Figure 5.21, we record the total number of back-off slots selected by each vehicle for a period of 100 simulation seconds. A clear correlation between the "ups" and "downs" of the number of selected back-off slots can be observed. The decreasing trend in the graph is due to the new vehicles that appear on the road and hence, they transmit for a shorter period of time. This demonstrates that the proposed use of PRNG in PBS maintains the effect of uniform random probability selection of back-offs as used in IEEE 802.11p.

5.3.4.2 Message Reception and Reliability

The key objective of the PBS is to avoid selecting the back-off as selected by the subject vehicle. Therefore, in the performance evaluation, we configure a vehicle having high longitudinal and later dynamics. We configure a 1 km highway scenario with different densities of the vehicles and the message frequency is set at 10 Hz for all vehicles. During the simulation, all neighbors of the subject vehicle attempt to select a back-off



Figure 5.22: Comparing the average number of beacon reception from a specified node using 802.11p and the proposed approach with 20 dBm transmit power

value different from the subject vehicle. Figure 5.22 shows the average number of received beacons from the subject vehicle over a period of 200 simulation seconds. We observe that PBS achieves a better message reception with respect to the IEEE 802.11p for varying vehicular densities.

Knowing that the subject vehicle may only be present briefly, in Figure 5.23, we evaluate a more realistic scenario where the receivers of a subject vehicle use PBS for only 5 seconds (the duration can be trivially adjusted to more than 5 seconds). We assume that after 5 seconds the subject vehicle's movement is back to normal (e.g., driver of a manual car restarts and drives off the vehicle which stalls at a traffic junction) and the use of PBS is no longer required. In Figure 5.23, we record the average per-vehicle reliability on receiver vehicles calculated as the ratio of the number of received beacons from the subject vehicle to the total number of sent beacons by the subject vehicle. Over different vehicular densities, the PBS clearly outperforms the 802.11p standard. Within a specified



Figure 5.23: Comparing the average per-vehicle reliability achieved by PBS and 802.11p in different vehicular densities

region, we record the reliability for all neighbors of the subject vehicle. The improved reliability demonstrated that PBS minimizes beacon collisions transmitted by the subject vehicle using the PRNG back-off selection.

We use the same simulation setup to further illustrate the reception quality of PBS on every receiver of the subject vehicle. In Figure 5.24, the x-axis shows the receiver vehicle IDs on the basis of increasing distances from the subject vehicle. Observe that for 20 dBm transmit power, the PBS gives a higher beacon reception rate for all neighbour vehicles over different vehicular densities. In Figure 5.25, we configure vehicles to transmit at 32 dBm to observe the beacon reception in the same way. Note that the average overall beacon reception of PBS still remains higher than the 802.11p. However, some interesting result could be seen for the per vehicle beacon reception in Figure 5.25 (see the highlighted portion). The first four vehicles have a lower beacon reception rate in PBS than the 802.11p. This is due to the hidden node collisions that we briefly discussed in Chapter



Figure 5.24: Comparing the number of messages received from a source vehicle over increasing distance when using 802.11p and the PBS by using 20 dBm transmit power

4. According to the simulation setup, the PBS algorithm becomes active only when the subject vehicle is in the middle of the 1 km highway. At this time, the nearby neighbours of the subject vehicle are more susceptible to hidden collisions because vehicles at either end of the highway are outside the communication range of each other.



Figure 5.25: Comparing the number of messages received from a source vehicle over increasing distance when using 802.11p and PBS with 32 dBm transmit power

5.3.4.3 Implications of the PBS Design

We have shown that synchronous collisions from a particular vehicle can be minimized with the PRNG-inspired back-off selection. However, predicting the back-off of a subject vehicle and re-selecting a different back-off over a longer period of times can increase overall collisions in the network (not to be confused with physical collisions between vehicles). Explicitly, in an effort to minimize collisions from a subject vehicle,



Figure 5.26: Comparing the overall average number of collisions in a network using 802.11p and the proposed approach with 20 dBm transmit power

the number of available back-off slots are reduced to n - 1 (where *n* represents all the slots) at the neighbor vehicles. This results in more synchronous collisions among the neighbors due to smaller contention window sizes. The results of overall collisions for different vehicular densities using 20 dBm and 32 dBm are presented in Figure 5.26 and Figure 5.27, respectively. We observe that relative difference among overall collisions at 32 dBm is minimal as compared to the 20 dBm. This is due to the increasing interferences and hidden node collisions which normalize the collisions caused due to the reduction of contention window size in PBS.

Our findings demonstrated that there is a tradeoff between achieving a high reliability of beacon receptions transmitted by the subject vehicle and reducing the overall beacon collisions in the network. However, assuming that a subject vehicle can exist for a short period of time, a higher overall collisions in the network can be realistically tolerated to acquire a higher beacon reception from a specified node.



