Efficient data dissemination protocols for V2X communication networks

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**NANYANG
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SINGAPORE

**EFFICIENT DATA DISSEMINATION PROTOCOLS
FOR V2X COMMUNICATION NETWORKS**

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SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING
2019**

Efficient Data Dissemination Protocols for V2X Communication Networks

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A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirements for the degree of
Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodies in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University, Singapore and that the research data are presented honestly and without prejudice.

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Associate Professor Guan Yong Liang

Authorship Attribution

Statement

This thesis contains materials from three published paper(s) in the following peer-reviewed journals and conferences where I was the first and/or corresponding author.

1. Chapter 4 is published as: Y. Gao, P. H. J. Chong, and Y. L. Guan, "BSM dissemination with network coded relaying in VANETs at NLOS intersections," in *2017 IEEE International Conference on Communications (ICC)*, 2017.

- I proposed the network-coded relaying protocols, analyzed the performance of the proposed protocols and conducted computer simulations. I also wrote the manuscript and revised the manuscript with the other co-authors.

- Prof. Guan initiated the title and helped revise the manuscript.

- Prof. Chong helped me with the manuscript revision.

2. Chapter 5 is published as: Y. Gao, X. Xu, Y. L. Guan, and P. H. J. Chong, "V2X content distribution based on batched network coding with distributed scheduling," *IEEE Access*, vol. 6, pp. 59449-59461, 2018.

- I proposed the V2X content distribution protocols, given the performance analysis, conducted computer simulations. I also wrote the manuscript and revised the manuscript with Dr. Xu and Prof Guan.

- Dr. Xu provided guidance in the research idea and the application of BATS code. I discussed with Dr. Xu closely throughout the preparation of the manuscript.
 - Prof. Guan revised the manuscript and provided guidance in the presentation of the manuscript.
 - Prof. Chong provided comments on the manuscript revision.
3. Chapter 6 is published as: Y. Gao, X. Xu, Y. Zeng, and Y. L. Guan, "Optimal scheduling for multi-hop video streaming with network coding in vehicular networks," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, 2018.
- I proposed the video-streaming protocol, conducted computer simulations. I wrote the manuscript and revised the manuscript with Dr. Xu, Dr. Zeng and Prof Guan.
 - Dr. Xu provided guidance in the research topic and assisted in the performance analysis. I discussed with Dr. Xu closely throughout the preparation of the manuscript.
 - Prof. Guan provided guidance in the research direction, the manuscript revision and the presentation of the manuscript.
 - Dr. Zeng helped with the non-convex optimization and assisted in the manuscript revision.

Besides the above published peer-reviewed journals and conferences papers, this thesis contains the materials from the following paper which is under review.

1. Chapter 3 contains the content in: Y. Gao, X. Xu, Y. L. Guan, K. K. Leung, and P. H. J. Chong, "Throughput enhancement by contention window optimization for periodic V2V broadcast," *IEEE Transactions on Intelligent Transportation Systems*.

- I proposed the idea. I gave the analysis of the MAC-layer modeling and the contention-window optimization, and I conducted computer simulations. I also wrote the manuscript and revised the manuscript with Dr. Xu, Prof. Leung and Prof. Guan.
- Prof. Leung and Prof. Guan provided guidance in the research idea and proposed solutions. They edited the manuscript and provided comments on the presentation of the manuscript.
- Dr. Xu helped revise the manuscript and provided detailed comments on the research direction.
- Prof. Chong gave comments on the manuscript and guidance in the research topic.

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Abstract

With the rapid development of intelligent transportation system (ITS) technology and applications, the real-time wireless connectivity of moving vehicles has attracted increasing attention in the academia and industries. Relying on vehicle-to-everything (V2X) communication, vehicles are enabled to communicate with vehicles directly, as well as with roadside infrastructures. V2X communication is able to support a variety of applications to address road safety concern and support commercial or regulatory ITS services. Confronted by dynamic vehicular environment and stringent latency requirements, the design of efficient V2X communication protocols are of great relevance. In this thesis, we aim to design efficient data dissemination schemes for a number of realistic V2X use-cases. To this end, we utilize techniques such as network coding and Markov chain modeling, and focus on media access control (MAC) layer enhancement and scheduling optimization.

Firstly, the impact of the contention-window size of the IEEE 802.11p standard for periodic broadcast of short messages using dedicated short-range communication (DSRC) among vehicles is investigated. We apply Markov chain to model the periodic broadcasting behavior (such as broadcasting basic safety message) of the vehicles under the IEEE 802.11p MAC layer standard for both saturated and unsaturated network conditions. We attain enhancements by analytically optimizing the window size for maximizing the communication throughput, which are then verified by computer simulations.

Secondly, a reliable basic safety message (BSM) dissemination scheme is pro-

posed for the non-line-of-sight (NLOS) road intersection scenario. The periodic BSM exchanges by all vehicles are particularly crucial for preventing car collisions at road intersections without traffic signals. Large concrete buildings and obstacles may create a NLOS condition, leading to severe signal blockage. In order to address this problem and meet the timeliness requirement of BSM dissemination, we exploit random linear network coding and introduce controlled repetitive transmission patterns. Two promising network-coded relaying schemes are proposed to improve the reliability and scalability of the system.

Thirdly, an efficient V2X content distribution scheme based on batched sparse (BATS) code (a two-layer network code) with distributed scheduling is studied, in which digital maps or entertainment content are distributed from a roadside unit (RSU) to a group of vehicles passing by. To improve the transmission reliability in the lossy vehicular communication environment and possibly disconnected RSU cells, the original file is encoded with a BATS code for broadcast by a RSU, then a cooperative vehicle-to-vehicle (V2V) data sharing phase follows to repair the packets lost in the first I2V phase. To reduce the total content-distribution delay, a utility-based distributed algorithm is proposed to efficiently schedule the cooperative V2V data sharing phase. The proposed content distribution scheme is evaluated by extensive computer simulations, considering multi-lane road and realistic vehicular traffic settings, and shown to significantly reduce the transmission delay and communication overhead compared with known protocols such as CodeOn and CodeTorrent.

Finally, the problem of optimal scheduling for multi-hop V2V video streaming with network coding (applied to mitigate the well-known curse of exponential multi-hop throughput drop) in a Cellular-V2X setting is studied. The proposed network-coded scheduling algorithm considers not just the direct V2V communication link, but also the RF overhearing link, in the multi-hop V2V network. To further improve the system performance, channel reuse is applied for long multi-hop networks. Simulation results show that the proposed network-coded

scheduling scheme achieves substantial end-to-end throughput (achievable normalized generation rate) gain over conventional packet erasure correction coding schemes.

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List of Symbols

$ \cdot $	Absolute value
$ \mathcal{A} $	Cardinality of set $\mathcal{A}$
$\mathbb{F}_q$	Finite field of order q
$\mathbb{E}(\cdot)$	Expectation
$\mathbb{P}(\cdot)$	Probability
$\text{rank}(\mathbf{A})$	Rank of matrix $\mathbf{A}$
$\mathcal{N}(\mu, \sigma^2)$	Gaussian distribution with mean μ and variance σ^2
$\mathcal{B}(n, p)$	Binomial distribution with parameters n and p
$\exp(\lambda)$	Exponential distribution with mean $1/\lambda$
$\Gamma(x)$	Gamma function
$\gamma(a, x)$	Lower incomplete gamma function
$\Gamma(a, x)$	Upper incomplete gamma function
$\text{erf}(\cdot)$	Error function
$Q(\cdot)$	Q function
$\lfloor x \rfloor$	Greatest integer less than or equal to x
$\lceil x \rceil$	Least integer greater than or equal to x

List of Abbreviations

ITS	Intelligent transportation system
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
BSM	Basic Safety Message
CAM	Cooperative Awareness Message
DSRC	Dedicated Short-Range Communication
C-V2X	Cellular Vehicle-to-Everything
OBU	On-Board Unit
RSU	Roadside Unit
5G	Fifth Generation
3GPP	Third Generation Partnership Project
FCC	Federal Communication Commission
NHTSA	National Highway Traffic Safety Administration
NLOS	Non-Line-Of-Sight

LOS	Line-Of-Sight
EDCA	Enhanced Distributed Channel Access
AIFSN	Arbitration Inter-Frame Space Number
PHY	Physical Layer
MAC	Medium Access Control
SNR	Signal Noise Ratio
SINR	Signal Interference Noise Ratio
CW	Contention Window
CBR	Channel Busy Ratio
WLAN	Wide Local Area Network
NC	Network Coding
RLNC	Random Linear Network Coding
BATS(Coding)	BATched Sparse (Coding)
RF	Radio Frequency
BP	Belief Propagation
BS	Base Station
eNodeB	evolved Node B
UE	User Equipment
OFDMA	Orthogonal Frequency Division Multiple Access
SC-FDMA	Single Carrier Frequency Division Multiple Access
RB	Resource Block
MCS	Modulation and Coding Scheme
TB	Transport Block
SCI	Sidelink Control Information

Chapter 1

Introduction

1.1 Background

In the modern society, vehicles have dominated the form of transportation and become essential to the functioning of everyday life. The beginning of the 21st century witnesses the revival and commercialization of the electric vehicles (EVs) and the plug-in electric vehicles (PEVs), further expanding the automobile market. In recent years, with more advanced mobility technologies and the growth of people's living standard, the mission of automotive mobility is no longer limited to high speed or convenience, but also includes the safety, comfort, autonomy, efficiency, and intelligence. Among these objectives, enhancing road safety is the priority task. According to the World Health Organization (WHO) Report on Road Safety [2], the annual number of fatalities caused by the vehicle accident has climbed to 1.35 million by the end of 2016. To alleviate the traffic accidents, an intelligent transportation system (ITS) that integrates communication and management solutions in the form of vehicular network, was established [3]. Nowadays, the advent of new mobility concepts and vehicular services such as cooperative driving, mobility-as-a-service (MaaS) [4], multi-media streaming, and autonomous vehicles (AVs) [5], creates new goals for ITS development. ITS is envisioned to create an accident-free vehicular environment, improve transportation

efficiency and support various onboard infotainment services.

Communication technologies play a fundamental role in the development of ITS [6, 7]. The concept of vehicle-to-everything (V2X) communication is introduced to subsume all possible communication modes on road, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P)¹ communications. Vehicles function as smart mobile nodes in the V2X communication networks. Coordination among vehicles, infrastructures and vulnerable road users (e.g., pedestrians) is enabled to create a safer and smarter transportation system. The development of V2X communications also paves the path for autonomous driving [12] and teleoperated driving [13, 14].

Generally, V2X communications are designed to provide a variety of ITS-related applications for road safety concern, navigation, traffic efficiency, commercial interests, etc. Safety-related services basically aim to assist drivers in acquiring the real-time driving status of surrounding vehicles hence warning the drivers in case of any dangerous situations. As elaborated in [6, 15–17], typical safety services include intersection collision avoidance, emergency call services, lane-change warning and blind-zone assistance. There are two types of safety messages: periodic messages broadcast by every vehicle, and warning messages triggered by emergent events. The periodic short message is generated and broadcast by each moving vehicle and referred to as Basic Safety Message (BSM) under the U.S standard [18], or Cooperative Awareness Message (CAM) under the European standard [19]. BSM or CAM conveys a vehicle’s critical driving state information like velocity, moving direction, position and steering. Such information can be collected from the sensors and Global Positioning System (GPS) or Global Navigation Satellite System (GNSS) installed on a vehicle, hence individual

¹V2P communication has been leveraged for protecting vulnerable road users from dangerous traffic situations in some studies but further exploration is needed [8–11]. Pedestrians are expected to carry portable devices like mobile phones to communicate with vehicles. The V2P and V2V communications have some similarities whereas the V2P communication influenced by the low device battery has its own design requirement. In this thesis, we focus on the V2V and V2I communications and look forward to conducting more studies on the V2P communication in the future.

vehicle is able to construct its neighborhood map and disseminate key information periodically. Receiving the BSMs from peer vehicles enables a vehicle to learn the instantaneous position and speed of others, keeping the driver aware of the surrounding and enabling maneuver in time. On the other hand, it has drawn a lot of interests to provide reliable onboard infotainment and commercial services to vehicles. These services may include multi-media streaming, internet surfing, road navigation, onboard video conference, and so on. Most of the mentioned services can be realized via two popular data dissemination methods, i.e., content distribution and video streaming. Note that content distribution and video streaming can contribute to both non-safety and safety services, which are determined by the types of information. Specifically, content distribution can be utilized for delivering informative contents like digital maps, safety information like accident report, commercial materials like promotional video. This type of data dissemination usually involves both I2V² and V2V communications. Video streaming provides visualizing ability to the conventional data communication, for instance, streaming the camera and streaming live television programs for entertainment. The streaming content may be triggered by a leading vehicle and propagated to the subsequent vehicles with the assistance of multi-hop transmissions.

Increasing efforts have been made in the studies of emerging V2X technologies by both academia and industry. There are two widely-recognized communication technologies to support V2X networks. One is Dedicated Short Range Communication (DSRC) technology which has been exclusively deployed for the ITS-related services since 1999 [20]. DSRC operates with a stack of protocols [21,22]: (1) The protocols of physical layer (PHY) and medium access control (MAC) layer are based on the IEEE Standard 802.11p, under which vehicles adopt the enhanced distributed channel access (EDCA) scheme for channel contention. (2) Higher layers follow the Wireless Access in Vehicular Environments (WAVE) protocols in the U.S [23–25] or European Telecommunications Standards Institute (ETSI) ITS-

²I2V can be regarded as another type of V2I communication where information is propagated from the infrastructure to vehicle.

G5 standards in European countries. In the DSRC network, vehicles are equipped with onboard unit (OBU) devices while roadside unit (RSU) devices are mounted on roadside infrastructures such as traffic lights and lamp posts.

Another V2X technology that rides on the existing Long-Term Evolution (LTE) cellular communication networks is called cellular-V2X (C-V2X). C-V2X communication was first considered as part of the cellular ecosystem in the Third Generation Partnership Project (3GPP) Release 14, published in 2016 [26–29]. Further enhancements to the C-V2X are foreseen in the future with the coming of 5G technology, as expected by 5G Automotive Association (5GAA) [30]. The LTE network supports V2I and V2V (or V2P) communications via Uu interface and PC5 interface, respectively. The V2V communication is carried out via the dedicated LTE sidelink. Release 14 has proposed two modes for the V2V resource allocation: Mode 3 is the cellular-assisted resource allocation whereas vehicles under Mode 4 determine their resources in a distributed manner without the assistance of the base station (BS) [31–34]. As C-V2X is newer than the mature DSRC standard, large-scale deployment of the 5G C-V2X services will possibly not roll out until 2024 [35]. The development of a heterogeneous network comprised of different technologies is the trend of the next-generation V2X. The interworking of DSRC and C-V2X is believed to complete different V2X services and provide complementary solutions for offloading the congested traffic [36, 37].

Using DSRC or LTE, each vehicle on the road may perform as a source node for data dissemination. Due to large vehicle density on the road, the channel efficiency and packet congestion might become problems that affected the system performance. The lossy vehicular environment and the dynamic vehicle movement cause packet loss, posing challenges on the reliable transmission and successful reception. The non-line-of-sight (NLOS) conditions, e.g., signal blockage caused by buildings or large obstacles, significantly aggravate the received signal degradation, resulting in unreliable or broken communication links. On the other hand, some V2X applications such as BSM broadcast, content distribution and video stream-

ing have stringent latency requirements. To realize an efficient communication network, appropriate data dissemination protocols must be carefully designed by considering both the vehicular environment and the intrinsic application requirements. To this end, in this thesis, we focus on the MAC layer enhancement and scheduling optimization and eventually propose data dissemination protocols for four use cases.

1.2 Research Motivations

In this section, the research motivations for designing efficient data dissemination protocols with respect to four V2X use cases are discussed.

1.2.1 DSRC Broadcast Throughput Enhancement for Periodic Messages

Markov chain modeling is an effective tool for describing the DSRC MAC layer of the V2V periodic broadcast. The periodic message may be the basic safety messages (BSMs) that contain the instantaneous driving status, or the explored local map for safety concern and route discovery purpose. For the V2X communication, a simple but accurate Markov chain needs to take the following factors into account: the periodic packet arrival process, the dependency of the occurrence of the frozen counter in the EDCA backoff process for different vehicles, and the saturation probability of the network load. As the existing works are unable to satisfy all the mentioned requirements [38–45], a new Markov chain model for both the unsaturated and saturated network loads awaits to be proposed.

The contention window (CW) size of the backoff algorithm plays a crucial role in improving the DSRC performance. Intuitively, a large window size prolongs the average delay of delivering a packet but possibly decreases the vehicle transmission rate, hence reduces the interference caused by packet collision. Communication throughput is used to quantify the channel efficiency that is related to both the

delay and transmission rate. The current DSRC MAC layer utilizes a fixed CW size for message broadcast, which may end up with under-performing throughput. Therefore, based on different vehicle densities, a theoretical optimal CW size for the throughput enhancement awaits to be analyzed and derived.

In addition, the vehicle density can reflect the congestion level of the network which influences the performance of V2V communications under the DSRC MAC layer standard. Therefore, the vehicle density also affects the choices of the optimal CW size. The existing literature usually assumes that the vehicle density is known to the network but in reality, the vehicle density is difficult to be observed by each individual vehicle directly. To address this problem, a vehicle-density estimation approach that utilizes the PHY attainable information, is investigated in Chapter 3. Then, based on the new Markov chain model, the analytical solution to the optimal CW size for throughput maximization is discussed.

1.2.2 Dissemination of Periodic Safety Messages at NLOS Intersections

The WHO report on road safety [2] has revealed that around 1.35 million road traffic deaths occur globally every year, of which the intersection collisions account for almost 30% [46]. Drivers are vulnerable to traffic junctions especially when there is no traffic lights ³. Relying on the V2X communication technology, each vehicle generates a safety message (e.g., BSM) that contains the real-time driving information of a vehicle. Such message is exceptionally critical for the vehicles in the intersection area to prevent collisions. A BSM containing the latest vehicle statistics is generated every 100ms and is supposed to be received by all the vehicles that may benefit from this message in the intersection area. However, vehicles on different directions of the road may be blocked by the roadside concrete buildings and obstacles which may create a non-line-of-sight (NLOS) condition [47]. As a

³In fact, even in some urban areas, e.g., Lisbon, Portugal, there is no traffic light at some traffic junctions.

result, a notable degradation in the received signal strength is observed and hence the communication links are prone to breakdown. Therefore, to guarantee that the message delivery can meet the stringent delay requirement, it is imperative to have a reliable BSM dissemination protocol for the NLOS intersections.

One-hop relaying could be a promising solution to alleviate the aforementioned NLOS communication. As no acknowledgement is produced by the vehicle when broadcasting the BSM packets, the erased packets due to significant channel fading or shadowing or blockage at some receiving vehicles will not be re-transmitted, leading to a certain loss probability. To combat the adverse impact of the channel impairments and to improve the transmission reliability in the meantime, a controlled repetitive transmission (RT) [48] is inspired to cooperate with the one-hop relaying. Unfortunately, based on the controlled repetition pattern, with many packets to be relayed, the transmission probability of a single packet is reduced. Thus, the completion of BSM exchanges within the time constraint by the other vehicles may not be guaranteed. This problem can be addressed by exploiting the benefit of network coding (NC) [49] or random linear network coding (RLNC) [1]. Motivated by these research incentives, the work in Chapter 4 elaborates on the design of the network-coding assisted relaying with repetitive transmission pattern at the NLOS intersections.

1.2.3 V2X Content Distribution

Content distribution in the vehicular communication networks is an important form of communication to achieve both safety and non-safety types of services. As introduced in Section 1.1, the content distribution can be utilized for delivering digital maps, accident reports and commercial materials. Different from the periodic broadcast of short messages that only uses the V2V communication channel, based on the DSRC technology, the content is sent by the roadside unit (RSU) to the vehicles which are equipped with onboard units (OBUs) via the I2V

communication⁴. An explicit requirement of the content distribution protocol is to ensure complete delivery and low downloading delay for all the intended receiving vehicles. But due to the dynamic vehicular environments and high mobility of vehicles, the channel between the RSU and passing vehicles is prone to packet loss. Meanwhile, considering the cost and location restriction of RSU deployment, in some situations, it is not always possible to have unbroken RSU coverage in certain regions. So the insufficient connection time between the vehicle and the RSU poses challenges on the transfer of the complete file. To tackle these problems, the I2V content dissemination process could be extended to involve the assistance of V2V communication [50]. Specifically, after moving out of the RSU range, vehicles may share the collected, possibly incomplete, data with neighboring vehicles and help each other recover the uncollected pieces, performing V2V collaborative sharing. To successfully receive the complete file with short downloading delay for all vehicles without flooding the V2V channel, it is crucial to have a smart transmission coordination among the vehicles.

Network coding (NC) has been adopted in many existing content distribution protocols [50–53] to enhance the transmission reliability under the fading channel for both I2V and V2V communications. On the basis of NC, [50,53,54] propose different scheduling schemes. Nevertheless, they rely on the frequent exchange of the packet reception status and require the successful decoding of every network-coded block at all vehicles, which increase the network overhead and the transmission delay. To address the problems of NC-based protocols, a joint design for I2V and V2V content distribution based on a two-stage version of the BATched Sparse (BATS) network code [55] is considered⁵.

Based on BATS code, the transmissions during the V2V cooperative sharing should not be totally uncontrolled, otherwise the V2V channel will be flooded, with no meaningful outcome. Therefore, a distributed scheduling scheme to prioritize

⁴Content distribution can also be operated in the cellular V2X communication network where the based station plays a similar role as the RSU in the DSRC whereas the I2V is through downlink as well as uplink communication channels.

⁵The advantages of BATS coding over the network coding are discussed in Section 2.2.2.

the transmissions with higher utility and finally achieve a short transmission delay awaits to be developed. Moreover, to achieve high coding efficiency, the BATS code should be optimized at the source node. This is determined by the channel rank distribution. The analysis of the channel rank distribution is much more complicated in the V2X scenario than that in a line network [55, 56]. With these motivations, we will study on the design of the content distribution protocol based on the BATS code in Chapter 5.

1.2.4 V2X Multi-Hop Video Streaming

Video streaming provides visualization to data for both safety and non-safety applications [57], such as dashboard camera sharing in truck platooning, live broadcast of real-time traffic conditions and pushed multimedia advertisements. The streaming content may be triggered on a leading vehicle and propagated to the subsequent vehicles, which usually involves multi-hop transmissions in large vehicular networks. However, in the V2X communication environment, the communication links between any two vehicle experience packet erasure due to channel impairments. Packets sent through the multi-hop links will suffer from exponential packet loss rate. Therefore the end-to-end achievable network throughput will drop significantly. Retransmission is one solution to combat the erased channel. To benefit from the retransmissions without causing too much packet redundancy, instant and reliable packet-reception feedbacks should be provided for any V2V communication link, but this is difficult to be achieved in the large and dynamic vehicular networks. In short, simple retransmissions would lower the transmission efficiency and prolong the end-to-end delay. Due to the inherent delay constraints of large-size streaming content, a fast and reliable delivery beyond simple reliance on retransmissions is critical to an efficient streaming technique.

Network coding (or random linear network coding), as discussed before, is able to compensate the lossy channel by re-generating lost packets at the immediate nodes. The use of BATS coding for content distribution has been inspired in

Section 1.2.3 where at each vehicle, sufficient BATS coded packets among different batches are required to be received before the joint decoding. However, in the case of video streaming, each vehicle requires a fast video decoding and may skip some lost video frames. Therefore, instead of the BATS coding, the streaming video can be divided into small blocks and RLNC can be applied within each block. The source vehicle sequentially propagates the blocks of RLNC packets. As long as any block of coded packets is successfully received, the vehicle can immediately decode them, maintaining a certain video quality while reducing the end-to-end transmission at the same time.

Nevertheless, considering the total number of transmissions to deliver a block of packets, the video at the source node should be properly compressed to be commensurate with the channel link quality to avoid buffer overflow and unbounded delay [58]. Thus, the design of an optimal scheduling of network coded transmissions at each vehicle is of great importance to guarantee an efficient and reliable streaming protocol with low network latency. The Mode 3 in the cellular V2X protocol supports direct V2V communication using the LTE sidelink [33]. An optimal scheduling for video streaming can be realized in Mode 3 cellular V2X multi-hop communication by carefully assigning the number of transmissions slots at each vehicle. Moreover, thanks to the broadcast nature of wireless communication, a vehicle not only can receive the packets from its immediate upstream vehicles, but also can overhear the packets from earlier upstream vehicles, through the RF overhearing channel. In some situations when the multi-hop network is formed by a long platoon, channel reuse could further be exploited. However, the concurrent transmissions may lead to additional signal interference which may worsen the channel congestion. Thus, how to schedule the multi-hop video transmissions by considering all above problems remains a question to be answered. In Chapter 6, we propose an efficient video streaming protocol that exploits network coding, RF overhearing and channel reuse to meet the delay requirement, as well as to maintain a good video quality.

1.3 Main Contributions

In the light of the problems presented in Section 1.2, the main contributions of this thesis can be summarized as follows:

1. In Chapter 3, we maximize the DSRC throughput for broadcasting short messages by optimizing the contention window size.
 - (a) We propose a new discrete Markov chain model to accurately characterize the DSRC MAC protocol for periodic broadcast of short messages. The model is applicable to both the non-saturation and saturation conditions.
 - (b) We propose a distributed scheme for estimating the network density via the local channel busy ratio obtained from the PHY layer measured by each individual vehicle.
 - (c) We derive the analytical solution to the optimal CW size that maximizes the throughput and prove the effectiveness of the proposed throughput-maximization scheme by computer simulations.

The main results reported in this chapter have been presented in the following paper:

- **Y. Gao**, X. Xu, Y. L. Guan, K. K. Leung, and P. H. J. Chong, “Throughput enhancement by contention window optimization for periodic V2V broadcast,” *IEEE Transactions on Intelligent Transportation Systems* under review.
2. In Chapter 4, we propose two safety-message dissemination protocols based on the network coded relaying at NLOS road intersections.
 - (a) We introduce a controlled repetitive transmission (RT) pattern with optimal parameter settings to combat the lossy channel under the NLOS intersection scenario. The performance of RT and the DSRC IEEE 802.11p has been compared through numerical simulations.

- (b) We combine the random linear network coding together and relaying and hence propose two network-coded relaying schemes, namely RT-NCI (Repetitive Transmission with Network Coded Relaying only at the Intersection vehicle) and RT-NCA (Repetitive Transmission with Network Coded Relaying at All vehicles), to enhance the BSM dissemination reliability at the NLOS intersection with channel impairments.
- (c) We apply a finite-time Markov chain model to accurately analyze the packet successful reception probability with delay constraint and validate its effectiveness through computer simulations.

The main results reported in this chapter have been presented in the following papers:

- **Y. Gao**, P. H. J. Chong, and Y. L. Guan, “BSM dissemination with network coded relaying in VANETs at NLOS intersections,” in *2017 IEEE International Conference on Communications (ICC)*, 2017.
 - **Y. Gao**, G. G. M. N. Ali, P. H. J. Chong, and Y. L. Guan, “Network coding based BSM broadcasting at road intersection in V2V communication,” in *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*, 2016.
3. In Chapter 5, we propose a joint I2V and V2V content distribution protocol based on BATS (batched sparse) code and a utility-based distributed V2V scheduling scheme.
- (a) We apply the BATS code in the V2X (joint I2V and V2V) content distribution scenario and analyze the reception status for both I2V and V2V phases.
 - (b) We propose a utility-based V2V scheduling scheme to allow each vehicle to schedule the transmissions of the coded packets in a distributed manner. The proposed scheme reduces the communication overhead

and the transmission delay.

- (c) We propose an analytical approach to approximate the rank distribution of all the batches in a simplified but accurate way. The rank distribution determines the design of an optimal degree distribution of BATS code at the source node, which is crucial to the BATS optimization for achieving high coding efficiency.

The main results reported in this chapter have been presented in the following papers:

- **Y. Gao**, X. Xu, Y. L. Guan, and P. H. J. Chong, “V2X content distribution based on batched network coding with distributed scheduling,” *IEEE Access*, vol. 6, pp. 59449-59461, 2018.
 - X. Xu, **Y. Gao**, and Y. L. Guan, “Applications of temporal network coding in V2X communications,” in *International Conference on Smart Grid Inspired Future Technologies*, Springer, 2018, pp. 53-63.
4. In Chapter 6, we propose an optimal network-coded scheduling algorithm with the RF-overhearing and channel reuse in the multi-hop C-V2X network.
- (a) We apply Gaussian approximation and derive explicit expressions for the number of network coded packets to be generated at each vehicle with RF overhearing, to ensure every vehicle in the multi-hop platoon can successfully decode the coding block
 - (b) We propose an appropriate channel-reuse approach for maximizing the achievable video generation rate. The optimal channel reuse distance is obtained by solving a convex optimization problem.
 - (c) We validate the proposed coding and scheduling scheme by computer simulations and prove that the proposed scheduling outperforms the conventional packet erasure correction coding scheme. With the proposed channel reuse distance, the achievable video generation rate can

be significantly improved.

The main results reported in this chapter have been presented in the following papers:

- **Y. Gao**, X. Xu, Y. Zeng, and Y. L. Guan, “Optimal scheduling for multi-hop video streaming with network coding in vehicular networks,” in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, 2018.

1.4 Thesis Organization

The rest of this thesis is organized as follows. Chapter 2 reviews the DSRC and cellular V2X technologies, the network coding theory including the linear network coding and batched sparse network coding, and existing literature related to V2X communications. Chapters 3 - 6 propose promising data dissemination protocols in the V2X communication network. These four chapters are organized according to the application types. The protocols in Chapter 3 and Chapter 4 are designed for V2V periodic messages while the protocols in Chapter 5 and Chapter 6 focus on the contention distribution and streaming services which may involve I2V communications. Specifically, Chapter 3 discusses the throughput enhancement of the periodic message broadcast based on the DSRC standard and proposes the analytical framework for choosing the optimal contention window size. Chapter 4 focuses on the reliability improvement of the BSM dissemination at the NLOS road intersection and introduces two promising network-coded relaying protocols combined with controlled repetitive transmission mechanism. Chapter 5 investigates an efficient V2X content-distribution protocol that is based on the BATS coding and a utility-prioritized V2V scheduling, for reducing the transmission delay and network overhead. Chapter 6 elaborates on the network-coded multi-hop video streaming protocol with RF overhearing and channel reuse capabilities. The proposed scheduling scheme is optimized to achieve the maximum video generation

rate. Chapter 7 concludes the thesis and proposes promising research directions in the V2X communication system.

Chapter 2

Fundamental Concepts and Related Works

2.1 V2X Communications

2.1.1 DSRC

The U.S. Federal Communication Commission (FCC) allocates 75 MHz DSRC spectrum in the 5.9 GHz band to provide several-hundred-meter range for supporting the V2X services. The DSRC spectrum is divided into seven 10 MHz channels and one guard band with 5 MHz [20]. The current channel structure of DSRC is shown in Fig. 2.1 [18]. Generally, a DSRC device has two types of radios. One radio is dedicated for broadcasting safety messages like BSMs and other safety-related traffic messages, using the Channel 172. The other radio is utilized for data transmission and control messages via the service channel (SCH) and the control channel (CCH), respectively. In addition, Channel 184 is reserved for high-power public safety use [59]. In the U-NII-4 proposal introduced by the FCC, compared with the current 10 MHz channel, a variety of wide channels ranging from 20 MHz to 60 MHz, can be supported by combining the existing channels together [60]. For instance, Channel 175 is a combination of two adjacent 10 MHz channels. DSRC is comprised of a stack of protocols, of which

Figure 2.1: DSRC channel arrangement.

the PHY and MAC layer are defined by IEEE 802.11p standard. The PHY utilizes the orthogonal frequency-division multiplexing (OFDM) modulation scheme with four possible modulations: BPSK, QPSK, 16QAM and 64QAM, to achieve bit rates ranging from 3 to 27 Mbps. The enhanced distributed channel access (EDCA) is adopted for the MAC layer. The EDCA combines the carrier sensing multiple access with collision avoidance and the slotted binary exponential backoff (BEB) mechanism, consisting of two quality-of-service (QoS) parameters in the broadcast mode, i.e., the arbitration interframe space numbers (AIFSNs) and the contention window (CW) sizes of the backoff algorithm. The EDCA mechanism allows four access categories (ACs) of messages to be transmitted with different priorities. The parameters different ACs are given in Table 2.1. The message that belongs to the AC[0] has the highest transmission priority and it is assigned with the lowest arbitration inter-frame space number (AIFSN) value. So the AC[0] message will experience the shortest AIFS time before being transmitted by the vehicle. Moreover, middle layers of DSRC are structured by IEEE 1609 working group. Specifically, IEEE 1609.4 is adopted for MAC sublayer extension, determining how the channel coordination. IEEE 1609.3 takes care of the network and transport layer while IEEE 1609.2 is adopted for security services. The elements of the BSM frame are specified according to the SAE J2735 Message Dictionary Standard [61].

Table 2.1: EDCA Access Categories.

Access Categories	Priority	$CW_{\min}$	$CW_{\max}$	AIFSN
AC[0]	Highest	3	7	3
AC[1]	2nd Highest	7	15	3
AC[2]	3rd Highest	15	1024	6
AC[3]	Lowest	15	1024	9

Figure 2.2: Resource pool for C-V2X communications.

2.1.2 Cellular V2X

C-V2X is a new paradigm to realize the short-range vehicular communications based on the existing LTE networks. The ubiquitous coverage of the C-V2X can directly provide services for the V2I communication without the assistance of additional infrastructures. Distinct from the uplink and downlink in the cellular network, the LTE sidelink was introduced in 3GPP Release 12. The sidelink was originally used for the public safety. Two sidelink communication modes, Mode 1 and Mode 2 were designed for prolonging the battery life of mobile devices. However, they are not suitable for the C-V2X communications which require low latency, high reliability and network scalability. To achieve these goals, Release 14 [28] proposed Mode 3 and Mode 4 for allocating the channel resource to the vehicles in centralized and distributed manners, respectively. Mode 3 operates within the coverage of the LTE infrastructure so that the eNodeB (BS) assists vehicles in

selecting the channel resource based on the requirement and network congestion situation acquired from the vehicles. The central scheduling follows either the dynamic allocation scheme (vehicles request the allocation by the eNodeB for every transmission) or the semi-persistent scheduling (SPS) scheme (the eNodeB reserves the channel for each vehicle for a period time) [62]. In this thesis, we will apply the dynamic scheduling scheme under Mode 3 in Chapter 6 for video streaming scheduling. In contrast to Mode 3, vehicles under Mode 4 may be out of the coverage of the eNodeB. Vehicles can select and reserve channel resources by adopting a sensing-based SPS in a distributed manner. The operation of the sensing-based SPS has been summarized in [33, 63].

The C-V2X PHY and MAC layer are based on single carrier frequency division multiple access (SC-FDMA). A spectrum of 10MHz or 20MHz is reserved for the sidelink communication channel and each consists of subframes (in the time domain) and subchannels (in the frequency domain). As shown in Fig. 2.2, a subframe is equivalent to 1 ms and a subchannel consists of a number of resource blocks (RBs), each of which corresponds to 180 kHz. The number of RBs in a subframe is not fixed and determined by the number of RBs that carry the data packet and the control information in response to different modulation and coding schemes (MCSs). The data packet, in the form of a transport block (TB) and its associated sidelink control information (SCI) are transmitted over the physical sidelink shared channels (PSSCH) and physical sidelink control channels (PSCCH), respectively. Both QPSK and 16 QAM can be used for the TB transmission whereas the SCI applies the QPSK modulation scheme. A normal SCI occupies 2 RBs containing the coding scheme and modulation information. The number of RBs utilized by one TB varies from applications to applications. For instance, considering that a 300-byte safety packet is coded using QPSK with a 0.5 code rate, the TB part will occupy 20 RBs. The TB and its associated SCI can be transmitted in adjacent RB, hence a subchannel (TB+SCI) actually contains 22 RBs and the 10 MHz-channel can support two subchannels. Alternatively, the TB

and the SCI can be transmitted in non-adjacent RBs but in the same subframe.

2.2 Network Coding Theory

2.2.1 Linear Network Coding

Network coding was introduced in [49] to improve the efficiency, reliability and scalability of the entire network. In the conventional routing networks, information is stored and forwarded by the intermediate node while network coding allows the intermediate node to encode several received packets together for transmission. Li *et al.* [64] proposed a linear network coding such that the encoding operation at the intermediate node is actually a linear combination of a certain number of messages. It also proved the linear network coding could achieve the capacity of the single-session multicast networks. Koetter and Médard [65] provided an algebraic framework to extend the network coding structure to an arbitrary and robust network. To construct the network code or network coefficients in the multicast network, a polynomial-time centralized method was proposed by Jaggi *et al.* [66]. Such network code greatly relies on the network topology and has to be determined before the transmission.

A random linear network coding (RLNC) introduced by Ho *et al.* [1] is independent of the network topology but with a sufficiently high probability to achieve the network capacity. The network coefficients are determined in a distributed manner, which are randomly chosen from the Galois field (a finite field) [67] and proven to be robust to the dynamic network topology. Since the vehicular network environment is dynamic and prone to the packet loss, we apply the RLNC to BSM dissemination scheme at the NLOS intersections and the multi-hop video streaming protocol in this thesis. We use a simple multicast network shown in Fig. 2.3 to illustrate the RLNC operation. Consider that a node S intends to multicast X_1 and X_2 , which are two source packets, to the receivers R_1 and R_2 . The line between two nodes represents the communication link and the number of links in-

Figure 2.3: An example illustrating random linear network coding [1].

indicate the channel capacity. Other than receivers, all nodes perform RLNC on the incoming transmissions to generate coded outputs. Node S selects independent coefficients α_1, α_2 to create P_1 . Coefficients are determined in a distributed manner by choosing a value from $\mathbb{F}_q$ with a finite field size of q elements. Coefficient overhead is linearly proportional to the number of packets encoded together. For instance, the overhead for the coded packet P_1 is $2 \log_2 q$ bits. Coefficients α_1, α_2 are stored as a vector in the header of P_1 and forwarded to the next node. When the packet length of P_1 is sufficiently large, the overhead is negligible. When the receiver R_1 successfully receives P_1 and P_3 , since it knows all the coefficients, it can decode and recover the original X_1 and X_2 by applying the matrix inversion algorithm, like the Gaussian Elimination [68].