Figure 5.27: Comparing the overall average number of collisions in a network using 802.11p and the proposed approach with 32 dBm transmit power

5.4 Conclusion

In this chapter, we have evaluated the proposed beaconing designs in this thesis. The objective of this chapter was twofold: a) to verify the correct implementation of the beaconing approaches according to the proposed design and b) to evaluate the performance of proposed approaches. Simulation tools including OMNeT++ 4.2.2, Sumo-0.17.1 and veins-2.1 were used for verification and performance evaluation.

The performance evaluation has shown that the proposed beaconing designs perform according to their design objectives, which are quantified using metrics such as channel busy time, channel access time, packet delivery ratio, throughput, reliability, collision rates, fairness index, and collisions from a particular source.

CHAPTER 6 : CONCLUSION

In a vehicular ad hoc network, the status information about neighbours and road/traffic scenarios is shared among vehicles and infrastructure using periodic beacons. It implies that the use of effective beacon dissemination strategies is key to provide safer and more enjoyable commuting experience on roads through ITS applications. Since beacon dissemination occurs on a shared wireless medium it is intrinsically unpredictable. Therefore, the focus of this thesis has been on the adaptive beaconing designs for improved performance of ITS applications. Specifically, this thesis has addressed two key performance requirements for adaptive beaconing approaches i.e., controlling congestion and minimizing collisions on the control channel. In the following, we summarize the contributions of the thesis.

6.1 Summary of Contributions

Despite a long list of adaptive beaconing strategies in literature, the qualitative analysis of beaconing strategies is not well documented. Therefore, the initial part of this thesis has been dedicated to establishing a better understanding of beaconing approaches. This was achieved through a qualitative literature review, which included a survey of beaconing approaches, classifications of beaconing approaches based on design and architectural characteristics and qualitative capability evaluations. In the second part of this thesis, we have been proposing and evaluating adaptive beaconing designs that have the potential to enhance congestion and awareness control in VANETs. In the following we list key contributions of the proposed adaptive design for beaconing approaches:

1. Unlike naïve frequency-based congestion control strategies, we have shown that an event-based congestion control strategy based on transmit power can be more

141

effective in reducing channel saturation while maintaining a high level of mutual awareness. Through a game-theoretic approach, we proposed the notion of providing fairness in the power reduction as and when congestion occurs. Regarding the fairness in power decrease during congestion, we concluded that the use of shapely values for considering vehicles' marginal contributions towards congestion is an effective approach. Note only does AC3 effectively translates marginal contributions into fair power decrease for congestion control, it also provides acceptable transmission opportunities for the vehicles.

- 2. We presented a second power control technique which accounts for multiple but relevant parameters for transmitting power adaptation such as channel states, expected beaconing load and application requirements. The MPC metric is locally computed and it is adaptable with respect to the channel congestion as well as the transmission range requirements of an application. The simulation results verify the significance of MPC in enhancing reliability and reducing collisions in different vehicular densities. This illustrates that congestion and awareness control requires an evolving transmit power adaptation behaviour for the efficient use of the CCH. Indeed, the efficient use of CCH is enabled by the best effort approach in MPC, which determines highest transmit power for event driven messages under a free channel. Whereas, the general purpose messages under congested channel are transmitted with the lowest transmit power. In all other cases, the MPC tries to avoid congestion and provides adequate coverage for periodic beacons.
- 3. The standard IEEE 802.11p contention mechanism has been modified to eliminate the aggressive behaviour of the binary exponential back-off with a weighted contention window adaptation, which has been proved to have reduced synchronous collisions significantly in large-scale ITS deployments. That is, the design trans-

lates the channel busy times into meaningful weights for selecting the window size in the post transmit phase. After a successful transmission, the default aggressive behaviour of BEB is replaced such that a higher probability of selecting the minimum window is applicable in situations of less channel congestion and vice verse. Moreover, the window adaptation design also makes provisions for prioritized channel access to vehicles experiencing dropped beacons. The simulation results clearly demonstrate better reliability of beacon transmission as compared to the IEEE 802.11p standard.

4. A specific safety-specific scenario of a potentially dangerous vehicle is used to propose a simple yet intuitive PRNG-inspired back-off selection design to enhance reliable delivery of beacons transmitted by the dangerous vehicle to the vehicles in its transmission range. The key feature of the PBS technique is the use of PRNG for back-off selection. By carefully selecting the seed, the PRNG has the capability to select back-off within the current contention window. More importantly, it can predict to a certain extent the back-off used by the influential mode (e.g. subject vehicle) and hence, avoids synchronous collisions of beacons transmitted by the subject vehicle. The simulated results indicated that PBS is superior in providing reliable message delivery for beacons transmitted by the subject vehicle when used for both short and long durations. However, there is a tradeoff between high reliability of beacons transmitted by the subject vehicle and the increase in overall collisions in the network.

6.2 Future Work

In this section, we first give the possible extension of the work done in this thesis followed by some general research directions.

6.2.1 Possible Extension of this Research

This thesis has addressed the issue of congestion and awareness control through adaptive beaconing designs, however; we have not considered non-safety applications and their effect on the proposed beaconing designs. Therefore, the following is a possible direction in which the work done in this thesis could be extended.