Based on the types of information to be encoded, in general, network coding has spatial and temporal dimensions. For the spatial network coding, packets from different communication links are encoded together at the intermediate nodes, for instance, the network coded relaying at the NLOS intersections. For the temporal network coding, the intermediate node encodes the packets from the same link but different time slots, for example, the multi-hop video streaming. Now, we provide a general algebraic expression that is applicable to both the spatial and

temporal RLNC. Let $\mathbf{B} = [b_1, b_2, \dots, b_K]^T$ be the matrix formed by the K input packets. With the temporal or the spatial RLNC, the receiver obtained K' linearly independent coded packets, where $K' \leq K$. These K' coded packets can form a matrix $\mathbf{Y} = [y_1, y_2, \dots, y_{K'}]^T$. Network coefficients extracted from the packet header of the coded packets form a matrix denoted by $\mathbf{H}_{K' \times K}$. Hence, the linear relation between $\mathbf{B}$ and $\mathbf{Y}$ is

$$\mathbf{Y} = \mathbf{H} \times \mathbf{B}. \quad (2.1)$$

When $K' = K$, we assume $\text{rank}(\mathbf{H}) = K$ when each element of $\mathbf{H}$ is randomly chosen from a large finite field $\mathbb{F}_q$. Then, K original packets can be successfully decoded by performing matrix inversion, i.e.,

$$\mathbf{B} = \mathbf{H}^{-1} \mathbf{Y}. \quad (2.2)$$

Assuming each of K original packets contains ℓ bits, the encoding of a packet takes $O(K\ell)$ operations and the decoding complexity is $O(K^2 + K\ell)$.

RLNC can effectively mitigate the exponential throughput drop in multi-hop network under the lossy wireless channel. As shown in Fig. 2.4, an n -hop network has a source node s , $n - 1$ intermediate nodes $r_1, r_2, \dots, r_{n-1}$, and a receiver node t . The packet loss rate is ϵ per hop. With routing at each intermediate node, the network experiences cumulative packet losses over n hops. The maximum achievable throughput is $(1 - \epsilon)^n$ packets per use. In a large network, the end-to-end throughput $(1 - \epsilon)^n \rightarrow 0$. The throughput can be significantly enhanced when the RLNC is operated at the intermediate nodes so that each intermediate node can re-encode the received the coded packets and generate sufficient coded packets to combat the packet loss. The achievable end-to-end throughput is $(1 - \epsilon)$, same as the throughput for a single hop.

In the broadcast scenario under the lossy channel, the feedback from each receiver is disabled. To ensure each receiver can receive all the original packets, the source node is prone to generating a large number of redundant packets. However,

Figure 2.4: An n -hop network with packet loss rate ϵ .

if we apply the RLNC, the source node can encode the original packets and broadcast on average $\frac{1}{1-\epsilon}$ coded packets, where ϵ is the packet loss rate of the bottleneck communication link. In addition, other research topics on network coding include network security [69–71] and network error correction coding [72, 73].

2.2.2 Batched Sparse Coding

Batched sparse (BATS) code is a class of linear network coding that combines the extended fountain code with the RLNC [55, 74, 75]. BATS code takes advantages of the rateless nature of the fountain code and the robustness of the RLNC against the dynamic network topology and the lossy channel. In general, BATS code consists of an outer code and an inner code. The outer code generalizes the fountain code [76] by generating M coded packets from a group of input packets to form a batch, where M is referred to as the batch size. The BATS inner code which is RLNC, can be performed within each batch at the intermediate nodes such as vehicles in the V2X content distribution scenario, to generate coded packets. The outer and inner code can be jointly decoded with efficient belief propagation (BP) algorithm. Similar to RLNC, the coding and decoding operations are performed in a finite field $\mathbb{F}_q$.

With the assistance of the Tanner graph in Fig. 2.5, we will explain the operation of BATS code in detail. Consider there is a set of K input packets, represented by the input matrix $\mathbf{B} = [b_1, b_2, \dots, b_K]$. To form a batch X_i of M coded packets, d_i input packets are uniformly and randomly chosen from a set $\mathbf{B}_i, \mathbf{B}_i \subset \mathbf{B}$, following a degree distribution $\Psi = (\Psi_0, \Psi_1, \dots, \Psi_K)$. That indicates the degree d_i is sampled with probability Ψ_i . As shown in Fig. 2.5, the check nodes in the second row are the batches that are generated by the outer code. A typical

Figure 2.5: Tanner graph for BATS code.

i th batch X_i has the following relationship with the input packets

$$\mathbf{X}_i = \mathbf{B}_i \times \mathbf{G}_i \quad (2.3)$$

where G_i is the generator matrix [55] with a dimension of $d_i \times M$. The elements in G_i can be created by randomly choosing values from a generation matrix. The source node can sequentially and ratelessly transmit the outer-code generated batches to the intermediate nodes. The intermediate nodes apply the RLNC (inner code) within each received batch. As illustrated by the third row of the Tanner graph (Fig. 2.5), the check nodes correspond to the batches generated by the inner code. Denote by H_i the transfer matrix of the RLNC operation. The output packets from i th batch can be written as

$$\mathbf{Y}_i = \mathbf{X}_i \times \mathbf{H}_i = \mathbf{B}_i \mathbf{G}_i \mathbf{H}_i. \quad (2.4)$$

This transfer matrix $\mathbf{H}_i$ is carried in the packet header and hence the $\mathbf{G}_i \mathbf{H}_i$ is assumed to be known by the receiver. We apply the low-complexity BP decoding to decode the input packets $\mathbf{B}_i$. By combining the two rows of check nodes together, we are able to associate the check node i with the variable nodes that belong to $\mathbf{B}_i$

via a new transfer matrix $\mathbf{G}_i\mathbf{H}_i$. The check node i is decodable if $\text{rank}(\mathbf{G}_i\mathbf{H}_i) = d_i$. Following the rule of BP decoding, we repeat the decode-substitute steps and finally decode the input packets. The design of degree distribution Ψ of BATS code at the source node is critical to achieving high coding efficiency. As proposed in [55], (2.4) can be modeled as a linear operator channel (LOC) where $\mathbf{H}_i$ is the random matrix or state information of a channel and $\mathbf{X}_i$ is the input. The rank of $\mathbf{H}_i$ follows a certain distribution, so we usually name this distribution as the (channel) rank distribution. The rank distribution determines the optimal design of the degree distribution Ψ . In this thesis, we propose a V2X content distribution protocol based on BATS code, of which the rank distribution is given in a closed expression.

Compared with the conventional RLNC, BATS code has much lower coding overhead that is determined by the batch size, and lower encoding and decoding complexity, which makes it suitable for the computation-limited devices, e.g., the communication device installed on the vehicle or the mobile phone. Assuming that K packets with packet length ℓ are transmitted via intermediate nodes to the destination. To generate a batch with M coded packets, the encoding complexity is $O(M\ell)$ while the decoding complexity is $O(M^2 + M\ell)$ per packet. Based on the computation complexities presented in the last section and the fact that $K \gg M$, we can see that BATS code has a much lower encoding/decoding complexity.

2.3 Related Works in V2X Communications

2.3.1 DSRC Performance for Periodic Broadcast

The DSRC performance analysis and enhancement have been investigated in many previous works [38–45, 77–79]. The unicast analytical models analyzed in [77–79] cannot be used for the broadcast scenario since feedback cannot be sent in case of transmission failure. The MAC protocol for periodic broadcast has been modeled by using a Markov chain in [38] for both the saturation and non-saturation

conditions. The proposed Markov chain regarded the saturation situation as an independent Markov state, leading to inaccuracy to the system modeling. Hassan *et al.* [39] analyzed the packet delay and packet delivery ratio, and proposed packet re-transmissions to trade increased delay for decreased packet loss. Yao *et al.* [40] proposed a new Markov chain model for periodic broadcast that is suitable for a low packet generation rate, followed by the evaluation of the packet reception rate and the transmission delay. However, the proposed model therein was unable to maintain its accuracy for a high packet generation rate. The authors of [41] elaborated on the relationship between the delay, throughput, data rate and packet arrival rate. The authors of [42] studied the DSRC performances for various transmission ranges and rates of the safety messages, and hence proposed a feedback control to realize the transmission range adaptation. Hafeez *et al.* [43] proposed an adaptive algorithm to change the transmission parameters based on the estimated vehicle density which could be reflected by the changes of moving speeds. Zheng *et al.* [44] analyzed the EDCA with respect to both saturation and non-saturation conditions and additionally discussed the impacts of the vehicle density on the transmission probability and the collision probability.

The aforementioned literature proposes various methods for modeling the DSRC MAC standard but mainly focused on the DSRC enhancement by adapting transmission power, inter-vehicle distance, transmission range and vehicle density. The evaluation of CW size and adaptation have been studied in the WLAN system based on IEEE 802.11 standard [80–82]. In [80], the transmission failure probability was estimated based on the acknowledgement of the failed transmission and hence the optimal CW size was obtained for improving the channel capacity. However, the proposed analytical model was purely based on the average values for parameters and could not be used for the periodically generated message and broadcast mode in the DSRC. The authors in [81] adapted the CW size according to each slot time hence tried to enhance the WLAN throughput. Their back-off process did not consider the real data generation of the periodic message in

the DSRC and each station tuned its own CW size could possibly lead to the designed throughput unattainable. Additionally, Khatua *et al.* [82] formulated the CW optimization for saturation throughput improvement and designed a new CW adaptation scheme for the IEEE 802.11e networks. Whereas our work in the thesis follows the original IEEE 802.11p standard and analytically solves the optimal CW size according to the estimated vehicle density in both saturation and non-saturation situations. Different from the CW optimization problems in the WLAN mentioned above, the DSRC throughput maximization may take the vehicle topology, vehicle density and packet arrival process into account. Furthermore, the simulation results of CW optimization for DSRC MAC standard was studied in [83], showing that the different vehicle densities could affect the decision of the CW sizes. Rossi *et al.* [45] theoretically analyzed the relationship between the CW and the throughput thus obtained the optimal CW size. However, the optimization problem in [45] was solved through numerical examples and the DSRC performance was only evaluated when the network load was saturated. In this thesis, we provide an analytical method to find the optimal CW size for DSRC throughput maximization for both the non-saturation and saturation conditions.

The vehicle density can reflect the congestion level of the network which influences the performance of V2V communications under the DSRC IEEE 802.11p standard. Hence the density also affects the optimal CW size. In reality, the vehicle density is difficult to be observed by each individual vehicle directly. However, the vehicle density can be reflected by the information collected from the PHY layer, namely, channel busy ratio (CBR) [84]. The CBR is measured by each vehicle independently and it is usually used for the data rate control in the vehicular network [85, 86].

2.3.2 Relaying at Road Intersections

Road intersection is a challenging vehicular environment. Different from the path-loss models for the LOS V2V communication [87, 88], the received signal power

at the intersection has been proved to drop quickly with the increasing distance from the intersection caused by the signal blockage by the roadside buildings and large obstacles [47,89,90]. According to the study in [90], the packet delivery ratio decreases notably when the vehicles at around 40m to 50m or even farther away from the intersection. This statement was also analyzed and evaluated in [91,92]. To characterize the vehicle positions, an analytical framework was proposed in [93].

To mitigate the signal degradation at NLOS intersections, relaying at road intersection has been taken into account. Le *et al.* [94] proposed a GeoNetworking protocol so that the RSU is the relay node to help exchange BSMs among vehicles. The effects of the omnidirectional and directional antennas on the relaying at the RSU were investigated in [95]. Noor-A-Rahim *et al.* [92] analyzed the performance of BSM broadcast at road intersections by partitioning the intersection area into sections. A RSU-based relaying was proposed to relay the BSMs where the RSU was installed with the bidirectional sector antennas and enabled to relay the BSM with a higher frequency.

Network coded relaying was considered in [96] where the BSMs generated by two vehicles were designed to be encoded together. The network coefficients therein were chosen from $\{0,1\}$. The effectiveness of the network coded relaying was verified through simulation alone. Ali *et al.* [97] proposed a vehicle-relaying protocol at the NLOS intersection and introduced the application-level quality-of-service (QoS) parameters to evaluate the performance of the opportunistic network coded relaying.

2.3.3 V2X Content Distribution

Routing-based V2V sharing protocols for content distribution in vehicular networks were investigated in [98–100]. These protocols are prone to generating duplicate transmissions and significant overhead which prolong the distribution delay. To enhance the transmissions reliability under the fading channel, many existing protocols applied network coding to the content distribution [50–53,101–104].

CodeTorrent [51] was the pioneer work that combined the file swarming with network coding. Some similar researches [52, 101, 102] have been conducted to investigate the benefit of the network coded transmissions in the aspect of reducing total downloading delay. Zhu *et al.* [103] extended the work in [102] to study the PMFs of the data downloading time for multiple-vehicles by using the random, feedback and NC-based schemes under the perfect channel condition. Xing *et al.* [104] solved the successful transmission probability of the NC-source data when vehicles faced the channel fading and co-channel interference by using the stochastic geometry.

Unlike the aforementioned schemes which focus on the system analysis but lack careful scheduling design for the V2V sharing, CodeOn [50] exploited the symbol-level NC and the exchanged packet decoding status to determine the V2V transmission priority. However, the frequent status exchange leads to large traffic overhead and the symbol-level network coding requires large computational complexity. Similar work was conducted in [54], requiring the frequent update of the packet reception status. A SNR-based scheduling strategy was proposed in [105] for data dissemination where large-scale channel loss and vehicle positions were assumed to be well predicted by RLS. However, the impact of the small-scale fading on the utility of the vehicles were not considered which may make difference to the scheduling strategy. Moreover, a centralized TDMA-based scheduling scheme was proposed in [106] to control the V2V communication. Liu *et al.* [53] also utilized the RSU to give the scheduling decision and built an effective cache strategy but the network overhead due to the frequent packet status exchange could not be avoidable.

To further improve the current content distribution protocols and avoid the undesirable problems in the aforementioned protocols, BATS code is a new yet more effective solution. The V2X content distribution can make the best of the rateless nature of the BATS code to reinforce the usefulness of each transmitted packet in the lossy channel and introduces a smart distributed scheduling method

so that each vehicle can determine the transmission sequence locally. BATS code (details are discussed in Section discussed in 2.2.2) was originally proposed for multi-hop line network in [55] and it consists of fountain code (outer code) and random linear network code (inner code). The inner code and outer code can be jointly decoded with efficient belief propagation (BP) algorithm [55]. The application of BATS code for distributing a file from a common source node to a group of closely-located receivers in a static ad-hoc network has been discussed in [107]. A static network was considered in [107] where the number of source transmissions could be simply adjusted according to the channel statistics. In this thesis, our work in Chapter 5 extends the application of BATS code to V2X networks where each vehicle has a short connection time with the RSU. Meanwhile, vehicles face a varying channel in the I2V communication. The channel-induced loss is different for each vehicle at different time instances. So it is still necessary to investigate the system performance as well as the design of an efficient BATS code.

2.3.4 V2X Video Streaming

To improve the video playback quality and meet the delay requirement of the video streaming in the V2X communication scenario, some existing works have investigated the frame skipping and transcoding techniques in the application layer [108]. An adaptive MAC retransmission limit scheme in [109] was proposed to enhance the playback streaming quality. However, in large and dynamic vehicular networks, the instant and reliable feedbacks are difficult to be achieved, otherwise, a great amount of streaming latency will be induced, leading to freezing or jump of pictures during the streaming video playback. A simple-retransmission scheme in [108] would possibly incur duplicate frames or packets. To address this problem, some protocols were proposed to exploit the benefit of network coding [49] against the lossy networks to combat the throughput drop, especially in the multi-hop network. Park *et.al.* in [110] proposed the safety-related streaming by using the

RLNC. The group of vehicles in the opposite direction of the road could perform as data mule to carry the streaming data in the disconnected vehicle group. However, the divergent number of coded packets received by each vehicle due to the inter-vehicle distance was not taken into consideration. Actually, in the multi-hop video streaming network, an efficient streaming scheduling is expected to be proposed in order to reduce the unnecessary redundant coded packets transmitted by each vehicle, and hence shorten the end-to-end delay. The authors in [111] incorporated the symbol-level network coding and proposed the CodePlay protocol to divide the vehicles into segments and to select the retransmission nodes. However, symbol-level network coding may incur much larger coding overhead and computational complexity than the packet-level network coding schemes. Zhu *et al.* [103] elaborated on the theoretical gains by using network coding over random broadcasting as well as the feedback based scheme. The aforementioned works have not yet considered packet overhearing due to the wireless broadcasting nature of vehicular communication, and hence the network throughput is usually compromised. In [112], the authors proposed an efficient network coding scheme for data dissemination in vehicular ad-hoc network with packet overhearing enabled. However, the network coding block size for video streaming is usually much smaller than the content distribution applications considered in [112] due to the stringent delay requirement. When the coding block size is small, the number of received packets may deviate from the expected value with high probability. Therefore, in the absence of channel feedback, more coded packets are required to ensure high decoding probability at the receiver. Furthermore, the application of the channel reuse, which is important to enhance the spectrum efficiency and reduce the network latency for multi-hop communications, is not considered in [112].

Chapter 3

DSRC Throughput Enhancement by Contention Window Optimization for Periodic Message Dissemination

3.1 Introduction

In this chapter, the impact of the contention window (CW) size of the IEEE 802.11p standard on the periodic broadcast of short messages using DSRC is investigated, and an analytical solution that maximizes the throughput by optimizing the CW size is provided. To this end, we first introduce a new Markov chain for accurately modeling the IEEE 802.11p MAC protocol for the periodic broadcast which satisfies both the saturated and unsaturated network conditions. Then, we propose a distributed yet effective method for vehicle-density estimation using an attainable statistics from the physical layer, channel busy ratio (CBR). As the CW size of the backoff algorithm plays a key role in the DSRC MAC protocol, we provide an analytical framework to derive the optimal CW size for the communication throughput maximization with delay constraint. Extensive com-

Figure 3.1: System model of V2V communication on the highway.

puter simulations are conducted to validate the proposed Markov chain model and vehicle density estimation method. It is shown that in terms of periodic broadcast throughput, the network with the optimized CW size can significantly outperform the benchmark schemes with fixed window sizes.

3.2 Modeling DSRC MAC Protocol

In this section, we will establish a mathematical model to describe the communications of vehicles on the multi-lane highway. Since the communication range of a vehicle under the DSRC IEEE 802.11p protocol ranges up to hundreds of metres, the width of a lane is relatively negligible. Hence, the stretches of the multi-lane highway can be abstracted to a one-dimensional line. As illustrated in Fig. 3.1, vehicles are distributed according to a homogeneous Poisson point process (PPP) [113] with density β vehicles per meter. We assume that each vehicle is equipped with the GPS and sensors for tracking locations and speeds, and a DSRC radio for packet transmission and reception. All vehicles are assumed to have the same transmission power. Assuming that the signal with strength above the threshold (e.g., -89 dBm) can be successfully detected at the receivers. The maximum distance of the signal detection, denoted by R_{cs} , is assumed to be equal to the carrier sensing range, beyond which the interference is negligible. Let N_{cs} be the expected number of neighbor vehicles in the carrier sensing range of the

tagged node u which is given by

$$\begin{aligned} N_{cs} &= \mathbb{E} \left(\sum_{i=0}^{\infty} i \frac{(2\beta R_{cs})^i}{i!} e^{-2\beta R_{cs}} - 1 \right) \\ &= 2\beta R_{cs} - 1. \end{aligned} \quad (3.1)$$

Therefore, there are on average $N_{cs}+1$ vehicles sharing the same frequency channel. Any concurrent transmissions among $N_{cs}+1$ vehicles will cause interference to each other. The packets generated at each vehicle are assumed to follow the Poisson process with a generation rate λ for broadcasting. The packets are assumed to have the same packet length and transmission rate. The transmission time of a packet is denoted by t_p . Packet transmission from each vehicle can be modeled as a M/G/1 queue with an infinite buffer so the packet drop due to buffer overflow will not be considered.