The ITS applications use a common CCH for one hop dissemination of beacons and for Wireless Service Advertisements (WSAs). The beacons are critical for cooperative safety applications while the later are to initiate a Basic Service Set (BSS) on SCH for non-safety applications. In this perspective, the coexistence of safety and non-safety ITS applications is highly dependent upon the efficient adaptive beaconing strategies. In particular, the ITS coexistence problem originates from the key objectives of the existing adaptive beaconing designs: 1) rapid event detection, 2) high awareness degree of potential collision partners, and 3) reliable delivery of beacons. Through this thesis, it could be observed that these objectives are only achievable to a restricted spatial variation in the transmission range while maintaining an acceptable level of channel saturation. This spatial variation could be considered as the critical range that covers only a set of immediate neighbors that pose a potential hazard. It implies that message dissemination beyond the critical range is of least interest to the safety applications and it is unreliable. In contrast, this notion affects the WSAs, which require distant transmission defined by the vehicles at the edge of the transmission range for maximum advertisement coverage. Additionally, for robust non-safety communications, the provider of a service needs a high level of accuracy about SCH utilization in all WAVE enable vehicles. However, the standards in the WAVE/ETSI stack use local information about SCH utilization in order to select a suitable SCH for non-safety communications. It implies that unreliable transmission beyond the critical range results in suboptimal advertisement coverage while the over-simplistic use of local information for SCH utilization produces inconclusive inferences about the SCH utilization at the provider.

While this thesis focused on the reliable and efficient performance of safety applications, the predicted growth in the demand for non-safety applications demand more flexible adaptive beaconing designs for the coexistence of safety and non-safety applications. Therefore, as an extension of the research work in this thesis, we are investigating adaptive beaconing designs on the notion ITS coexistence. The significance of this aspect could contribute to the field by presenting a novel perception by which to investigate and facilitate ITS coexistence as a benchmark towards sustainable mobility.

In the following we present some more research ideas.

6.2.2 Flexible Channelization for Spatial Reuse

According to (Marinho & Monteiro, 2012), an assigned wireless spectrum can be underutilized if the communication activity is sporadic. Likewise, 5 GHz spectrum for VANETs can be considered as a special case of the underutilized spectrum having a majority of communication activity in the CCH. That is, subject to empirical evaluation, multiple SCHs are underutilized due to 1) deterministic nature of traffic transmission and 2) flexibility of switching to any SCH upon availability. However, 802.11p multi-channel access is inflexible in the choice of channel selection for system-control and safety-critical data. Considering a high-priority transmission on CCH, there is a need for more flexible approaches that allows opportunistic access to SCH for CCH data as and when desired. Such an approach requires a cognitive behavior in which vehicles can assess a suitable channel and more importantly a seamless mechanism for decentralized channel switching for vehicles.

6.2.3 Heterogeneous Network Communication for Scalability

Most beaconing approaches address the problem of scalability under scarce CCH resources and increase in vehicle density. Alternatively, in situations of sparse network connectivity, these approaches will not be suitable, as they assume a certain level of vehicular density. Besides, the lack of vehicles, sparse connectivity also defines the suboptimal propagation conditions, which reduce the transmission range of a vehicle. Subsequently, network clusters become prominent and ITS services are affected. Recently, use of satellite communication has been proposed for non-safety applications under sparse connectivity. However, a critical implication of satellite network communication is the delay that affects the information freshness. Further investigation is required for suitable heterogeneous communication patterns that can reduce the effects of sparse connectivity and retain information freshness at the same time.

REFERENCES

- Artimy, M. M., Robertson, W., & Phillips, W. J. (2005). Assignment of dynamic transmission range based on estimation of vehicle density. In *Proceedings of the 2nd acm international workshop on vehicular ad hoc networks* (pp. 40–48).
- Bai, F., Stancil, D. D., & Krishnan, H. (2010). Toward understanding characteristics of dedicated short range communications (dsrc) from a perspective of vehicular network engineers. In *Proceedings of the sixteenth annual international conference on mobile computing and networking* (pp. 329–340).
- Behrisch, M., Bieker, L., Erdmann, J., & Krajzewicz, D. (2011). Sumo–simulation of urban mobility. In *The third international conference on advances in system simulation* (simul 2011), barcelona, spain.
- Bohm, A., Jonsson, M., & Uhlemann, E. (2011). Adaptive cooperative awareness messaging for enhanced overtaking assistance on rural roads. In *Vehicular technology conference (vtc fall), 2011 ieee* (pp. 1–5).
- Böhm, A., Jonsson, M., & Uhlemann, E. (2013). Co-existing periodic beaconing and hazard warnings in ieee 802.11 p-based platooning applications. In *Proceeding of* the tenth acm international workshop on vehicular inter-networking, systems, and applications (pp. 99–102).
- Boukerche, A., Rezende, C., & Pazzi, R. W. (2009). Improving neighbor localization in vehicular ad hoc networks to avoid overhead from periodic messages. In *Global telecommunications conference, 2009. globecom 2009. ieee* (pp. 1–6).
- Camp, J., & Knightly, E. (2010). Modulation rate adaptation in urban and vehicular environments: cross-layer implementation and experimental evaluation. *Networking*, *IEEE/ACM Transactions on*, 18(6), 1949–1962.
- Campolo, C., & Molinaro, A. (2013). Multichannel communications in vehicular ad hoc networks: a survey. *Communications Magazine, IEEE*, *51*(5), 158–169.
- Campolo, C., Molinaro, A., Vinel, A., & Zhang, Y. (2012). Modeling prioritized broadcasting in multichannel vehicular networks. *Vehicular Technology, IEEE Transactions on*, 61(2), 687–701.
- Campolo, C., Vinel, A., Molinaro, A., & Koucheryavy, Y. (2011). Modeling broadcasting in ieee 802.11 p/wave vehicular networks. *Communications Letters*, *IEEE*, 15(2), 199–201.

Carson, J. S., et al. (2002). Model verification and validation. In Simulation conference,

2002. proceedings of the winter (Vol. 1, pp. 52–58).

- Céspedes, S., Lu, N., & Shen, X. (2013). Vip-wave: On the feasibility of ip communications in 802.11 p vehicular networks. *Intelligent Transportation Systems, IEEE Transactions on*, 14(1), 82–97.
- Consortium, C. V. S. C., et al. (2005). Vehicle safety communications project: task 3 final report: identify intelligent vehicle safety applications enabled by dsrc. *National Highway Traffic Safety Administration, US Department of Transportation, Washington DC*.
- Dar, K., Bakhouya, M., Gaber, J., Wack, M., & Lorenz, P. (2010, May). Wireless communication technologies for its applications [topics in automotive networking]. *IEEE Communications Magazine*, 48(5), 156-162. doi: 10.1109/MCOM.2010.5458377
- Di Felice, M., Ghandour, A. J., Artail, H., & Bononi, L. (2012). On the impact of multichannel technology on safety-message delivery in ieee 802.11 p/1609.4 vehicular networks. In *Computer communications and networks (icccn)*, 2012 21st international conference on (pp. 1–8).
- Eckhoff, D., & Sommer, C. (2012). A multi-channel ieee 1609.4 and 802.11 p edca model for the veins framework. In *Proceedings of 5th acm/icst international conference on simulation tools and techniques for communications, networks and systems: 5th acm/icst international workshop on omnet++.(desenzano, italy, 19-23 march, 2012). omnet.*
- ETSI, E. (n.d.). 302 665, 3 (2010) intelligent transport systems (its). *Communications Architecture*.
- ETSI, T. (2009a). Intelligent transport systems (its); vehicular communications; basic set of applications; definitions (Tech. Rep.). Tech. Rep. ETSI TR 102 638.
- ETSI, T. (2009b). Its; harmonised channel specifications for intelligent transport systems operating in the 5 ghz range. *DTS-0040016*.
- European Commission, E. F. P. f. R., & Innovation. (n.d.). *Horizon 2020*. Retrieved 1.2.2016, from https://ec.europa.eu/programmes/horizon2020/
- Fernandes, B. F., Alam, M., Gomes, V., Ferreira, J., & Oliveira, A. (2016, January). Automatic accident detection with multi-modal alert system implementation for its. *Vehicular Communications*, 3(1), 1 - 11. doi: http://dx.doi.org/10.1016/j.vehcom .2015.11.001
- Gabbard, J. L., Fitch, G. M., & Kim, H. (2014). Behind the glass: Driver challenges and opportunities for ar automotive applications. *Proceedings of the IEEE*, *102*(2), 124–136.