3.2.1 Backoff Process

In DSRC, the EDCA allows four access categories (ACs) for a vehicle to operate with different transmission priorities. The event-driven messages are usually assigned with higher priorities. For instance, the emergency message triggered by the accident situation has the highest transmission priority AC[0]. In this thesis, we focus on the periodic messages generated by the vehicles, such as Cooperative Awareness Message (CAM), BSM or other types of information to be shared with neighboring vehicles frequently. Such messages belong to the background traffic (BK) using AC[3]. Since the event-driven messages are generated with very low probability, the interference from the higher-priority ACs is negligible. When a packet is generated at the source vehicle, it will wait for a period of an arbitration inter-frame space (AIFS) before transmission. AIFS is determined by the AIFS number (AIFSN): $\text{AIFS} = \text{SIFS} + \text{AIFSN} \cdot t_s$, where $t_s = 13\mu s$ is the length of one slot time and SIFS is the short inter-frame space. If the channel is sensed busy, the vehicle will continuously observe the channel until the channel is idle again

Table 3.1: Related Notations in Chapter 3.

Notations	Definition
β	Vehicle density
δ	Propagation delay
D	Average packet delay
N_{cs}	Expected number of neighbor vehicles in the carrier sensing range of the tagged node
ρ	Probability of having saturated load
P_0	Probability that at least one packet arrives at the empty queue
P_b	Channel blocked probability
P_c	Channel occupied probability
λ	Packet arrival probability for the Poisson process
τ	Transmission probability
t_{es}	Effective slot time
t_p	One packet transmission time
t_s	One slot time
t_{qc}	Average queue-checking time
W	Contention window size

for an AIFS period. At that moment, the vehicle initiates the backoff countdown process in which the vehicle randomly and uniformly chooses a backoff counter value from $[0, W - 1]$, where W is known as the contention window size. Note that for EDCA broadcast mechanism, W is set to the minimum feasible CW size of the chosen AC in the existing DSRC MAC standard. The backoff counter is decreased by one when the channel is sensed idle for a slot time t_s . Once the transmission from any other node is detected, the backoff counter is frozen and resumes decrement after the channel is sensed idle for an AIFS period again. Once the backoff counter value reaches 0, the packet will be transmitted immediately. In the broadcast mode, there will be no acknowledgement frame to indicate the successful reception, hence no subsequent re-transmissions will be triggered.

stationary distribution is b_e corresponds to the unsaturation scenario where the vehicle has no packet in its queue for a new transmission and needs to wait for the arrival of the packet. The empty state transits to the backoff states when at least one packet arrives at the empty queue with probability P_0 . On the other hand, under the saturation condition, the queue must be non-empty after the previous transmission. The probability of having saturated load is denoted by ρ .

According to the Markov chain property, i.e., $\sum_{i=0}^{W-1} b_i + b_e = 1$, we can derive the stationary distribution of each backoff state

$$b_i = \frac{W-i}{W} \tau, \quad i = 0, 1, \dots, W-1. \quad (3.2)$$

Hence, the transmission probability τ can be expressed as

$$\tau = b_0 = \frac{1}{\frac{W+1}{2} + \frac{1-\rho}{P_0}}. \quad (3.3)$$

For the tagged node u , we define the probability that the channel is sensed busy in the carrier sensing range of node u as the channel blocked probability (CBP), denoted by P_b . Since we have excluded the channel-blocked slots from the total slots in our model, the transmission probability of each vehicle based on the Markov chain shown in Fig. 3.2 can be approximated as independent events. Such approximation is used in [42, 45] and verified by simulations. So the channel blocked probability, P_b can be approximated as

$$P_b \approx 1 - (1 - \tau)^{N_{cs}}. \quad (3.4)$$

After each transmission, there is an AIFS period before the channel is available. With probability of P_b , the channel is occupied by the transmission of any nodes within the carrier sensing range of the tagged node u for a period of $t_r = t_p + \text{AIFS} + \delta$, where t_p is the transmission time of a packet and δ is the propagation delay. On the other hand, the channel is idle with probability of $1 - P_b$.

Assume a typical node u is at the Empty state. As far as the channel is busy due to the transmissions of neighbors, the backoff countdown process will not be initiated or resume. Therefore, the average interval time that node u checks its empty transmission queue to see whether a new packet comes into the queue is given by

$$t_{qc} = (1 - P_b) \cdot t_s + P_b \cdot t_r. \quad (3.5)$$

Note that t_{qc} is also the average transition time from two consecutive backoff states. As aforementioned, the packet arrival follows the Poisson process with arrival rate λ . Hence, the probability that at least one packet arrives at the empty queue is

$$P_0 = 1 - e^{-\lambda t_{qc}}. \quad (3.6)$$

The probability that the queue has a packet for transmission immediately after the previous transmission is actually the utilization of the MAC queue. Therefore, the probability that the network load becomes saturated is calculated by

$$\rho = \min(\lambda D, 1) \quad (3.7)$$

where D is the average packet delay that is computed from the moment the packet is at the head of the transmission queue till the packet is transmitted. It is equivalent to the expected time that the node is in the backoff process plus the transmission time of the packet. Since the backoff counter value is chosen randomly with equal probability, the average packet delay can be derived as

$$\begin{aligned} D &= \frac{1}{W} \sum_{i=1}^{W-1} i \cdot [(1 - P_b)t_s + P_b t_r] + t_p \\ &= \frac{W-1}{2} [(1 - P_b)t_s + P_b t_r] + t_p. \end{aligned} \quad (3.8)$$

Note that the average packet delay has already taken the channel-blocked slots into consideration. We assume λ is determined by the application while N_{cs} can be

estimated from the channel busy ratio which will be discussed in the next section.

3.3 Channel Busy Ratio for Vehicle Density Estimation

The vehicle density is an important factor in the performance evaluation of the DSRC MAC protocol. Most of the existing literature assumes that the vehicle density is known by the whole system, which is usually not true in practice. In this section, we propose an effective approach to estimate the vehicle density by using a practical parameter, i.e., the channel busy ratio (CBR).

The WAVE and ETSI standards [84] define CBR as an effective metric to measure the load on the channel. The value of CBR that is perceived at each individual vehicle is obtained from the PHY through the equipped radio delivered by the chipsets [85]. The CBR is defined as the average fraction of time that the channel is reported to be busy. Provided that T_{CBR} and T_{busy} are the CBR measurement interval and the duration of the busy channel, respectively, the CBR is computed as $T_{\text{busy}}/T_{\text{CBR}}$. Intuitively, we know that busy time of the channel reflects the congestion level of the network, which is further determined by the vehicle density. Hence, by processing the CBR, the vehicle density can be estimated.

For a typical vehicle u , its CBR shows the ratio of the channel occupancy due to the vehicles within its carrier sensing range. Alternatively, it reflects the congestion level in vehicle u 's local environment. We use CBR_0 to represent this locally perceived CBR. Adopting the local information provides a distributed way to evaluate the congestion level and hence the vehicle density. The local CBR_0 s for different vehicles may have a bit discrepancy whereas using the CBR for vehicle density estimation is still effective because we consider the one-dimensional highway scenario where vehicles are distributed according to a homogeneous PPP.

As described in Section 3.2, vehicles follow the Poisson distribution with the

vehicle density β . The average number of the total vehicles within R_{cs} is $N = N_{cs} + 1 = 2\beta R_{cs}$. We use P_c to represent the channel occupied probability (COP), which measures the probability that the channel is busy due to the transmissions of N vehicles. P_c is given by

$$P_c \approx 1 - (1 - \tau)^N. \quad (3.9)$$

As any transmission will prolong the duration of staying in one state of the Markov chain, it possibly takes more than t_s to change to another state. In order to characterize the average transition time of any one state to another of the Markov chain, we introduce the effective slot time which is denoted by t_{es} , and given by

$$t_{es} = (1 - P_c)t_s + P_c t_r. \quad (3.10)$$

The definition of the CBR can be interpreted as the portion of a measurement period, which is the effective slot time such that the channel is used for transmission. So the theoretical CBR, denoted by CBR_t , is computed as

$$\text{CBR}_t = \frac{P_c \cdot t_p}{t_{es}}. \quad (3.11)$$

We use CBR_0 to approximate CBR_t , i.e., $\text{CBR}_0 \approx \text{CBR}_t$.

Lemma 3.1. *Given the locally perceived CBR denoted by CBR_0 , the estimated vehicle density β can be approximated by*

$$\beta \approx \frac{1}{2R_{cs}} \left[\log_{(1-\tau)} \frac{t_p - \text{CBR}_0 \cdot t_r}{t_p - \text{CBR}_0 (t_r - t_s)} \right]. \quad (3.12)$$

Proof. Please refer to Appendix A.1. ■

Based on the Markov chain modeling in the last section, we know that τ is determined by the contention window size W . The value of β can be obtained from (3.12) together with (3.3) - (3.8). Since CBR_0 is the only input acquired

from the PHY at each vehicle, our proposed approach for the estimation of the vehicle density is simple and highly efficient.

3.4 Contention-Window Size Optimization

In order to improve the performance of the DSRC, various factors such as transmission power, distance between the source and the destination, and vehicle density have been studied in the existing work [38–45, 77–79]. In fact, contention window size W is another key parameter that directly impacts the performance of the channel contention. In this section, we focus on the optimal CW size for maximizing the throughput, which is an important metric to quantify the channel efficiency. We first provide a mathematical analysis on how the CW size affects the throughput in both the non-saturation and saturation conditions, and then propose the analytical solution to the optimal W for maximizing the throughput.

For a typical vehicle u , there are on average $N_{cs} = 2\beta R_{cs}$ vehicles within its carrier sensing range, where β can be obtained using the method proposed in Section 3.3. To achieve successful transmissions within a period of observation time, e.g., effective slot time t_{es} , there should be no interference in the air with the presence of $N = N_{cs} + 1$ contending vehicles. We adopt the same concept of throughput as in [38, 41] and give the definition as follows

Definition 1. Throughput, denoted by S , measures the fraction of time that the channel is in use to successfully transmit payload bits [38, 41]. The expression of S as a function of τ is given by

$$S(\tau) = \frac{\binom{N}{1} \tau (1 - \tau)^{N-1} t_p}{t_{es}}. \quad (3.13)$$

In Section 3.2, (3.3) to (3.8) link the variable τ with W , so the transmission probability τ can be expressed as a function of W , denoted by $\tau = f(W)$. Optimizing the CW size for throughput maximization is equivalent to solving the

following discrete optimization problem:

$$\begin{aligned}
 & \underset{W}{\text{maximize}} && S(\tau) \\
 & \text{s.t.} && \tau = f(W), \\
 & && 0 \leq S(\tau) \leq 1, \\
 & && 0 < \tau < 1, \\
 & && D \leq D_c, \\
 & && W \in \mathbf{E}
 \end{aligned} \tag{3.14}$$

where D_c is the packet delay constraint, which determines the maximum allowable packet delay based on the application requirement. In addition, $\mathbf{E}$ represents the finite set possible window sizes. In reality, the contention windows are standardized values according to different AC requirements. So let $\mathbf{E} = \{2^i | i \in \mathbb{N}_+, i \in \mathbf{I}\}$, where $\mathbf{I}$ is determined by AC [38].

To find the optimal window size W that achieves the maximal $S(\tau)$ in the given domain, we take the first derivative of $S(\tau)$ with respect to τ from (3.13). After simplification, $S'(\tau)$ is given by

$$S'(\tau) = \frac{1 - \alpha(1 - \tau)^N - N\tau}{Nt_pt_r(1 - \tau)^{N-2} \{t_s + (t_r - t_s)[1 - (1 - \tau)^N]\}^2} \tag{3.15}$$

where $\alpha = (t_r - t_s)/t_r$ is a constant. Note that since $t_r > t_s$, α is smaller than 1. To find the extreme value, we force $S'(\tau) = 0$.

Lemma 3.2. *There exists a unique solution $\tau = \tau_o$ to make the throughput $S(\tau)$ attain its maximum value in the domain $\tau \in (0, 1)$.*

Proof. Please refer to Appendix A.2. ■

According to Lemma 3.2, τ_o is the unique optimal transmission probability to achieve the maximum throughput. Since $y(\tau)$ is zero at $\tau = \tau_o$, we have $1 - \alpha(1 - \tau_o)^N - N\tau_o = 0$. With $\tau < 1$, the second term of the expression is expanded by the Taylor series and can be approximated to the following expression

using the second-degree Taylor polynomial

$$(1 - \tau)^N \approx 1 - N\tau + \frac{N(N-1)}{2!}\tau^2. \quad (3.16)$$

Hence, we are able to provide a closed-form solution to the optimal transmission probability τ_o

$$\tau_o = \frac{-N(1 - \alpha) + \sqrt{N^2(1 - \alpha)^2 - 2N(N-1)\alpha(\alpha-1)}}{N(N-1)\alpha} \quad (3.17)$$

where $\alpha = (t_r - t_s)/t_r$.

The relationship between the transmission probability and the CW size has been characterized in (3.3). However, the coupling of different system parameters makes it difficult to directly obtain the corresponding optimal window size W_o from τ_o . To overcome this difficulty, we analyze the saturation and non-saturation conditions, and obtain W_o for each case separately. By comparing the maximum achievable throughput of both cases, we then can decide the optimal CW size.

3.4.1 Saturation Condition

The saturation situation happens when the queue is not always empty after any transmission, which usually occurs when the CW size is relatively small or when the vehicle density is relatively high. Based on the analytical model of vehicle behavior, the saturation condition implies the following inequality: $\lambda D \geq 1$. So the probability that there is a packet in the transmission queue after each transmission defined in (3.7) is equal to 1. After some simplifications, the expression of (3.3) can be written as

$$\tau = \frac{2}{W+1}. \quad (3.18)$$

Let τ_s denote the transmission probability with which the network load is just saturated, i.e., $\lambda D = 1$. By substituting (3.18) into the expression of D in (3.8),

and based on the fact that $\lambda D = 1$, we have

$$-\alpha(1 - \tau_s)^N - \tau_s \left[\frac{1}{\lambda t_r} - \frac{t_p}{t_r} + 1 \right] + 1 = 0 \quad (3.19)$$

where $\alpha = (t_r - t_s)/t_r$ is a constant value as aforementioned. To solve τ_s , similarly to what has been done in (3.16), we apply the second-degree Taylor-polynomial approximation. Hence, the approximated τ_s is given by

$$\begin{aligned} \tau_s = & \frac{\sqrt{\left(\alpha N - 1 + \frac{t_p}{t_r} - \frac{1}{\lambda t_r}\right)^2 + \alpha(1 - \alpha)N(N - 1)}}{\alpha N(N - 1)} \\ & + \frac{\alpha N - 1 + \frac{t_p}{t_r} - \frac{1}{\lambda t_r}}{\alpha N(N - 1)}. \end{aligned} \quad (3.20)$$

Since the saturation case has $\lambda D \geq 1$, the transmission probability τ satisfies

$$\tau \leq \tau_s. \quad (3.21)$$

Let W_s be the CW size at the saturation critical point. We have, $W_s = 2/\tau_s - 1$. So the saturation case yields a boundary of the CW size: $W \geq W_s$. Under the saturation condition, the optimal transmission probability τ_o in (3.17) is achievable when it is less than or equal to τ_s , hence the optimal CW size W_o can be obtained

$$W_o = \frac{2}{\tau_o} - 1. \quad (3.22)$$

As one of the constraints of the optimization problem, the contention windows that can be implemented in the PHY should be $W \in \mathbf{E}$. We denote two feasible window sizes that are close to W_o by W_{o-} and W_{o+} , where $W_{o-} \leq W_o \leq W_{o+}$. They are given by

$$W_{o-} = 2^{\lfloor \log_2(\frac{2}{\tau_o} - 1) \rfloor} \quad (3.23)$$

$$W_{o+} = 2^{\lceil \log_2(\frac{2}{\tau_o} - 1) \rceil}. \quad (3.24)$$

Therefore, between W_{o-} and W_{o+} , the one leading to a greater throughput is the optimal window size in the saturation scenario.

To meet the delay constraint, the allowable average delay should be less than or equal to D_c , i.e., $D \leq D_c$. Let τ_c represent the transmission probability when the average packet delay is D_c . Similar to how we derive τ_s , τ_c can be obtained as

$$\begin{aligned} \tau_c = & \frac{\sqrt{\left(\alpha N - 1 + \frac{t_p}{t_r} - \frac{D_c}{t_r}\right)^2 + \alpha(1 - \alpha)N(N - 1)}}{\alpha N(N - 1)} \\ & + \frac{\alpha N - 1 + \frac{t_p}{t_r} - \frac{D_c}{t_r}}{\alpha N(N - 1)}. \end{aligned} \quad (3.25)$$

We use W_c to denote the CW size at τ_c , then $W_c = 2/\tau_c - 1$. When $D \leq D_c$, the transmission probability is $\tau \geq \tau_c$. Taking this delay constraint into account, the optimal τ_o is achievable under the saturation condition if it satisfies $\tau_c \leq \tau_o \leq \tau_s$. Correspondingly, the window size relationship $W_s \leq W_o \leq W_c$ can be obtained based on the reverse proportional relationship between τ and W in (3.18).

3.4.2 Non-saturation Condition

When the network load is unsaturated, the value of λD is smaller than 1, thus $\rho = \lambda D$. By re-arrangement and some simplifications, (3.3) is written as

$$\tau = \frac{1}{\frac{W+1}{2} + \frac{1-\lambda t_p - \frac{1}{2}\lambda(W-1)\{t_s + (t_r - t_s)[1 - (1-\tau)^{N-1}]\}}{1 - \exp\{-\lambda t_s - \lambda(t_r - t_s)[1 - (1-\tau)^{N-1}]\}}}. \quad (3.26)$$

The complex expression imposes challenges on the analysis of the relationship between τ and W . So we adopt a certain approximation to simplify the expression. We consider the component of the exponential function in (3.26), i.e., $\lambda t_s + \lambda(t_r - t_s)[1 - (1 - \tau)^{N-1}]$. It satisfies the following inequality

$$\lambda t_s + \lambda(t_r - t_s)[1 - (1 - \tau)^{N-1}] < \lambda \{t_s + (t_r - t_s)[1 - (1 - \tau)^N]\} \quad (3.27)$$

where $\lambda \{t_s + (t_r - t_s) [1 - (1 - \tau)^N]\} = \lambda t_{es}$. Provided that t_{es} is the effective slot time that measures the average transition time between any two adjacent states of the Markov chain, τ/t_{es} is the rate of transmission at an individual vehicle. The transmission rate and the packet generation rate are in equilibrium with the unsaturated load. So we know $\lambda = \tau/t_{es}$, hence $\lambda t_s + \lambda(t_r - t_s) [1 - (1 - \tau)^{N-1}] < \tau < 1$. Thus, according to $1 - e^{-x} \approx x$, we have $e^{-\lambda t_s - \lambda(t_r - t_s)[1 - (1 - \tau)^{N-1}]} \approx 1 - \lambda \{t_s + (t_r - t_s) [1 - (1 - \tau)^{N-1}]\}$. Therefore, (3.26) can be approximated and simplified to

$$\begin{aligned} \tau &\approx \frac{1}{\frac{W+1}{2} + \frac{1 - \lambda t_p - \frac{1}{2} \lambda (W-1) \{t_s + (t_r - t_s) [1 - (1 - \tau)^{N-1}]\}}{\lambda \{t_s + (t_r - t_s) [1 - (1 - \tau)^{N-1}]\}}} \\ &\approx \frac{1}{\frac{1}{2} + \frac{1 - \lambda t_p + \frac{1}{2} \lambda \{t_s + (t_r - t_s) [1 - (1 - \tau)^{N-1}]\}}{\lambda \{t_s + (t_r - t_s) [1 - (1 - \tau)^{N-1}]\}}} \end{aligned} \quad (3.28)$$

The parameter W is turned out to be eliminated in the above approximated τ expression. It indicates that τ is not sensitive to the variation of W under the non-saturation scenario. The effectiveness of this approximation will be validated by the simulations in the later section. In fact, based on empirical results, when W increases, the transmission probability τ will slightly increase. Let $\Delta\tau$ represent the increment of τ due to the increase of W , then $\Delta\tau \ll 10^{-2}$. This statement can be alternatively proved by verifying $d\tau/dW$ is slightly greater than 0, the detailed proof of which will be omitted here due to space limitation. In the non-saturation case, we assume that for $W < W_s$, the impact of W on τ is negligible. We denote the closest feasible window sizes on the left and right hand sides of W_s by W_{s-} and W_{s+} , respectively. They can be obtained by

$$W_{s-} = 2^{\lfloor \log_2(\frac{2}{\tau_s} - 1) \rfloor} \quad (3.29)$$

$$W_{s+} = 2^{\lceil \log_2(\frac{2}{\tau_s} - 1) \rceil}. \quad (3.30)$$

Based on the above analysis and assumption, the transmission probability for

$W < W_s$ is approximately equal to the transmission probability obtained at W_{s-} . Moreover, due to the continuity at τ_s , we have $\tau_{s-} \approx \tau_s$. Therefore, in the non-saturation scenario, τ_o is achievable when τ_o is rounded to τ_s . Considering the slight increment of τ with the increase of W in practice, the optimal window size should be W_{s-} .

3.4.3 Optimal Contention Window Size

Now we combine two cases of saturation and non-saturation together. As τ is a function of W , namely $\tau = f(W)$, the expression of τ can be viewed as a pairwise function, shown as below

$$\tau = f(W) = \begin{cases} f_1(W), & 0 < W < W_s \\ f_2(W), & W \geq W_s \end{cases} \quad (3.31)$$

Function $f_1(W)$ defines the non-saturation case, of which the equation is shown in (3.26), while $f_2(W)$ represents the saturation case. Given an input W , based on (3.3) to (3.8), $f_1(W)$ can be solved by using Newton-Raphson method. On the other hand, $f_2(W)$ is simple and straightforward, i.e., $f_2(W) = 2/(W + 1)$. After obtaining τ_o from (3.17), we can derive the feasible optimal window size based on the different ranges of τ_o : (1) Taking the maximum delay constraint into count, when $\tau_c < \tau_o < \tau_s$, the optimal window size is obtained by comparing the performance between W_{o-} and W_{o+} . (2) When $\tau_o = \tau_s$, the optimal window size may fall in the non-saturation or saturation region. (3) Furthermore, τ_o might not exist in either scenario, which means the optimal transmission probability is unattainable. The suboptimal CW size becomes the solution to the optimization problem. There are two possible situations: (a) when $\tau_o > \tau_s$, the optimal window size is actually the achievable window size determined by the suboptimal transmission probability τ_s ; (b) when $\tau_o < \tau_c$ under the saturation condition, $W_o > W_c$ causes the average packet delay to exceed the allowable maximum delay. Denote the largest feasible

window size that is no larger than W_c by W_{c-} , where $W_{c-} = 2^{\lfloor \log_2(\frac{2}{\tau_c} - 1) \rfloor}$. So the solution to the optimization problem is W_{c-} .

Therefore, as the solution to the optimization problem, the practical optimal window size denoted by W_p , is given by the following

$$W_p = \begin{cases} W_{c-}, & \tau_o < \tau_c \\ \arg \max [S(f(W_{o-})), S(f(W_{o+}))], & \tau_c < \tau_o < \tau_s \\ \arg \max [S(f(W_{s-})), S(f(W_{s+}))], & \tau_o \geq \tau_s \end{cases} \quad (3.32)$$

Recall that τ_o , τ_s and τ_c can be acquired through (3.17), (3.20) and (3.25), respectively. The procedure of finding W_p , the solution to the optimization problem is summarized in **Algorithm 1**. Hence, the maximum throughput is readily obtained.

3.5 Numerical Simulations and Discussions

In this section, extensive simulations are conducted to validate the proposed analytical model of periodic broadcasting behavior of vehicles with the DSRC technology, followed by the performance evaluation of the proposed method for estimating the global vehicle density through the channel busy ratio. Numerical results are given to verify the analytical optimization of CW size to maximize the throughput. The simulations are conducted by MATLAB for a two-lane highway scenario where vehicles have the same transmission power of 20 dBm. The lane width is 3m. Vehicles on the highway are assumed to follow the Poisson point process, same as the system model. It is assumed that all the studied vehicles are moving towards the same direction with a similar moving speed ν . We denote the distance between any two vehicles by d . Then the large-scale path loss is characterized by

Algorithm 1 Find the optimal contention window size for throughput maximization

Input: Vehicle density β .

Output: Optimal window size W_p .

Obtain τ_o , τ_s , τ_c based on (3.17), (3.20) and (3.25), respectively.

if $\tau_o < \tau_c$ **then**

$W_p = W_{c-}$.

else if $\tau_c < \tau_o < \tau_s$ **then**

if $S(f(W_{o-})) > S(f(W_{o+}))$ **then**

$W_p = W_{o-}$.

else

$W_p = W_{o+}$.

end if

else

if $S(f(W_{s-})) > S(f(W_{s+}))$ **then**

$W_p = W_{s-}$.

else

$W_p = W_{s+}$.

end if

end if

the following dual-slop model [87]:

$$PL = \begin{cases} PL_0 + 23\log_{10}\frac{d}{d_0}, & d_0 < d \leq d_c \\ PL_0 + 23\log_{10}\frac{d_c}{d_0} + 27\log_{10}\frac{d}{d_c}, & d > d_c \end{cases} \quad (3.33)$$

where PL_0 is the free space path loss at the reference distance $d_0 = 10\text{m}$, and $d_c = 80\text{m}$ is the critical distance. The carrier sensing threshold is assumed to be -89 dBm . Then we can derive the carrier sensing range is 200m . Other settings include: a packet transmission time $t_p = 700\mu\text{s}$, a slot time $t_s = 13\mu\text{s}$, AIFS = $149\mu\text{s}$, propagation delay $\delta = 1\mu\text{s}$, and the finite set $\mathbf{E} = \{16, 32, \dots, 1024\}$ in

Table 3.2: System Configuration.

Transmission time t_p	$700\mu s$
Slot time t_s	$13\mu s$
SIFS	$32\mu s$
AIFSN	9
Propagation delay δ	$1\mu s$
Finite set $\mathbf{E}$	$\{16, 32, \dots, 1024\}$
Vehicle density β	varies from 0.075 to 0.2

Figure 3.3: Average packet delay versus packet generation rate using the proposed Markov chain model and the benchmark model.

accordance to AC[3]. Parameters for the system configurations are summarized in Table 3.2.

First, we evaluate the performance of the proposed Markov chain model for analyzing the MAC protocol for both saturated and unsaturated network loads. According to AC[3], W is fixed at 16. The vehicle density is set to 0.05. Fig. 3.3 plots the relationship between the average packet delay and the packet generation rate λ , while Fig. 3.4 shows the throughput against λ . We compare our Markov chain model with a benchmark model proposed by Yao *et al.* [40] and the simulation results. Yao's model does not exclude the channel-blocked slots from the total slots, so the transmission events for different vehicles are not independent, as

Figure 3.4: Throughput versus packet generation rate using the proposed Markov chain model and the benchmark model.

explained in Section 3.2. That leads to inaccuracy to the channel busy probability hence influences the average packet delay and the throughput. Such impact on the modeling becomes more significant with higher λ . Therefore, the benchmark model performs well at a lower generation rate but diverges from the simulation when λ increases. In contrast, our proposed model alleviates this issue by excluding the channel-blocked slots from the total slots thus provides a more accurate model regardless of λ values. Hence, the periodic broadcast of short messages by the vehicles in the highway scenario can be effectively characterized under both the saturation and non-saturation conditions. Both Fig. 3.3 and Fig. 3.4 confirm the accuracy of our proposed model. With the increase of the packet generation rate, the average packet delay increases. However, the curve of the throughput declines after a certain packet generation rate, which is a result of larger interference in the air caused by the higher packet generation rate.

Next, we evaluate the vehicle-density estimation method by tracking the locally perceived CBR_0 , and conduct the simulations for the following settings: W is 16 according to the minimum window size of AC[3] and λ is set to 50. As shown

Figure 3.5: Performance of the proposed method for vehicle density estimation.

in Fig. 3.5, by adopting the local CBR, the estimated vehicle density follows the reference line closely. As discussed in Section 3.3, the CBR perceived at each individual vehicle from the PHY is defined by the WAVE and ETSI standards and contained in the periodic message broadcast by the vehicle. Therefore, it is feasible for every vehicle on the highway to utilize the proposed method for vehicle density estimation.

In Fig. 3.6 and Fig. 3.7, we compare the modeling performances between the proposed model and the benchmark for different CW sizes. With $\lambda = 50$ pkts/s and $\beta = 0.1$, our proposed Markov chain model is observed to be more accurate than the benchmark model. Meanwhile, these two figures also show the impacts of CW sizes on the average packet delay and the throughput. Intuitively, increasing the contention window size leads to longer packet delay. For a fixed vehicle density, a peak throughput point is observed in Fig. 3.7 and there exists a practical optimal window size W_p to achieve the corresponding maximum throughput.

The proposed analytical method to obtain the optimal CW size W_p to maximize the throughput for different vehicle densities are verified in Fig. 3.8 and Fig. 3.9. Given $\lambda = 50$, both scenarios where the delay constraint is inactive (i.e., $D_c = \infty$)

Figure 3.6: Average packet delay versus contention window sizes using the proposed Markov chain model and the benchmark model.

Figure 3.7: Throughput versus contention window sizes using the proposed Markov chain model and the benchmark model.

Figure 3.8: Optimal contention window size W_p without delay constraint and with delay constraint for different vehicle densities.

Figure 3.9: Maximum throughput by using the optimal contention window size W_p without delay constraint and with delay constraint for different vehicle densities.

and the delay constraint D_c is set to 40ms are evaluated.

We evaluate the achievable throughput when the derived optimal window size W_p is adopted and the throughput that is obtained with fixed window sizes. With a 40ms-delay constraint, the throughput results for different vehicle densities are shown in Fig. 3.10. The bars in red color correspond to the throughput when every vehicle applies the derived optimal W_p . The conventional fixed window sizes are also applied for benchmarking purpose. In a relatively large vehicle network with high vehicle density, some large fixed window sizes (e.g., $W = 1024$) are prone to leading to a large packet delay that exceeds the delay constraint. Hence, the window sizes do not satisfy the delay constraint causing the throughput to drop to zero. The derived optimal window size W_p can achieve the maximum throughput for all possible vehicle densities, introducing throughput gain to the conventional fixed window sizes. In practice, the vehicle densities can be estimated by utilizing the vehicle-density estimation method via the CBRs in the distributed manner as proposed in Section 3.3. Then each vehicle is able to derive the practical optimal window size W_p that leads to the maximum throughput. Without further communication overhead, the vehicles can choose the optimal window size hence realize the largest throughput and the highest channel efficiency. In practice, by utilizing the vehicle density estimation method via the CBRs in the distributed manner, each vehicle is able to derive the optimal window size W_p that leads to the maximum throughput. Without further communication overhead, the vehicles can choose the optimal window size hence realize the largest throughput and the highest channel efficiency.

3.6 Summary

In this chapter, we propose a new Markov chain to model the MAC layer of DSRC V2V periodic broadcast. Yao's model [40] is used for benchmarking. With Yao's model, the predication of average packet delay becomes inaccurate when the packet

Figure 3.10: Achieved throughput (with 40ms delay constraint) by using the optimal contention window size W_p versus using the fixed window sizes W for different vehicle densities β .

arrival rate became larger than 25 pkts/s and the analytical throughput diverges from the simulation. Our proposed model largely improves the modeling accuracy by reducing the impacts of the correlated transmission probabilities, i.e., separating the channel-blocked slots from the total slots and addressing them separately. Based on the proposed model, we optimize the contention window size to have the maximum throughput. The delay constraint is also taken into consideration which has not been done in many existing works. Not relying on the numerical trials to find the optimal contention-window size, we provide analytical solutions in response to different vehicle densities. With the derived optimal contention window size, the throughput could reach its maximum value and significantly outperform the one using fixed window sizes. Furthermore, in the implementation of the contention-window optimization, we do not make the simplistic assumption that vehicle density is known by each vehicle. Instead, we link the channel busy ratio (CBR) perceived by each vehicle's physical layer, with the proposed Markov

chain model and we provide the closed-form expression for the vehicle density as a function of CBR. This enables each vehicle to estimate the vehicle density in a distributed manner and hence to adapt the contention window size practically (without the need to rely on system information).

Chapter 4

Network-Coded Relaying for Periodic Safety Message Dissemination at NLOS Intersections

4.1 Introduction

In this chapter, an enhanced periodic message dissemination scheme is proposed to mitigate the non-linear-of-sight (NLOS) problem at road intersection. Such message like BSM has a stringent delay requirement and it is periodically broadcast by each vehicle on the road to assist drivers in getting awareness of the surrounding and reacting promptly in case of any danger. The dissemination of BSMs is particularly crucial for vehicles near the road intersections without traffic signals. However, large concrete buildings and obstacles may create a non-line-of-sight (NLOS) condition, resulting in severe signal degradation or signal blockage. Thus, the delivery of BSMs may not be able to meet the timeliness requirement and increases the chance of vehicle collisions. To solve this problem, a controlled repetitive transmission pattern is introduced in this chapter, which can maximize

Figure 4.1: V2X Communication at NLOS road intersection.

the successful reception probability of the whole system. Then, by exploiting the benefit of network coding, two promising network-coded relaying schemes are proposed and evaluated.

4.2 Problem Formulation

4.2.1 System Model

We consider n vehicles inside an intersection area where concrete buildings are located at the sides of the road. Each vehicle is equipped with a radio for safety-related message broadcast and represented by a node shown in Fig. 4.1. Every node broadcasts its BSM and is expected to receive the safety messages generated by its $n - 1$ neighbors. Due to the blockage of the roadside concrete buildings, the communication links between some vehicles are non-line-of-sight (NLOS) [91,92].

As illustrated in Fig. 4.1, an arbitrary node w , is unable to receive BSMs generated by a certain number of nodes located on the perpendicular road. We assume there exists a vehicle that is much closer to the intersection centre so that it maintains a good connectivity with any other $n - 1$ neighboring nodes. Such vehicle is referred as *Intersection Vehicle* and denoted by node I . Hence, the line-of-sight (LOS) communication is observed between node I and node w .

We assume that the NLOS communication is fully blocked and the LOS communication experiences a V2X channel fading (e.g., Nakagami-m fading), of which the average signal outage probability is denoted by p_e . The packet loss probability caused by the fading channel is assumed to be equivalent to the average signal outage probability p_e . Therefore, a node can successfully receive a broadcast packet via the LOS communication channel with probability $1 - p_e$.

For any node w , based on the assumption that the V2V communication channel between its NLOS neighbor nodes and itself is fully blocked, we can learn that the effective communication range of node w is reduced. On top of the effective communication range, we partition w 's $n - 1$ neighbor nodes into two sets: the nodes that are outside the effective communication range of w and the nodes that are inside the effective communication range of w . The number of nodes in these two sets are represented by n_w^{out} and n_w^{in} , respectively. Assuming that f_w is the fraction between the number of outside-the-range nodes and the total number of w 's $n - 1$ neighbors, then n_w^{out} and n_w^{in} are given by,

$$n_w^{out} = \lceil (n - 1) \cdot f_w \rceil \quad (4.1)$$

$$n_w^{in} = (n - 1) - \lceil (n - 1) \cdot f_w \rceil. \quad (4.2)$$

As we know n_w^{out} nodes will not be able to receive the safety packets broadcast by node w , it is needed to introduce a certain relay node (nodes) help bridge the communications between an arbitrary node w and its NLOS nodes. We know that node I is the closest one to the intersection centre hence having LOS communi-

cations with all other nodes in the system. Therefore, if only one node in the system is to be selected for relaying, node I is definitely the best candidate. We will explore different relaying strategies in the later sections which both consider only relaying at node I and relaying at all nodes in the system.

4.2.2 Controlled Message Repetition Mechanism

Each vehicle generates a message containing its own driving status every 100ms (at a frequency of 10Hz) and creates a new one in the next interval. So 100ms is regarded as the lifetime of a message and hence it is important to investigate the packet reception status within the lifetime. Note that in some V2X use cases, T window time, an application-level metric is applied to measure the tolerant time. T window is actually the average time interval between two messages that are successfully received by any vehicle [97, 114]. However, since BSM dissemination at NLOS road intersection is critical to help drivers avoid traffic accidents and potential hazards, instead of using T window time to evaluate the system performance, we focus on the design of a reliable BSM dissemination protocol following which the BSMs can be received by each vehicle in the intersection area within the message lifetime. As discussed in Chapter 3, vehicles under the DSRC IEEE 802.11p standard follows a backoff algorithm to contend the channel for BSM broadcast. However, there is no acknowledgement for any successful transmission in this broadcast mode. Thus, there is no retransmission for any lost packet that may be caused by the channel fading or channel congestion and the unsuccessful BSM reception with a certain probability is unavoidable. To solve this problem and enhance the successful reception probability of all the vehicles in the system, we improve the DSRC MAC layer by introducing a controlled repetitive transmission, **RT** in short. As it is shown in Fig. 4.2, the BSM lifetime is equally partitioned into M slots and the duration of each slot is $\frac{L}{r}$, where L represents the packet length and r is the data rate. In any slot, each node transmits the packet with probability p . That means on average, each node repeats k times in M slots,

Figure 4.2: Controlled repetitive transmission pattern.

i.e, $k = p \cdot M$. All nodes are synchronized to a global clock by using the GPS installed on the vehicles. Therefore, in a slot time, more than one node might attempt to access the channel. Since the interval between any two repetitions of a node is random, the probability of successful transmission in a slot, p_t exists. It follows the geometric distribution and can be calculated as

$$p_t = p \cdot (1 - p)^{n-1}. \quad (4.3)$$

To maximize the p_t without the loss of transmission chances, the optimal controlled RT parameter p is obtained by using the following lemma.

Lemma 4.1. *The optimal repetitive transmission probability p for maximizing the probability of successful transmission in a single time slot, is given by*

$$p = \frac{1}{n}. \quad (4.4)$$

Proof. Please refer to Appendix B.1. ■

Note that in this chapter, we focus on the reliability of BSM transmission within its lifetime (100 ms). Thus, we regard any moving vehicle as a static node during the transmissions of one BSM packet.

4.2.3 Performance Metric

We use *success probability*, $\mathcal{P}_s$, as the performance metric to evaluate the transmission reliability of the system. $\mathcal{P}_s$ is defined as the probability that all nodes in the system are able to complete the successful exchange of BSMs within a BSM lifetime or M slots. A system with a higher success probability is considered to be more reliable. It has good scalability if the success probability does not dramatically decline with the increase of the number of nodes.