- Ghafoor, K. Z., Lloret, J., Bakar, K. A., Sadiq, A. S., & Mussa, S. A. B. (2013). Beaconing approaches in vehicular ad hoc networks: a survey. *Wireless personal communications*, 73(3), 885–912.
- Gozalvez, J., & Sepulcre, M. (2007). Opportunistic technique for efficient wireless vehicular communications. *Vehicular Technology Magazine*, *IEEE*, 2(4), 33–39.
- Guan, W., He, J., Bai, L., & Tang, Z. (2011). Adaptive congestion control of dsrc vehicle networks for collaborative road safety applications. In *Local computer networks* (*lcn*), 2011 ieee 36th conference on (pp. 913–917).
- Guan, X., Sengupta, R., Krishnan, H., & Bai, F. (2007). A feedback-based power control algorithm design for vanet. In 2007 mobile networking for vehicular environments (pp. 67–72).
- Gupta, P., & Kumar, P. R. (2000). The capacity of wireless networks. *Information Theory, IEEE Transactions on*, 46(2), 388–404.
- Halati, A., Lieu, H., & Walker, S. (1997). Corsim-corridor traffic simulation model. In *Traffic congestion and traffic safety in the 21st century: Challenges, innovations, and opportunities.*
- Härri, J., Filali, F., & Bonnet, C. (2009). Mobility models for vehicular ad hoc networks: a survey and taxonomy. *Communications Surveys & Tutorials, IEEE*, 11(4), 19–41.
- Harsanyi, J. C., Selten, R., et al. (1988). A general theory of equilibrium selection in games. *MIT Press Books*, *1*.
- He, J., Chen, H.-H., Chen, T. M., & Cheng, W. (2010). Adaptive congestion control for dsrc vehicle networks. *IEEE communications letters*, 14(2), 127–129.
- Henderson, T. R., Lacage, M., Riley, G. F., Dowell, C., & Kopena, J. (2008). Network simulations with the ns-3 simulator. *SIGCOMM demonstration*, 14.
- Hu, D., & Mao, S. (2013). On co-channel and adjacent channel interference mitigation in cognitive radio networks. *Ad Hoc Networks*, *11*(5), 1629–1640.
- Huang, C.-L., Fallah, Y. P., Sengupta, R., & Krishnan, H. (2009). Information dissemination control for cooperative active safety applications in vehicular ad-hoc networks. In *Global telecommunications conference*, 2009. globecom 2009. ieee (pp. 1–6).
- Huang, C.-L., Fallah, Y. P., Sengupta, R., & Krishnan, H. (2010). Adaptive intervehicle communication control for cooperative safety systems. *Network, IEEE*, 24(1), 6–13.
- Huang, C.-L., Sengupta, R., Krishnan, H., & Fallah, Y. P. (2011). Implementation and evaluation of scalable vehicle-to-vehicle safety communication control. *Communi*-

cations Magazine, IEEE, 49(11), 134–141.

- Hurley, P., Le Boudec, J.-Y., & Thiran, P. (1998). A note on the fairness of additive increase and multiplicative decrease (Tech. Rep.).
- Hwang, L.-J., Sheu, S.-T., Shih, Y.-Y., & Cheng, Y.-C. (2005). Grouping strategy for solving hidden node problem in ieee 802.15. 4 lr-wpan. In Wireless internet, 2005. proceedings. first international conference on (pp. 26–32).
- Ieee standard for information technology-part 11 wireless access in vehicular environments. (2010, July). IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009), 1-51. doi: 10.1109/IEEESTD.2010.5514475
- 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. (2012, March). *IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007)*, 1-2793. doi: 10.1109/IEEESTD.2012.6178212
- Ieee standard for wireless access in vehicular environments (wave)–multi-channel operation. (2011, Feb). *IEEE Std 1609.4-2010 (Revision of IEEE Std 1609.4-2006)*, 1-89. doi: 10.1109/IEEESTD.2011.5712769
- Ieee standard for wireless access in vehicular environments (wave) networking services. (2010, Dec). *IEEE Std 1609.3-2010 (Revision of IEEE Std 1609.3-2007)*, 1-144. doi: 10.1109/IEEESTD.2010.5680697
- IIHSHLDI. (n.d.). Fatality facts, 2013. Retrieved 1.2.2016, from http://www.iihs.org/ iihs/topics/t/general-statistics/fatalityfacts/state-by-state-overview
- Issariyakul, T., & Hossain, E. (2011). *Introduction to network simulator ns2*. Springer Science & Business Media.
- Jabbarpour, M. R., Noor, R. M., Khokhar, R. H., & Ke, C.-H. (2014). Cross-layer congestion control model for urban vehicular environments. *Journal of Network and Computer Applications*, 44, 1–16.
- Jain, R., Durresi, A., & Babic, G. (1999). *Throughput fairness index: An explanation* (Tech. Rep.). Tech. rep., Department of CIS, The Ohio State University.
- Jiang, D., Chen, Q., & Delgrossi, L. (2008). Optimal data rate selection for vehicle safety communications. In *Proceedings of the fifth acm international workshop on vehicular inter-networking* (pp. 30–38).

Karnadi, F. K., Mo, Z. H., & Lan, K.-c. (2007). Rapid generation of realistic mobility

models for vanet. In *Wireless communications and networking conference*, 2007. *wcnc* 2007. *ieee* (pp. 2506–2511).