4.3 BSM Relaying with Network Coding

In this section, we will discuss three relaying strategies at NLOS intersections to help vehicles exchange BSMs and ensure the successful reception of BSMs within the message lifetime. The relaying strategies are on top of the controlled repetitive transmission pattern (RT) so each node has multiple transmission attempts within 100 ms. Based on the system presented in Section 4.2.1, we know that node I is the one that is located closest to the intersection centre with the best communication link quality with other $n - 1$ nodes in the intersection area. Naturally, we may consider using node I to relay any received safety packets generated by others. We use **RT-I** to indicate this relaying strategy that the packets are only relayed by the Intersection node I . Since node I itself is also a vehicle periodically generating BSMs, node I also needs to broadcast its own safety packet occupying at least one time slot. In such case, the relayed packets and I 's packet have to share the transmission opportunities, thus the transmission probability of relaying one packet or broadcasting its own packet is reduced, much lower than p . Meanwhile, the channel fading may cause the loss of the relayed or its own packet at the relay node I . So if only the RT-I is applied to the network, nodes may still suffer from the reception failure.

To solve this problem, we apply the random linear network coding (RLNC) for leveraging the usefulness of each broadcasting packet at the relay node hence im-

proving the packet reception probability of the network. On top of the controlled RT, we first introduce a relaying strategy that the packets are encoded (using RLNC) and relayed only by the Intersection vehicle, node I . We use **RT-NCI** to denote this strategy. Note that different from RT-I relaying strategy, the relay node I will do the network-coded relaying by sending out network coded packets. Then, we increase the number of relay nodes by proposing another relaying strategy called **RT-NCA**. With RT-NCA, ALL nodes become relay nodes and they can perform network coding on the received packets and relay the coded packets. The main difference between RT-NCA and RT-NCI is the number of network-coded relay nodes while the repetitive transmission probability and other factors remain unchanged. The proposed strategies, RT-NCI and RT-NCA, are expected to outperform the RT-I and the RT-NCA may have the best performance, which will be analyzed in the following subsections.

4.3.1 RT-I

For RT-I relaying strategy, all n nodes follow the repetitive transmission pattern but only the node I performs the packet relaying. If node I has received any packet from other nodes, node I can relay this packet when it has the chance to broadcast. Otherwise, node I will only broadcast its own packet. For analysis purpose, we assume when the relay node I happens to have the transmission opportunity, the packets awaiting to be relayed and I 's own packet share the equal probability of being selected. To simplify our analysis, herein we use a constant probability $\frac{1}{n}$ to calculate this probability.

Since we need to evaluate whether this relaying scheme is able to guarantee the successful exchange of BSMs within the message lifetime, we apply a finite-time Markov chain to characterize the BSM reception status of a node, shown in Fig. 4.3. The state of Markov chain relates to the number of original safety packets that are received by an arbitrary node w . These original safety packets may be the packets that are directly received by node w or the relayed packets obtained

Figure 4.3: Markov chain model for RT-I relaying strategy.

from node I . The transition probability between any two states is s_{ij} , where i and j represent the states in Markov chain. The time from the initial state to the absorbing state follows the discrete phase-type distribution [115]. The transition matrix P of dimension $n \times n$ has $n - 1$ transient states and one absorbing state. We use $\mathbf{e}$ to represent a column vector of ones of appropriate dimension. The transition matrix P is given below,

$$P = \begin{bmatrix} T & \mathbf{T}^0 \\ \mathbf{0} & 1. \end{bmatrix} \quad (4.5)$$

$$\mathbf{T}^0 = \mathbf{e} - T\mathbf{e}. \quad (4.6)$$

The discrete phase-type distribution is represented by the pair $(\boldsymbol{\alpha}, T)$, where the initial probability vector is $\boldsymbol{\alpha} = [1 \ 0 \ 0 \ \dots 0]$. RT-I has the following T matrix.

$$T = \begin{bmatrix} s_{00} & s_{01} & 0 & \cdots & 0 \\ 0 & s_{11} & s_{12} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & s_{(n-2)(n-2)}. \end{bmatrix}$$

The entry s_{ii} of the T matrix is $1 - s_{ij}$. The number of packets received by the relay node I affects the transition probability between two consecutive states. So in order to describe the completion time in a quantitative manner, here we have

an assumption: at the start of every slot, the relay node I is able to provide node w with one packet that was not received before. So s_{ij} is given by,

$$\begin{aligned} &\text{For } 0 \leq i \leq n_w^{in} - 2, j = i + 1, \\ &\quad s_{ij} = \binom{n_w^{in} - 1 - i}{1} p_t(1 - p_e) + \frac{1}{n} \cdot p_t(1 - p_e) \\ &\text{For } n_w^{in} - 1 \leq i \leq n - 2, j = i + 1, \\ &\quad s_{ij} = \frac{1}{n} \cdot p_t(1 - p_e). \end{aligned} \tag{4.7}$$

Note that the reception status of the system can be reflected by a single node. Therefore, we can use the completion time of a typical node to represent that of the whole system. The average completion time from the initial state to the absorbing state is denoted by a random variable τ . According to the definition of the performance metric, when the completion time is less or equal to M slots, all nodes can successfully receive BSMs of neighbors. So the formula of success probability of RT-I is,

$$\mathcal{P}_s^{Relay} = P(\tau \leq M) = 1 - \alpha T^M \mathbf{e}. \tag{4.8}$$

Note: A specific superscript is added to $\mathcal{P}_s$ to indicate the corresponding success probability by using different relaying strategies.

4.3.2 Proposed RT-NCI

As discussed at the beginning of this chapter, we improve the success probability of the whole system by proposing a new relaying strategy, named RT-NCI. As indicated by its name, this relaying strategy is also on top of the controlled repetitive transmission pattern. With this relaying strategy, one and only node I will do the relaying. But instead of pure relaying as RT-I, this proposed RT-NCI adopts RLNC [1] at the relay node so that each packet relayed by the relay node

I is a network coded packet.

If the relay node I did not receive any packet from other nodes, only its own safety packet will be broadcast but in the same data format as a network coded packet (that means this packet should have the randomly chosen network coefficients in the packet header). As long as this relay node I receives packets from others, it first stored the received packets and linearly combines all the stored packets $P_i, i = 1, 2, \dots, \tilde{n}$, to form a coded packet. The stored packet P_i may be its own packet or a certain number of packets received from $n - 1$ neighbors. So the coded packet is: $P_{coded} = \sum_{i=1}^{\tilde{n}} c_i \cdot P_i$, where $1 \leq \tilde{n} \leq n$. The network code c_i is randomly selected from Galois Field $\mathbb{F}_q$ and stored in the header of the coded packet. The size of the overhead depends on the finite field size q and the maximum number of original packets to be combined with. Therefore, each coded packet introduces extra $\log_2 q \cdot n$ bits to the packet header. The rest $n - 1$ nodes follow the same rule in RT-I that they are only allowed to repetitively broadcast their own packets. In order to maintain the same packet size as the coded packet, each original packet sent from $n - 1$ neighbors also has a randomly chosen network code stored in the header. With the knowledge of directly received packets as well as its own packet, nodes are able to decode the coded packets and retrieve other $n - 1$ original safety packets.

Node w keeps track of the network codes of the received packets and forms the network-code matrix $\mathbf{C}_w$. This matrix is updated whenever a new packet is obtained. When node w can successfully decode $n - 1$ original packets, $\mathbf{C}_w$ has a full rank. We use D_w to denote the dimension of the subspace spanned by packets received by node w . We have,

$$0 \leq D_w = \text{rank}(\mathbf{C}_w) \leq n - 1. \quad (4.9)$$

Node w 's subspace dimension D_w can be used to reflect the status of packet reception at node w . At arbitrary time t , for any node w , $n - 1$ neighbors can be categorized as innovative or non-innovative nodes. Innovative nodes are those

which can provide node w with new packets that increase D_w . In contrast, nodes are considered as non-innovative if their transmissions do not contribute to D_w .

Inspired by the work in [48], we analyze the performance of RT-NCI by investigating the relationship between the number of non-innovative nodes and the subspace dimension. Suppose D_w at time t is equal to i , $i \geq 1$. To satisfy $D_w = i$, the conventional RT-I relaying strategy requires that i packets are contributed by i distinct nodes. So at time t , the number of non-innovative nodes is exactly i . However, based on the proposed RT-NCI relaying, the relay node I has the ability to increment D_w by transmitting coded packets. If node I is an innovative node to node w when D_w is $i - 1$, it is possible that node I remains innovative after transmitting a coded packet. Thus, the number of non-innovative nodes keeps unchanged when D_w turns to i . Hence, the number of non-innovative nodes to node w at time t is in the interval $[i - 1, i]$. On the other hand, if node I is non-innovative to node w with the current subspace dimension of i , before D_w increases to $i + 1$, node I has the chance to become innovative by successfully receiving packets sent from existing innovative nodes.

Similar to RT-I, the discrete phase type distribution (α, T) is applied to analyze the average completion time for any node w . Each state of the Markov chain in Fig. 4.3 represents the subspace dimension under the propose RT-NCI relaying strategy. For differentiation purpose, we call those states as main states. Between two consecutive main states, e.g., state i and state $i + 1$, there is another finite time Markov chain to characterize the time for D_w to increment from i to $i + 1$, of which the states are called sub-states. As shown in Fig. 4.4, sub-states show the numbers of non-innovative nodes in regards to node w . The start of sub-states is the first time when D_w becomes i . We assume that the relay node I is non-innovative to node w initially (state $\mathbf{0}$). So the number of non-innovative nodes reaches its maximum value, i.e., $i - 0$. After receiving a new packet from other innovative nodes, node I transforms into an innovative node (state $\mathbf{1}$). Hence the number of non-innovative nodes in the system decreases to $i - 1$. Whenever node

Figure 4.4: Markov chain model of sub-states transition for RT-NCI relaying strategy.

w receives a new packet successfully, D_w changes from i to $i + 1$ (absorbing state) and the transition of sub-states stops. The absorbing state is also the next main state $i + 1$. We use matrix $\mathbf{S}_i$ to represent the transition between sub-states, of which the subscript describes the current subspace dimension. The relationship between the matrix T of the main states and the matrix $\mathbf{S}_i$ of sub-states is,

$$T = \begin{bmatrix} \mathbf{S}_0 & \mathbf{S}_0^0 & 0 & \cdots & 0 \\ 0 & \mathbf{S}_1 & \mathbf{S}_1^0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \mathbf{S}_{n-2} \end{bmatrix} \quad (4.10)$$

$$\mathbf{S}_i = \begin{bmatrix} x_{00} & x_{01} \\ 0 & x_{11} \end{bmatrix}, \quad \mathbf{S}_i^0 = \mathbf{e} - \mathbf{S}_i \mathbf{e}, \quad i \in [0, n - 2]. \quad (4.11)$$

The transition probabilities of sub-states follow the geometry distribution and are

calculated as follows,

$$\begin{aligned}
 &\text{For } 0 \leq i \leq n_w^{in} - 1, 0 \leq j \leq k \leq 1 \text{ and } j \neq k, \\
 x_{jj} &= 1 - \binom{n-1-(i-j)}{1} p_t + \binom{n_w^{in}-(i-j)}{1} p_t p_e^{2-j} \\
 &\quad + \binom{n_w^{out}}{1} p_t p_e^{1-j} \\
 x_{jk} &= \binom{n_w^{in}-(i-j)}{1} p_t (1-p_e)^{k-j} p_e^{2-k} \\
 &\quad + \binom{n_w^{out}}{1} p_t (1-p_e)^{k-j}
 \end{aligned} \tag{4.12}$$

$$\begin{aligned}
 &\text{For } n_w^{in} \leq i \leq n-2, 0 \leq j \leq k \leq 1 \text{ and } j \neq k, \\
 x_{jj} &= 1 - \binom{n-1-(i-j)}{1} p_t + \binom{n-2-(i-j)}{1} p_t p_e^{1-j} \\
 &\quad + \binom{1}{1} p_t p_e \\
 x_{jk} &= \binom{n-1-(i-j)}{1} p_t (1-p_e)^{k-j}.
 \end{aligned}$$

Therefore, with the initial probability vector $\alpha = [1 \ 0 \ 0 \ \dots 0]$, the success probability of the system using RT-NCI is given by: $\mathcal{P}_s^{NCI} = 1 - \alpha T^M \mathbf{e}$.

Note that in a real traffic scenario, the implementation of the proposed RT-NCI would require the network to identify the Intersection vehicle, node I , in the first place. One possible solution is to allow each vehicle to calculate its distance to the intersection and identify the closest one in a distributed manner. Relying on the GPS and the map embedded in the system, each vehicle on the road can calculate the distance to the intersection. The BSM exchange with neighboring vehicles provides each vehicle with the instantaneous location information. Based on the locations of its own and others, the vehicle which finds itself is the Intersection vehicle, can piggyback a few bits into its safety packet during the next-round BSM transmission. When other vehicles receive the BSM containing those bits, they will know the intersection vehicle has been selected and hence they will not claim themselves as intersection vehicles anymore.

Figure 4.5: Markov chain model of sub-states transition for RT-NCA relaying strategy.

4.3.3 Proposed RT-NCA

In addition to the network-coded relaying strategy, RT-NCI, in which only the node I encodes and relays the received packets (including its own packet), we propose another network coded relaying strategy. We enable each of the n nodes in the network to encode received packets and relay the coded packets. Subject to the controlled RT pattern, all nodes linearly combine the received packets as well as their own safety packets into coded packets. When anyone has the chance for transmission, it will relay the coded packet per time slot. We call this strategy as RT-NCA, where 'A' indicates *All* nodes will do the network-coded relaying.

As analyzed in Section 4.3.2, the number of non-innovative nodes in RT-NCI scheme is bounded by $i - 1$ and i when the subspace dimension is i . Here, the minimum number of non-innovative nodes can be as lower as 0 because every node in the system can transform from non-innovative to innovative with respect to node w . The relationship between matrix T and the sub-states matrix is represented by (4.10). As shown in Fig. 4.5, the sub-states between two consecutive main states i and $i + 1$ have $i + 1$ transient states and one absorbing state. The transition matrix of sub-states is shown below,

$$\mathbf{S}_i = \begin{bmatrix} x_{00} & x_{01} & x_{02} & \cdots & x_{0i} \\ 0 & x_{11} & x_{12} & \cdots & x_{1i} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & x_{ii} \end{bmatrix} \quad (4.13)$$

Network codes are randomly chosen from Galois Field so there is a small probability that two rows in the network-code matrix $\mathbf{C}_w$ are not independent. The function $f(q)$ is used to represent the probability that a newly received coded packet is independent from previously obtained one. $f(q)$ is calculated as: $f(q) = 1 - \frac{1}{q}$. Before considering $f(q)$, the transition probabilities between sub-states in Fig. 4.5 are represented by the following equations,

For $0 \leq i \leq n_w^{in} - 1$, $0 \leq j \leq k \leq i$ and $j \neq k$,

$$\begin{aligned} x_{jj} &= 1 - \binom{n-1-(i-j)}{1} p_t + \binom{n_w^{in}-(i-j)}{1} p_t p_e^{i-j+1} \\ &\quad + \binom{n_w^{out}}{1} p_t p_e^{i-j} \\ x_{jk} &= \binom{n_w^{in}-(i-j)}{1} p_t \binom{i-j}{k-j} (1-p_e)^{k-j} p_e^{i-k+1} \\ &\quad + \binom{n_w^{out}}{1} p_t \binom{i-j}{k-j} (1-p_e)^{k-j} p_e^{i-k} \end{aligned}$$

For $n_w^{in} \leq i \leq n-2$, $0 \leq j \leq i - n_w^{in}$ and $j < k \leq i$,

$$\begin{aligned} x_{jj} &= 1 - \binom{n-1-(i-j)}{1} p_t + \binom{n-1-(i-j)}{1} p_t p_e^{i-j} \\ x_{jk} &= \binom{n-1-(i-j)}{1} p_t \binom{i-j}{k-j} (1-p_e)^{k-j} p_e^{i-k} \end{aligned}$$

For $n_w^{in} \leq i \leq n-2$, $i - n_w^{in} < j \leq k \leq i$ and $j \neq k$,

$$\begin{aligned} x_{jj} &= 1 - \binom{n-1-(i-j)}{1} p_t + \binom{n_w^{in}-(i-j)}{1} p_t p_e^{i-j+1} \\ &\quad + \binom{n_w^{out}}{1} p_t p_e^{i-j} \\ x_{jk} &= \binom{n_w^{in}-(i-j)}{1} p_t \binom{i-j}{k-j} (1-p_e)^{k-j} p_e^{i-k+1} \\ &\quad + \binom{n_w^{out}}{1} p_t \binom{i-j}{k-j} (1-p_e)^{k-j} p_e^{i-k}. \end{aligned}$$

When taking innovative-packet probability $f(q)$ into account, the real transition probability is,

$$\begin{aligned} x_{jj} &= 1 - f(q) + f(q) \cdot x_{jj} \\ x_{jk} &= f(q) \cdot x_{jk}. \end{aligned} \tag{4.14}$$

By using above equations, the performance metric $\mathcal{P}_s^{NC}$ can be easily obtained based on the formula $\mathcal{P}_s^{NCA} = 1 - \alpha T^M \mathbf{e}$.

RT-NCA enables all of n nodes in the network to perform network-coded relaying. Compared with the single-node network-coded relaying RT-NCI, RT-NCA increases the opportunity for an arbitrary node to retrieve useful information from any received packet, hence shortens the time to recover original packets of neighbors. So the success probability $\mathcal{P}_s^{NCA}$ should be higher than $\mathcal{P}_s^{NCI}$.

Different from the implementation of RT-NCI discussed in the last sub-section, all vehicles that follow the proposed RT-NCA perform RLNC on BSM packets. Without generating too much heavy traffic loads caused by the repetitive transmissions, we need to define a distance from the vehicle to the intersection, beyond which the RT-NCA is not implemented. Since every vehicle knows the distance to the intersection from GSP and the map embedded, every vehicle is able to know when to initiate the RT-NCA protocol.

4.4 Numerical Simulations and Discussions

4.4.1 Simulation Setup

Our simulation environment is set up according to the system model described in Section 4.2. Various number of vehicles n are simulated and the evaluations will be presented in the later part. To simulate the single-node relaying strategy, RT-I, the node is placed at the intersection point of two stretched roads. This node is enabled to randomly relay the received packets or transmit its own packet.

Table 4.1: Parameters Used in Simulations.

Carrier Frequency	5.9 GHz
Communication Range	200m
Antenna Gain	2 dB
Data Rate	12 Mbps
Transmission Power	23 dBm
Thermal Noise Level	-96 dBm
Message Rate	10 Hz
Packet Size	128 Bytes
Fraction of outside-range nodes f_w	0.2

As for the proposed strategy RT-NCI, only the node at the intersection point can perform the network coding on the packets in the buffer which include its own packet and the packets received from any other nodes. The network codes are randomly selected from the Galois field $q = 2^8$ and stored in the header of each coded packet. The other proposed strategy RT-NCA allows all the studied vehicles to create RLNC packets. Moreover, the RT pattern is designed with the optimal transmission probability which is $1/n$. The values of the rest parameters are shown in Table 4.1. Basic safety message dissemination experiences Nakagami fading¹ and incurs a packet loss rate p_e . Based on the empirical measurement in [87], the shape factor takes 0.74 for simulations and path loss component is 2. Hence the loss rate can be calculated. In general, our simulations verify the effectiveness of the proposed RT-NCI and RT-NCA network-coded relaying strategies against the single-node relaying strategy, RT-I. The performance of RT-NCA is expected to be best in terms of the system reliability and scalability, followed by RT-NCI. The analyses of the success probability of three schemes are validated by simulations. All experiments are conducted repeatedly for 10^4 times.

¹The Nakagami fading expression and the signal outage probability due to the Nakagami fading is elaborated on in Section 5.3.1. So we omit the details here.

4.4.2 Numerical Examples

The system reliability can be improved when we apply the controlled repetitive transmission mechanism. We prove this point by comparing the controlled RT with the DSRC IEEE 802.11p, in terms of the successful reception probability. We consider a group of n vehicles with LOS communication channels suffer from packet loss caused by the channel fading with an average probability p'_e . No packet relaying or network coding is enabled in this case. As shown in Fig. 4.6, Fig. 4.7 and Fig. 4.8, the conventional DSRC IEEE 802.11p standard cannot guarantee the reliable BSM exchange within the message lifetime. Due to the fading channel, a certain number of packets will be lost without recovery hence the success probability defined in Section 4.2.3 drops significantly with the increasing number of vehicles. The repetitive transmission has a much better performance comparing with IEEE 802.11p because the RT pattern allows the vehicles to send multiple packets, increasing the reception possibility. On the other hand, we can see that the IEEE 802.11p is more sensitive to the packet loss probability and the repetitive transmission can enhance the success probability especially with a higher data rate.

We follow the simulation settings in Table 4.1 and conduct simulations to validate our proposed relaying schemes. As shown in Fig. 4.9, we compare two proposed relaying strategies, RT-NCI, RT-NCA with RT-I (relay at node I only) and RT-no relaying (no relay node is chosen). The proposed RT-NCA allows all nodes in the network to perform network coded relaying so whenever a node w receives a packet from any neighbor, the received packet is network coded and may contain some original packets that node w has not been received before. As long as node w has prior knowledge of other packets and can decode the received packet, node w can immediately benefit from the received packet, without waiting for a specific node (e.g., node I) to relay. One single coded packet could benefit multiple vehicles at the same time, and all nodes can relay network coded packets. This may lead to significant network coding gain. On the other hand, in RT-NCI,

Figure 4.6: Performance of success probability using the IEEE 802.11p standard and the controlled repetitive transmission mechanism, given data rate= 6 Mbps and $p'_e = 0.1$.

Figure 4.7: Performance of success probability using the IEEE 802.11p standard and the controlled repetitive transmission mechanism, given data rate= 6 Mbps and $p'_e = 0.2$.

Figure 4.8: Performance of success probability using the IEEE 802.11p standard and the controlled repetitive transmission mechanism, given data rate= 12 Mbps and $p'_e = 0.2$.

only the node I performs as the relay node, the coding gain from a single relay node will be smaller than that from RT-NCA. Therefore, the RT-NCA has the best performance among four schemes. However, if the number of vehicles that can actively participate in network coding is restricted by a certain regulation or the computational complexity becomes a major concern of the system when designing applications, RT-NCI is an alternative choice to enhance the system performance. These two network-coded relaying strategies, RT-NCA and RT-NCI can significantly improve the reliability for exchanging BSMs within the message lifetime. In contrast, when we use RT-I, even with a small number of vehicles inside the intersection region, the success probability is not high enough and declines quickly with the increase of vehicle numbers. Without using relaying, the RT-no relaying strategy is not able to ensure a reliable BSM dissemination due to the signal blockage at NLOS intersections. Such system unreliability has drastic impairment in providing vehicles around the traffic junction with accurate and timely intersection assistance.

Fig. 4.10 shows the simulation and analytical results in terms of the success

Figure 4.9: Impact of the number of nodes in the network on the performance of success probability using different relaying schemes.

probability of the completion of BSM exchanges. The proposed RT-NCA scheme is the most effective solution to reduce the failure probability, followed by RT-NCI. The simulation results of RT-NCI and RT-NCA follow tightly the theoretical plots, and prove their effectiveness of enhancing the system reliability. RT-NCA performs the best among the three schemes. Given a reasonable number of vehicles inside the intersection region, using RT-NCA, the probability that the BSMs can be successfully delivered within the message lifetime can be very high, indicating RT-NCA a promising strategy to guarantee reliable BSM dissemination as well as to enhance the scalability of the system in the NLOS environment.

In Fig. 4.11, we evaluate the success probability for different outside-range fractions f_w . This fraction determines the average number of nodes that are in the NLOS region with respect to an arbitrary node w . More communication links fail due to the NLOS with the increase of f_w . It is not surprising to see that the RT-NCA still outperforms the other relaying strategies.

Fig. 4.12 shows the average reception ratio of the three relaying strategies. The average reception ratio is the average fraction between the number of packets

Figure 4.10: Simulation and analytical results of success probability using different relaying schemes.

Figure 4.11: Impact of f_w on the performance of success probability using different relaying schemes, given $n = 35$.

Figure 4.12: Impact of the number of nodes in the network on the performance of average reception ratio using different relaying schemes.

received at each node and all $n - 1$ nodes. Both RT-NCI and RT-NCA have a very high reception ratio, which implies that by using network coding, most of packets generated by neighbors can be successfully received within the message lifetime. However, the performance metric evaluates the packet reception status from system level. A missing packet will cause the failure to the whole system. So it is not surprising to see that even with similar reception ratio, RT-NCI is not as reliable as RT-NCA.

4.5 Summary

In this chapter, we study the BSM dissemination at road intersections where the V2V communications between vehicles on perpendicular roads are blocked by roadside buildings. To assist the communication under such NLOS condition and meet the stringent delay requirement of BSM delivery, three relaying strategies are evaluated. Controlled repetitive transmission pattern (RT) is adopted and with optimized setting to increase the successful reception probability of the whole

system, providing enhancements to the existing DSRC standard to compensate the lost packets due to signal blockage and fading. By exploiting the benefit of network coding, two network coded relaying schemes RT-NCI and RT-NCA are proposed. RT-NCI applies the random linear network coding at a single relay node, whereas RT-NCA uses all nodes to perform network coded relaying. Compared with the relaying without network coding (RT-I), the proposed solutions can effectively enhance the BSM broadcast performance within the same message lifetime. RT-NCA is proven to have the most outstanding performance among the three schemes. It increases the probability of successful BSM exchanges within the message lifetime, providing a promising solution to improving the V2V system reliability and scalability.

Chapter 5

V2X Content Distribution Based on Batched Network Coding with Distributed Scheduling

5.1 Introduction

In this chapter, a V2X content distribution protocol based on the DSRC technology is studied. As an application in the ITS to assist vehicles in acquiring information such as digital maps, informative or entertainment materials, the content distribution is initiated from a single RSU to a group of vehicles. Considering the cost and location restriction of RSU deployment, in some situations, it is not always possible to have unbroken RSU coverage in certain regions. The connection time between the vehicles and the RSU could be limited because of the disconnected RSU cells. For some fast-moving vehicles, the connection time becomes much shorter. Moreover, the lossy channel causes packet drop. The insufficient connection time and the packet loss make it difficult for vehicles to receive the full content. Therefore, after the RSU broadcasting phase, the downloaded content needs to be further shared among vehicles. Many existing works applied the RLNC to enable this two-phase content distribution. However, the current

solutions introduce a large network overhead and their scheduling methods have limitations which prolong the transmission delay. To overcome the difficulties of the V2X content distribution and improve the latency performance of the existing protocols, we propose a joint I2V and V2V data dissemination protocol based on batched sparse (BATS) coding to minimize the traffic overhead and improve the transmission efficiency. In the I2V phase, the RSU encodes the original large-size file into a number of batches in a rateless manner and sequentially broadcasts them during the I2V connection period. In the V2V phase, vehicles perform the network coded cooperative sharing by re-encoding the received packets. The V2V cooperative transmissions are scheduled according to the proposed utility-based distributed algorithm for transmission-delay reduction. A closed-form expression for the expected rank distribution is formulated for designing the optimal BATS code. The proposed content distribution protocol is evaluated based on the realistic vehicular traffic settings and shown to outperform the existing protocols.

5.2 Problem Formulation

5.2.1 System Model

We consider a general system model of content distribution in the vehicular networks, where a RSU¹ is located at the place of interests, e.g., the campus entrance of a university. As illustrated in Fig. 5.1, the RSU by the side of the multi-lane road is actively pushing local informative contents such as high-resolution map and promotional video clip to the incoming vehicles. Assuming that only the vehicles that enter the campus are interested in the distributed file, we focus on the performance of content distribution in the uni-direction. Each vehicle carries a GPS device to calculate its geographical position, and each vehicle is equipped with two radios, which use control channel and service channel, respectively. The exchange of the control packets helps the vehicles obtain the speed and position

¹The proposed joint I2V and V2V content distribution scheme can be easily extended to multi-RSU case by considering prolonged connection time.

Figure 5.1: System model of the content distribution.

information of neighbors. So vehicles moving at relatively close speeds and within the same communication range can form a small cluster or a group. Vehicles with much higher or lower speeds will not be included in the same group². We assume a group has k vehicles denoted by $V_1, V_2, \dots, V_k$ from right to left. Their instantaneous moving speeds are v in kilometers per hour with at most $\pm 5\text{km/h}$ variations. The average distance between any two vehicles V_i and V_j can be derived from the control packet and represented by $\bar{S}_{i,j}$, where $i, j \in \{1, 2, \dots, k\}$. The communication range of the RSU is denoted by R . The reception probability beyond this range is assumed to be negligible. The length of the road that is within RSU's communication range is L .

As shown in Fig. 5.1, the content distribution consists of two phases. The first phase happens when the vehicles are passing through the coverage area of the RSU. The reception of received packets depends on both the distance between the RSU and the receiving vehicle as well as the instantaneous channel gain. Since the distance between two adjacent vehicles is of a much higher order than the wavelength, vehicles are assumed to have independent fading coefficients which follow the Nakagami-m distribution. Due to the short connection period with the RSU and the impact of the lossy channel, a single vehicle may not be able to receive enough packets for decoding the original file. Therefore, in addition to I2V communication, we introduce a broadcasting-based cooperative sharing method

²Such group assumption is valid in most of practical scenarios. Similar assumption and grouping technique have been applied in [116, 117].

Table 5.1: Related Notations in Chapter 5.

Notation	Definition
k	Vehicle group size
γ_{th}	Signal-to-noise ratio threshold
F	File size
ℓ	Packet length
N	Total number of packets sent by the RSU
J	Total number of batches sent by the RSU
M	Batch size
R_b	Data transmission rate
P_t/P'_t	Transmission power at the RSU / vehicle
P_N	Noise power
f	Carrier frequency
m_1/m_2	Fading shape factor for I2V / V2V channel
β	Path loss exponent

through V2V communication allowing vehicles to exchange the coded packets for further file recovery. These complementary transmissions in Phase 2 are initiated after the last vehicle leave the communication range of the RSU.

5.2.2 Encoding and Decoding of BATS Code

We assume the original file is divided into F packets. In the first phase, the RSU uses the outer code of BATS code to generate coded packets in batch. To form a typical batch with index j , $\mathbf{d}_j$ packets are uniformly and randomly chosen from F packets, and are linearly transformed into M coded packets. This random degree $\mathbf{d}_j$ follows the pre-determined degree distribution Ψ . Thanks to the rateless nature of BATS code, the RSU can continuously and sequentially generate and broadcast BATS coded batches. From the time the first vehicle V_1 enters the coverage area of the RSU until the last vehicle of the group leaves, the total number of packets sent by the RSU is denoted by N . As a batch consists of M packets, equivalently, $J = N/M$ batches can be delivered to the vehicle group. We label each packet by packet index n , where $n = 1, 2, \dots, N$, and the sequence number of the batches by batch index j , where $j = 1, 2, \dots, J$. So the j th batch contains the packets with

indices from $(j - 1)M + 1$ to jM . Denoted by ℓ the packet length in bits and $T_p \triangleq \ell/R_b$ the time for RSU sending one packet, where R_b is the RSU transmission rate.

For cooperative transmissions in Phase 2, vehicles apply the inner BATS code which is the random linear network code to further encode the received packets of the same batch and broadcast. With optimally designed BATS code, the original file can be decoded from any $F' = (1 + \epsilon)F$ innovative packets³, where $\epsilon \ll 1$ is the coding overhead.

5.3 Information Broadcast by RSU

Based on our system model, the number of BATS coded batches that can be broadcast by the RSU is limited by the connection time between the RSU and the vehicles. In this section, we analyze the theoretical number of innovative packets received by an individual vehicle and the whole group in Phase 1, respectively.

5.3.1 Reception Status of a Single Vehicle

We characterize the communication link between the RSU and the vehicle by a Nakagami-m fading channel. Since RSU is the only node that occupies the service channel for broadcasting data messages and all vehicles are in silent mode when receiving packets, there is no interfering signal posed by any vehicle. The signal outage probability of a vehicle is defined as the probability of its signal-to-noise ratio (SNR) dropping below the SNR threshold γ_{th} . When the RSU starts to distribute the n th packet, the distance between the RSU and the vehicle V_i is given by $d_{i,n}$. We assume that the transmission time of a packet is sufficiently small so the distance variation during a single packet's transmission is negligible. Given the RSU's transmission power P_t , noise power P_N and path loss exponent β , the SNR $\gamma_{i,n}$ of vehicle V_i when it starts receiving the packet n can be expressed

³A packet is innovative if it is independent of all other packets.

as

$$\gamma_{i,n} = \frac{P_t \cdot \alpha \cdot g \cdot (d_{i,n})^{-\beta}}{P_N} \quad (5.1)$$

where g is the channel gain and the constant α denotes the power gain at the distance $d = 1\text{m}$. The channel gain g of the Nakagami fading channel follows the gamma distribution with shape factor m_1 and average power $\Omega = \mathbb{E}[g]$, i.e.,

$$f_g(x) = \left(\frac{m_1}{\Omega}\right)^{m_1} \frac{x^{m_1-1}}{\Gamma(m_1)} \exp\left(-\frac{m_1}{\Omega}x\right). \quad (5.2)$$

We let $A(n, i) = \frac{\gamma_{th}}{\alpha} \frac{P_N}{P_t} (d_{i,n})^\beta$. The signal outage probability of V_i at the moment of starting receiving packet n is given by

$$\begin{aligned} P_{i,n} &= \mathbb{P}(\gamma_{i,n} < \gamma_{th}) \\ &= \mathbb{P}(g < A(n, i)) \\ &= \int_0^{A(n, i)} f_g(x) dx \\ &= 1 - \frac{1}{\Gamma(m_1)} \Gamma\left(m_1, \frac{m_1}{\Omega} A(n, i)\right) \end{aligned} \quad (5.3)$$

where $\Gamma(x)$ is the gamma function and $\Gamma(z, x)$ is the upper incomplete gamma function. Note that our study is not limited to the Nakagami-m fading channel. Any other channel model can be simply integrated into our proposed scheme by substituting the corresponding channel gain distribution g . Here we use the Nakagami fading channel since it has been widely applied in V2X research.

We use $P_i^{[j]}$ to represent the average signal outage probability of vehicle V_i , $i = 1, 2, \dots, k$ when receiving the packets of batch j . We have

$$P_i^{[j]} = \frac{1}{M} \sum_{n=(j-1)M+1}^{jM} P_{i,n} \quad (5.4)$$

where $P_{i,n}$ is the outage probability for V_i to start receiving packet n . The packets within each batch are sent consecutively by the RSU and hence the average SNR does not change much within the short transmission time of one batch. We

assume the channel-induced packet loss probability is equivalent to the average signal outage probability. Therefore, the number of received packets of batch j from the RSU can be approximated as a random variable following the Binomial distribution $\mathcal{B}(M, 1 - P_i^{[j]})$, with the average loss probability $P_i^{[j]}$. We denote the expectation value by $K_i^{[j]}$, then we have $K_i^{[j]} = M(1 - P_i^{[j]})$. Hence the expected total number of packets received by a typical vehicle V_i during the RSU broadcasting phase is given by $K_i = \sum_{j=1}^J K_i^{[j]}$.

5.3.2 Reception Status of the Whole Group

An innovative packet is received by the vehicle group when any one of the k vehicles successfully receives it in Phase 1. Denote the expected number of innovative packets received by the vehicle group from batch j by $K_g^{[j]}$. To find the expression for $K_g^{[j]}$, we first derive the packet loss probability for the vehicle group.

Consider a group of k vehicles passing through the coverage area of a RSU. A packet is totally lost if none of the vehicles within group has successfully received it, which occurs with probability $\prod_{i=1}^k P_{i,n}$. Therefore, the probability that a packet from batch j is not received by any vehicle is given by

$$P_g^{[j]} = \frac{1}{M} \sum_{n=(j-1)M+1}^{jM} \left(\prod_{i=1}^k P_{i,n} \right) \quad (5.5)$$

where $P_{i,n}$ is the probability that vehicle V_i fails to receive the n th packet. Accordingly, the expected number of innovative packets collected by the whole group from batch j is $K_g^{[j]} = M(1 - P_g^{[j]})$. The total number of innovative packets received by the vehicle group during the RSU broadcasting phase is then given by $K_g = \sum_{j=1}^J K_g^{[j]}$.

When a vehicle is travelling at a relatively high speed, it may not receive sufficient packets for decoding the file during the short connection period with the RSU. On the other hand, the vehicle group has a longer connection period and also benefits from spatial diversity. Therefore, we usually have $K_g \gg K_i, \forall i$. The

margin between K_g and K_i provides an individual vehicle with the opportunity to receive more packets for decoding via the cooperative V2V transmissions, which are elaborated in the next section.

5.4 Vehicle-to-Vehicle Cooperative Sharing

After the vehicles leave the communication range of the RSU, the cooperative sharing is initiated to compensate the inadequate number of packets received from the RSU. In this section, we propose a utility-based method to obtain the scheduling at each individual vehicle in a distributed manner, which maximizes the effectiveness of each transmission and hence minimizes the total transmission delay.

5.4.1 Distributed V2V Transmission

To fully utilize the spatial and temporal diversity, the BATS inner code is applied for V2V communications. Specifically, when a vehicle has the chance to transmit, it will generate and broadcast a coded packet from all the received packets of a batch. The main design problem is the scheduling at each vehicle, i.e., which batch should be selected at a given time instance. Generally, the proposed V2V-transmission algorithm consists of two steps: utility evaluation and distributed transmission scheduling. We elaborate on these two steps in the following sub-sections. In addition, the prior knowledge of each vehicle and the complete procedures of the proposed scheme are summarized in **Algorithm 2**.

Utility evaluation

When the last vehicle⁴ V_k leaves the communication range of the RSU, it signals other vehicles to initiate the packet-sharing mechanism. Different from the existing literature [50, 54], our distributed method does not require the exchange

⁴A vehicle may identify itself as the last vehicle in a group if there is no other vehicle from the same group behind it. It can be recognized from the distance between two vehicles, which can be derived from the periodic broadcast control packet from peers.

of reception status, so the extra communication overhead is reduced. Therefore, after detecting the initialization signal, each vehicle evaluates the utility that can be brought to peer vehicles.