- Kloiber, B., Härri, J., & Strang, T. (2012). Dice the tx powerimproving awareness quality in vanets by random transmit power selection. In *Vehicular networking conference* (*vnc*), 2012 ieee (pp. 56–63).
- Koubâa, A., Severino, R., Alves, M., & Tovar, E. (2009). Improving quality-of-service in wireless sensor networks by mitigating hidden-node collisions. *Industrial Informatics, IEEE Transactions on*, 5(3), 299–313.
- Lasowski, R., & Linnhoff-Popien, C. (2012). Beaconing as a service: a novel serviceoriented beaconing strategy for vehicular ad hoc networks. *Communications Magazine, IEEE*, 50(10), 98–105.
- Lasowski, R., & Schmidt, R. (2011). A multi-channel beacon forwarding approach in dual radio vehicular ad-hoc networks. In *Intelligent vehicles symposium (iv)*, 2011 *ieee* (pp. 522–527).
- Liu, Y., Niu, J., Ma, J., & Wang, W. (2013). File downloading oriented roadside units deployment for vehicular networks. *Journal of Systems Architecture*, 59(10), 938– 946.
- Mangold, S., Choi, S., May, P., Klein, O., Hiertz, G., & Stibor, L. (2002). Ieee 802.11 e wireless lan for quality of service. In *Proc. european wireless* (Vol. 2, pp. 32–39).
- Marinho, J., & Monteiro, E. (2012). Cognitive radio: survey on communication protocols, spectrum decision issues, and future research directions. Wireless Networks, 18(2), 147-164. Retrieved from http://dx.doi.org/10.1007/s11276-011-0392-1 doi: 10.1007/s11276-011-0392-1
- Mittag, J., Thomas, F., Härri, J., & Hartenstein, H. (2009). A comparison of singleand multi-hop beaconing in vanets. In *Proceedings of the sixth acm international workshop on vehicular internetworking* (pp. 69–78).
- Narayanaswamy, S., Kawadia, V., Sreenivas, R. S., & Kumar, P. (2002). Power control in ad-hoc networks: Theory, architecture, algorithm and implementation of the compow protocol. In *European wireless conference* (Vol. 2002).
- of Transport, U. D. (n.d.). *Reported road casualties in uk, q2 2015.* Retrieved 1.2.2016, from https://www.gov.uk/government/uploads/system/uploads/ attachment_data/file/473850/quarterly-estimates-april-to-june-2015.pdf
- Ota, K., Dong, M., Chang, S., & Zhu, H. (2014). Mmcd: Max-throughput and min-delay cooperative downloading for drive-thru internet systems. In *Communications (icc)*, 2014 ieee international conference on (pp. 83–87).

- Ota, K., Dong, M., Chang, S., & Zhu, H. (2015). Mmcd: cooperative downloading for highway vanets. *Emerging Topics in Computing, IEEE Transactions on*, 3(1), 34–43.
- Ota, K., Dong, M., Zhu, H., Chang, S., & Shen, X. (2011). Traffic information prediction in urban vehicular networks: A correlation based approach. In *Wireless communications and networking conference (wcnc), 2011 ieee* (pp. 1021–1025).
- Park, Y., & Kim, H. (2013). Collision control of periodic safety messages with strict messaging frequency requirements. *Vehicular Technology, IEEE Transactions on*, 62(2), 843–852.
- Rawat, D. B., Popescu, D. C., Yan, G., & Olariu, S. (2011). Enhancing vanet performance by joint adaptation of transmission power and contention window size. *Parallel and Distributed Systems, IEEE Transactions on*, 22(9), 1528–1535.
- Reinders, R., van Eenennaam, M., Karagiannis, G., & Heijenk, G. (2011). Contention window analysis for beaconing in vanets. In *Wireless communications and mobile computing conference (iwcmc), 2011 7th international* (pp. 1481–1487).
- Rezaei, S., Sengupta, R., & Krishnan, H. (2007). Reducing the communication required by dsrc-based vehicle safety systems. In *Intelligent transportation systems conference*, 2007. itsc 2007. ieee (pp. 361–366).
- Rezaei, S., Sengupta, R., Krishnan, H., Guan, X., & Student, P. (2008). Adaptive communication scheme for cooperative active safety system. *NewsBITS (December 2008)*, 4.
- Ros, F. J., Martinez, J. A., & Ruiz, P. M. (2014). A survey on modeling and simulation of vehicular networks: Communications, mobility, and tools. *Computer Communications*, 43, 1–15.
- Sargent, R. G. (2005). Verification and validation of simulation models. In *Proceedings* of the 37th conference on winter simulation (pp. 130–143).
- Schmidt, R., Leinmuller, T., Schoch, E., Kargl, F., & Schafer, G. (2010). Exploration of adaptive beaconing for efficient intervehicle safety communication. *Network*, *IEEE*, 24(1), 14–19.
- Schmidt, R. K., Brakemeier, A., Leinmüller, T., Kargl, F., & Schäfer, G. (2011). Advanced carrier sensing to resolve local channel congestion. In *Proceedings of the eighth acm international workshop on vehicular inter-networking* (pp. 11–20).
- Schmidt, R. K., Kloiber, B., Schüttler, F., & Strang, T. (2011). Degradation of communication range in vanets caused by interference 2.0-real-world experiment. In *Communication technologies for vehicles* (pp. 176–188). Springer.

- Schmidt-Eisenlohr, F., Torrent-Moreno, M., Mittag, J., & Hartenstein, H. (2007). Simulation platform for inter-vehicle communications and analysis of periodic information exchange. In Wireless on demand network systems and services, 2007. wons'07. fourth annual conference on (pp. 50–58).
- Schwartz, R. S., Ohazulike, A. E., Sommer, C., Scholten, H., Dressler, F., & Havinga, P. (2012). Fair and adaptive data dissemination for traffic information systems. In *Vehicular networking conference (vnc)*, 2012 ieee (pp. 1–8).
- Schwartz, R. S., Ohazulike, A. E., Sommer, C., Scholten, H., Dressler, F., & Havinga, P. (2014). On the applicability of fair and adaptive data dissemination in traffic information systems. *Ad hoc networks*, *13*, 428–443.
- Sepulcre, M., Gozalvez, J., Harri, J., & Hartenstein, H. (2010). Application-based congestion control policy for the communication channel in vanets. *Communications Letters*, *IEEE*, 14(10), 951–953.
- Sepulcre, M., Gozalvez, J., & Hernandez, J. (2013). Cooperative vehicle-to-vehicle active safety testing under challenging conditions. *Transportation research part C: emerging technologies*, 26, 233–255.
- Sepulcre, M., Mittag, J., Santi, P., Hartenstein, H., & Gozalvez, J. (2011). Congestion and awareness control in cooperative vehicular systems. *Proceedings of the IEEE*, 99(7), 1260–1279.
- Settawatcharawanit, T., Choochaisri, S., Intanagonwiwat, C., & Rojviboonchai, K. (2012). V-desync: Desynchronization for beacon broadcasting on vehicular networks. In Vehicular technology conference (vtc spring), 2012 ieee 75th (pp. 1–5).
- Shankar, P., Nadeem, T., Rosca, J., & Iftode, L. (2008). Cars: Context-aware rate selection for vehicular networks. In *Network protocols*, 2008. icnp 2008. ieee international conference on (pp. 1–12).
- Sommer, C., Tonguz, O. K., & Dressler, F. (2010). Adaptive beaconing for delay-sensitive and congestion-aware traffic information systems. In *Vehicular networking conference (vnc)*, 2010 ieee (pp. 1–8).
- Sommer, C., Tonguz, O. K., & Dressler, F. (2011). Traffic information systems: efficient message dissemination via adaptive beaconing. *Communications Magazine*, *IEEE*, 49(5), 173–179.
- Stanica, R., Chaput, E., & Beylot, A.-L. (2011). Simulation of vehicular ad-hoc networks: Challenges, review of tools and recommendations. *Computer Networks*, 55(14), 3179–3188.
- Stanica, R., Chaput, E., & Beylot, A.-L. (2012). Loss reasons in safety vanets and implications on congestion control. In *Proceedings of the 9th acm symposium on*

performance evaluation of wireless ad hoc, sensor, and ubiquitous networks (pp. 1–8).

- Stanica, R., Chaput, E., & Beylot, A.-L. (2014). Reverse back-off mechanism for safety vehicular ad hoc networks. Ad Hoc Networks, 16, 210–224.
- Tielert, T., Jiang, D., Chen, Q., Delgrossi, L., & Hartenstein, H. (2011). Design methodology and evaluation of rate adaptation based congestion control for vehicle safety communications. In *Vehicular networking conference (vnc)*, 2011 ieee (pp. 116– 123).
- Torrent-Moreno, M., Mittag, J., Santi, P., & Hartenstein, H. (2009). Vehicle-to-vehicle communication: fair transmit power control for safety-critical information. *Vehicular Technology, IEEE Transactions on*, 58(7), 3684–3703.
- Torrent-Moreno, M., Santi, P., & Hartenstein, H. (2005). Fair sharing of bandwidth in vanets. In *Proceedings of the 2nd acm international workshop on vehicular ad hoc networks* (pp. 49–58).
- Torrent-Moreno, M., Santi, P., & Hartenstein, H. (2006). Distributed fair transmit power adjustment for vehicular ad hoc networks. In Sensor and ad hoc communications and networks, 2006. secon'06. 2006 3rd annual ieee communications society on (Vol. 2, pp. 479–488).
- Tseng, H.-W., Yang, S.-C., Yeh, P.-C., & Pang, A.-C. (2011). A cross-layer scheme for solving hidden device problem in ieee 802.15. 4 wireless sensor networks. *Sensors Journal*, *IEEE*, 11(2), 493–504.
- Uzcategui, R., & Acosta-Marum, G. (2009). Wave: a tutorial. *Communications Magazine, IEEE*, 47(5), 126–133.
- Valerie Sathe, B., Richard, W., Joshua, C., Matt, S., & William, T. (2013). Expert opinion forecast of connected vehicle technology. *Michigan Department of Transportation* (*MDOT*), 1–16.
- Varga, A., et al. (2001). The omnet++ discrete event simulation system. In *Proceedings* of the european simulation multiconference (esm2001) (Vol. 9, p. 65).
- Wang, C. D., & Thompson, J. P. (1997, March 18). Apparatus and method for motion detection and tracking of objects in a region for collision avoidance utilizing a realtime adaptive probabilistic neural network. Google Patents. (US Patent 5,613,039)
- Wang, S.-Y., Chou, C.-L., & Yang, C.-M. (2013). Estinet openflow network simulator and emulator. *Communications Magazine*, *IEEE*, 51(9), 110–117.
- Willke, T. L., Tientrakool, P., & Maxemchuk, N. F. (2009). A survey of inter-vehicle communication protocols and their applications. *Communications Surveys & Tuto-*

rials, IEEE, 11(2), 3-20.

- Winter, E. (2001). *The shapely value, in the handbook of game theory.* RJ Aumann and S. Hart, North-Holland.
- Yang, K., Ou, S., Chen, H.-H., & He, J. (2007). A multihop peer-communication protocol with fairness guarantee for ieee 802.16-based vehicular networks. *Vehicular Technology, IEEE Transactions on*, 56(6), 3358–3370.
- Yang, Y. R., & Lam, S. S. (2000). General aimd congestion control. In Network protocols, 2000. proceedings. 2000 international conference on (pp. 187–198).
- Yoo, J. (2013). Receiver-centric physical carrier sensing for vehicular ad hoc networks. *Multimedia Tools and Applications*, 1–11.
- Zhang, H., Ma, Y., Yuan, D., & Chen, H.-H. (2011). Quality-of-service driven power and sub-carrier allocation policy for vehicular communication networks. *Selected Areas in Communications, IEEE Journal on*, 29(1), 197–206.

ITINERARY OF APPENDICES

The appendices include the implementation details of the proposed beaconing approaches. As aforementioned, the OMNeT++ 4.2.2 has been used for implementations. Usually, cross layer approach is required for beaconing approaches therefore, the application layer (i.e.*BaseWaveApplLayer.cc*) and the MAC layer (i.e.*Mac*16094.cc) has been modified predominantly in 802.11p. Instead of providing the complete C++ code (which is over-whelming in size), we choose to include the activity diagrams of the most relevant concepts presented in this thesis. The itinerary of appendices is as follows.

	Figure No.	Description	
	Appendix B	The UML activity diagram of the <i>initiliaztion()</i> method used in the AC3 algorithm. This method exists in the BaseWaveApplLayer.cc source module of the 802.11p application layer	
	Appendix C	The activity diagram of the <i>coalitionfinder()</i> method used for specifying the group of vehicles for the cooperative congestion control used in AC3 algorithm. This method exists in the BaseWaveApplLayer.cc source module of the 802.11p application layer	
	Appendix D	The UML activity diagram of the <i>findPermutations</i> () method used to calculate permutations after a coalition has been formed in the AC3 algorithm. This method exists in the BaseWaveApplLayer.cc source module of the 802.11p application layer	
	Appendix E	The UML activity diagram of the <i>computePlayerContribution</i> () method used to determine the marginal contribution of players within a coalition. This method exists in the BaseWaveApplLayer.cc source module of the 802.11p application layer	
	Appendix F	The UML activity diagram of the <i>findPayoffTable()</i> , which computes the pay- off for all the vehicles. Payoff in case of AC3 is the value of the transmit power in dBm by which a vehicle must reduce its transmit power. This method exists in the BaseWaveApplLayer.cc source module of the 802.11p application layer	
	Appendix G	The UML activity diagram of the <i>computeFairPowerReduction()</i> is used to compute the actual transmit power for the next beacon transmission based on the payoff values. This method exists in the BaseWaveApplLayer.cc source module of the 802.11p application layer	
	Appendix H	The UML activity diagram of the <i>prepareWSM</i> () shows the beaconing message which is used for the congestion event distribution in AC3. This method exists in the BaseWaveApplLayer.cc source module of the 802.11p application layer	
	Appendix I	The multimetric power control (MPC) is implemented in the MAC layer of the $802.11p$. The activity diagram of the <i>handleUpperMsg()</i> of the <i>Mac</i> 1609 ₄ .cc is shown, which acts as the main function. Whereas the <i>densityRange()</i> , <i>computeLoad()</i> and <i>mmetricTxPower()</i> functions are also illustrated	
	Appendix J	The UML activity diagram of <i>postTransmit()</i> method shows the implementa- tion of probabilities associated with different window sizes in the weighted con- tention window adaptation. This methods exists in the .cc source module in the 802.11p MAC layer	
	Appendix K	The UML activity diagram of <i>postTransmit()</i> method shows the implementa- tion of the PBS design for normal during absence and presence of an influential vehicle. This methods exists in the <i>MAC</i> 1609 ₄ .cc source module in the 802.11p MAC layer	

Table 1: List of figures in the appendix along with a brief description

APPENDIX B: AC3 INITIALIZATION


APPENDIX C: AC3 COALITION FINDER



APPENDIX D: AC3 PERMUTATIONS







APPENDIX G: AC3 FAIR POWER CALCULATION



APPENDIX H: AC3 MESSAGE PREPARATION & DISTRIBUTION



APPENDIX I: MULTI-METRIC POWER CONTROL



APPENDIX J: POST-TRANSMIT PHASE IN WEIGHTED CONTENTION

WINDOW ADAPTATION



APPENDIX K: POST-TRANSMIT PHASE OF THE PBS DESIGN