We use $\mathcal{N}_i^{[j]}$ to represent the set of packets of batch j received by a typical vehicle V_i from the RSU. The number of elements in set $\mathcal{N}_i^{[j]}$ is denoted by $Y_{i,j}$, i.e., $Y_{i,j} = |\mathcal{N}_i^{[j]}|$. Let $y = |\mathcal{N}_i^{[j]} \setminus \mathcal{N}_q^{[j]}|$, where y indicates the number of packets that are received by V_i but not received by its neighboring vehicle V_q . Since each vehicle encodes all received packets of a batch and generates a certain number of coded packets in the V2V sharing phase, y also represents the number of innovative coded packets of batch j that V_i can send to V_q . Though the packet set $\mathcal{N}_q^{[j]}$ is unknown to vehicle V_i , we can see that when $\mathcal{N}_i^{[j]} \not\subseteq \mathcal{N}_q^{[j]}$, $y \in (0, M]$. Based on the knowledge of $Y_{i,j}$ and the range of y , V_i can estimate the amount of innovative information that is obtained by V_q through each transmission of V_i . Here, we use utility to describe such amount of innovative information. As mentioned before, vehicle's critical information including position and speed is periodically broadcast via the control channel. The average distance between any two vehicles can be obtained, from which we can derive the packet loss probabilities between each pair of vehicles. We assume that the V2V communication channel has the Nakagami fading with shape factor m_2 . The transmission power of any vehicle is P'_t . Let α denote the power gain at the reference distance $d = 1\text{m}$. The SNR at receiver V_q when V_i is transmitting is given by $\gamma_{i,q} = \frac{P'_t}{P_N} g \alpha (\bar{S}_{i,q})^{-\beta}$, where $\bar{S}_{i,q}$ is the average distance between two vehicles. Hence the packet loss probability from V_i to V_q is

$$\begin{aligned} \hat{P}_{i,q} &= \mathbb{P}(\gamma_{i,q} < \gamma_{th}) \\ &= 1 - \frac{1}{\Gamma(m_2)} \Gamma \left(m_2, \frac{m_2}{\Omega} \frac{\gamma_{th}}{\alpha} \frac{P_N}{P'_t} (\bar{S}_{i,q})^\beta \right). \end{aligned} \quad (5.6)$$

Meanwhile, in the process of receiving packets from the RSU in Phase 1, vehicle V_i may build up the database of the channel environment. We assume that each vehicle knows the packet loss probability from RSU to all its peers, $\{P_{i,n}, \forall i, n\}$,

as well as that for the V2V channels, $\{\hat{P}_{i,q}, i, q = 1, \dots, k\}$. If V_i has received $Y_{i,j}$ packets from the RSU, the probability that it can provide V_q with y innovative coded packets of batch j , which is also the probability that y of $Y_{i,j}$ packets of batch j were not successfully received by V_q from the RSU, is given below

$$\begin{aligned} & \Pr(y|Y_{i,j}) \\ &= \begin{cases} \binom{Y_{i,j}}{y} \left(P_q^{[j]}\right)^y \left(1 - P_q^{[j]}\right)^{Y_{i,j}-y}, & y \leq Y_{i,j} \\ 0, & Y_{i,j} < y \leq M. \end{cases} \end{aligned} \quad (5.7)$$

Since each batch contains at most M innovative packets, we assume that the number of coded packets generated from each batch is no greater than M . Every time, network coefficients are randomly chosen from a finite field. The probability that different coded packets with the same batch index have dependent coefficients is negligible when the field size is sufficiently large, e.g., $GF(2^8)$. Hence we ignore the impact of network coefficients on the unsuccessful decoding throughout this chapter.

Since V_i can provide V_q with only y innovative packets for batch j , we know that beyond y times of transmissions, the coded packet will no longer benefit V_q unless some of the previous transmissions failed due to the channel-induced packet loss. The more times of coded packets are broadcast, the less utility they can provide to the receiver. In order to gain the maximal utility through a small number of V2V transmissions, it is important to know the transmission priority of a coded batch as well as to determine the number of transmissions of that batch. That is achieved by comparing utilities among different batches and different times of transmissions.

Now we calculate the probability that for a batch j , when t V2V transmissions have been conducted, the next transmitted coded packet from V_i is still innovative to V_q , which is denoted by $\Pr(E_{i \rightarrow q}^{[j]}|t)$. When the number of transmissions from V_i to V_q has not reached the number of innovative packets that V_i possesses, i.e.,

$t < y$, the transmission will increase the total number of innovative packets at V_q if it is successfully received. Otherwise, when $t \geq y$, the additional transmission may be useful only if V_q has failed to receive all y innovative packets from previous t transmissions. Hence, we define two events:

$E_1 = \{\text{The } (t+1)\text{th transmission is useful when at most } y-1 \text{ coded packets were received in previous } t \text{ transmissions}\}.$

$E_2 = \{\text{The } (t+1)\text{th transmission is useful regardless of the reception status of previous } t \text{ transmissions}\}.$

The probabilities of these two events are given below

$$\begin{aligned} \Pr(E_1) &= \sum_{y=1}^t \Pr(y|Y_{i,j}) \sum_{l=0}^{y-1} \binom{t}{l} (1 - \hat{P}_{i,q})^l \\ &\quad \times (\hat{P}_{i,q})^{t-l} \\ \Pr(E_2) &= \sum_{y=t+1}^M \Pr(y|Y_{i,j}). \end{aligned} \tag{5.8}$$

The number of previous transmissions t can be any value from $\{0, 1, \dots, M-1\}$. Thus, on condition that V_i has transmitted t times, the probability that the $(t+1)$ th transmission of the coded packet of batch j , is still innovative to V_q is expressed as

$$\Pr(E_{i \rightarrow q}^{[j]}|t) = \Pr(E_1) + \Pr(E_2). \tag{5.9}$$

This probability $\Pr(E_{i \rightarrow q}^{[j]}|t)$ measures the amount of innovative information that V_q will gain from the $(t+1)$ th transmission of V_i , which is called utility in this chapter. Hence, the total utility that all $k-1$ peers can obtain from this transmission is denoted by $\bar{U}(i, [j], t+1)$ and calculated by

$$\bar{U}(i, [j], t+1) = \sum_{q \neq i} \Pr(E_{i \rightarrow q}^{[j]}|t). \tag{5.10}$$

The total utility $\bar{U}(i, [j], t+1)$ reflects the transmission priority of batch j . However, some coded packets with different batch indices may have the same total

utility if the above formula is in use. In order to differentiate the transmission sequence for those packets, we introduce some randomness by adding a random jitter ε . For not mixing up the random jitter with the utility differences, we amplify $\bar{U}(i, [j], t + 1)$ by a value κ . So we derive the final expression of the total utility

$$U(i, [j], t + 1) = \kappa \bar{U}(i, [j], t + 1) + \varepsilon. \quad (5.11)$$

In practice, we choose 10^6 for κ and ε is a uniformly distributed real number in the interval $(0, 10)$, i.e., $\varepsilon = rand(0, 10)$.

Distributed transmission scheduling

Vehicle V_i locally calculates $U(i, [j], t + 1)$ for different batches $j = 1, 2, \dots, J$, and different times of transmissions $t + 1 = 1, 2, \dots, M$. The coded packet of the batch that has larger utility should be given higher priority for transmission. Therefore, V_i sorts these utilities in descending order. The corresponding sorted batch indices recorded in a row vector $\mathbf{R}_i$ indicate the scheduled transmission sequence of the coded packets. All k vehicles follow the same rule to decide their transmission sequences of coded batches in a distributed manner.

To reduce the latency for transmitter selection, we adopt a random channel access protocol. This proposed protocol is also applicable for other channel access technology, such as the C-V2X communication Mode 4. At the beginning of each slot, to avoid packet collisions, k vehicles contend the channel with a random backoff delay which is randomly chosen from $[0, \Delta t_{max}]$, where Δt_{max} is the maximum backoff delay. In order to accommodate more vehicles and ensure that the backoff difference can be recognized with the presence of signal propagation delay, we choose $\Delta t_{max} = 50\mu s$.

When vehicle V_i seizes the channel for broadcasting, it sequentially broadcasts one coded packet with the batch index as indicated in $\mathbf{R}_i$. Whenever a coded packet is received, the vehicle will check whether it is independent of the previously received packets. If the coded packet cannot increase the rank of the decoding

matrix of the corresponding batch, it will be dropped. A number of rounds of V2V transmissions are needed for all vehicles in the group to obtain F innovative packets or achieve a total rank of F . When a vehicle is able to decode the file, it piggybacks a stopping bit in its control packet to inform the peers. Once all vehicles have enough packets for decoding, the cooperative sharing stops.

5.4.2 Lower Bound of the Total Number of Transmissions

The lower bound of the total number of V2V cooperative transmissions is obtained when there is an ideal packet reception condition in Phase 1 such that every packet received by a vehicle from the RSU can contribute to all other neighboring vehicles for the file decoding. So in the V2V cooperative sharing phase, assuming a vehicle V_q will broadcast X_q coded packets, then each coded packet is innovative to all previously received packets by any other vehicle $V_i, i \neq q$. That means $\bar{U}(q, [j], t + 1)$ in (5.10) is equal to $k - 1$ for all possible t values. From a receiver V_i 's perspective, based on the number of packets collected from the RSU in Phase 1, we know that at least $F - \sum_{j=1}^J Y_{i,j}$ innovative packets should be received from the rest vehicles. Given the average packet loss probability calculated by (5.6), we can form an inequality relationship between X_q and $F - \sum_{j=1}^J Y_{i,j}$. To obtain the lowest number of V2V transmissions, we need to find the minimum value of the summation of transmissions at each vehicle, $X_i, i = 1, 2, \dots, k$. It is equivalent to solving the following linear optimization problem.

$$\begin{aligned}
 & \text{minimize} && \sum_{i=1}^k X_i \\
 & \text{s.t.} && \sum_{q \neq i} \left(1 - \hat{P}_{q,i}\right) X_q \geq F - \sum_{j=1}^J Y_{i,j}, \\
 & && 0 \leq X_i \leq \sum_{j=1}^J Y_{i,j}, \quad i = 1, 2, \dots, k.
 \end{aligned} \tag{5.12}$$

The solution of above problem defines the lower bound of the total number of V2V cooperative transmissions. Given packet length ℓ and maximum backoff delay

Algorithm 2 Part 1

```

1: Inputs:

2:  $J$ : number of batches;

3:  $M$ : batch size;

4:  $k$ : number of vehicles;

5:  $P_i^{[j]}, \hat{P}_{i,q}, \forall i, q \neq i$ : packet loss probability;

6:  $\mathcal{N}_i^{[j]}$ : set of received packets of batch  $j$  in the I2V phase, only known by the
   corresponding vehicle.

7: Outputs: Batch transmission sequence  $\mathbf{R}_i$  for  $V_i, \forall i$ .

8: Step 1 utility evaluation

9: for  $i = 1 : k$  do

10:    $Y_{i,j} \leftarrow |\mathcal{N}_i^{[j]}|$ 

11:   for times of transmissions  $t = 0 : M - 1$  do

12:     for  $q = 1 : k, q \neq i$  do

13:        $y$  denotes the number of innovative packets sent by  $V_i$  to  $V_q$ ;

14:       for  $y = 1 : t$  do

15:          $\Pr(y|Y_{i,j})$  is calculated according to (5.7);

16:          $\Pr(E_1)$  is calculated according to (5.8);

17:       end for

18:       for  $y = t + 1 : M$  do

19:          $\Pr(y|Y_{i,j})$  is calculated according to (5.7);

20:          $\Pr(E_2)$  is calculated according to (5.8);

21:       end for

22:        $\Pr(E_{i \rightarrow q}^{[j]}|t) \leftarrow \Pr(E_1) + \Pr(E_2)$ 

23:     end for

24:     The total utility of  $V_i$  when transmitting the coded packet of batch  $j$  for
       the  $(t + 1)$ th transmission is:

25:    $U(i, [j], t + 1) \leftarrow \kappa \sum_{q \neq i} \Pr(E_{i \rightarrow q}^{[j]}|t) + \varepsilon$ 

26:   end for

27: end for

```

Algorithm 2 Part 2

28: **Step 2 distributed transmission scheduling**

29: **for** $i=1:k$ **do**

30: V_i sorts $U(i, [j], t+1)$ for $j = 1, 2, \dots, M$ and $t+1 = 1, 2, \dots, M$ in descending order;

31: V_i creates a row vector $\mathbf{R}_i$ containing the corresponding sorted batch indices.

32: **end for**

Δt_{max} , the lower bound of the V2V cooperative sharing delay can be obtained.

However, the lower bound can hardly be achieved in reality because packets received during the RSU broadcasting phase are totally random and can be highly correlated as a result of short inter-vehicle distance. So the transmitted coded packets cannot always be innovative. Extra cooperative transmissions are required to ensure every vehicle successfully decodes the file. Nevertheless, this lower bound will provide a good reference for us to evaluate the effectiveness of the proposed scheduling method.

5.5 Determination of the Rank Distribution for BATS Design

The design of degree distribution Ψ of BATS code at the source node is critical to achieving high coding efficiency at the end of content distribution [118]. The optimal degree distribution can be obtained through a linear optimization problem defined in [55, 56], given the channel rank distribution, which is defined as the probability of the rank for each batch. Since our network involves cyclic topology, and the transmission priority is assigned according to the utility, resulting in a complicated analysis of the rank distribution. In this section, some approximations are adopted to obtain an accurate estimation of the channel rank distribution in a simplified way.

The last vehicle to successfully decode the file is referred to as the bottleneck

vehicle. Since other vehicles are guaranteed to decode the file if the bottleneck vehicles can decode, we optimize the BATS code to ensure the bottleneck user can decode the file with the minimum number of V2V transmission. So in this section, we focus on the rank evaluation of the bottleneck vehicle at the moment of successfully decoding the original file.

In the broadcasting phase, all the vehicles have roughly the same connection time with the RSU and hence they will receive the similar number of packets from the RSU. In the cooperative sharing phase, based on the random channel access protocol, each vehicle has an approximately equal transmission opportunity. However, due to the poorer channel connection with peers caused by longer average transmission distance, the front and back vehicles in the group experience larger packet loss probability when receiving coded packets from peers. Therefore, any of them is more likely to be the bottleneck user of the network, as shown in Fig. 5.1. Nevertheless, without loss of generality, we consider the bottleneck vehicle could be any one of k vehicles and denote this bottleneck vehicle by V_b . Based on the expected number of received packets from the RSU, we know that the bottleneck vehicle requires $\Delta = F - K_b$ innovative packets to be contributed by the rest of $k - 1$ vehicles. To estimate the rank distribution, we need to know how these Δ packets are distributed over batches and $(k - 1)$ vehicles according to the proposed utility-based transmission method. So our analysis comprises two parts: the probability of sending a particular batch which is determined by the utility, and the amount of innovative content of each batch generated by a vehicle.

Batch selection probability

For a typical vehicle, a batch with larger total utility for a single transmission is assigned with higher broadcasting priority. It indicates that the probability of sending a certain batch is proportional to the total number of innovative coded packets provided by that batch to peers. Coded packets generated by a non-bottleneck vehicle V_i ($i \neq b$) with batch index j are innovative to a peer vehicle V_q

if they are formed by the packets that are only received by V_i from the RSU. We use set $\mathcal{I}_{i,j}(q)$ to record these innovative packets. Hence based on the understanding of (5.4) and (5.5), the expected number of elements in set $\mathcal{I}_{i,j}(q)$ can be derived as below

$$|\mathcal{I}_{i,j}(q)| = \sum_{n=(j-1)M+1}^{jM} (1 - P_{i,n}) P_{q,n}. \quad (5.13)$$

Denote by $\rho(i, j)$ the probability that for a single transmission, V_i selects the coded packet with batch index j for V2V transmission. Hence $\rho(i, j)$ is defined by the ratio between the total utility of that particular batch and all batches, i.e.,

$$\rho(i, j) = \frac{\sum_{q \neq i} |\mathcal{I}_{i,j}(q)|}{\sum_{j=1}^J \sum_{q \neq i} |\mathcal{I}_{i,j}(q)|}. \quad (5.14)$$

Amount of innovative content

In this part, we are going to analyze the total amount of innovative content that the peer vehicles can offer the bottleneck vehicle. In general, V_b can be any vehicle from V_1 to V_k . For convenience of presentation, we use a simple mapping to represent the identifiers of the vehicles excluding the bottleneck vehicle by adopting the function $w(s)$, $s = 1, 2, \dots, k-1$. The mapping rule is as follows:

$$w(s) = \begin{cases} s, & s < b \\ s + 1, & s \geq b. \end{cases} \quad (5.15)$$

For instance, if $b = 2$, the vehicles except the bottleneck vehicle V_b are $V_1, V_3, \dots, V_k$. They can be represented by $V_{w(1)}, V_{w(2)}, \dots, V_{w(k-1)}$ correspondingly.

From the previous part, we know that a non-bottleneck vehicle $V_{w(s)}$ can provide V_b with $|\mathcal{I}_{w(s),j}(b)|$ innovative packets for batch j . In order to find the total number of innovative packets that can be provided from $k-1$ peer vehicles to V_b for a typical batch j , we need to find the number of elements in the union of $k-1$ sets, i.e., $|\bigcup_{s=1}^{k-1} \mathcal{I}_{w(s),j}(b)|$. This requires the elimination of the duplicate elements which appear in more than one set. Since the common elements that can appear

$$\begin{aligned}
 I(j) = & \sum_{s=1}^{k-1} \rho(w(s), j) \cdot |\mathcal{I}_{w(s),j}(b)| + \sum_{m=2}^{k-1} (-1)^{m+1} \\
 & \times \left\{ \sum_{1 \leq u_1 < \dots < u_m \leq k-1} \min[\rho(w(u_1), j), \dots, \rho(w(u_m), j)] \cdot |\mathcal{I}_{w(u_1),j}(b) \cap \dots \cap \mathcal{I}_{w(u_m),j}(b)| \right\}.
 \end{aligned} \tag{5.17}$$

in two sets, three sets, $\dots$, and at most $k - 1$ sets, we introduce a general formula to calculate the number of common elements in m sets. Given that $2 \leq m \leq k - 1$ and $1 \leq u_1 < u_2 < \dots < u_m \leq k - 1$, we have

$$\begin{aligned}
 & |\mathcal{I}_{w(u_1),j}(b) \cap \dots \cap \mathcal{I}_{w(u_m),j}(b)| \\
 & = \sum_{n=(j-1)M+1}^{jM} \left[\prod_{l=u_1}^{u_m} (1 - P_{w(l),n}) P_{b,n} \right].
 \end{aligned} \tag{5.16}$$

In each time slot of V2V transmissions, all k vehicles contend the channel with randomly selected backoff times. Therefore, every vehicle has an approximately equal opportunity to access the channel. For each transmission opportunity, the batch selection probability has been given in (5.14). Thus, we can calculate the amount of innovative content for a typical batch j that is delivered to the bottleneck vehicle when the V2V transmission is conducted once, denoted by $I(j)$. According to the Inclusion-Exclusion Principle as well as above analyses, the expression of $I(j)$ is shown in (5.17). Hence we determine a cutoff integer c to have

$$\Delta \approx c \cdot \sum_{j=1}^J I(j). \tag{5.18}$$

Therefore, the number of innovative packets of each batch that are contributed by $k - 1$ peers to the bottleneck vehicle is $cI(j), \forall j$. Since V_b in theory receives $K_b^{[j]}$ packets from the RSU, the expected number of innovative packets or the rank of batch j is given by $K_b^{[j]} + cI(j)$. Let r be the average rank of a batch, where $r = 0, 1, \dots, M$. Knowing the expected rank value of each batch, the equivalent probability that the batch j has an innovative packet to increment its rank by

the end of the content distribution is $p_e^{[j]} = \left[K_b^{[j]} + cI(j) \right] / M$. As a result, the estimated cumulative distribution function (CDF) of rank $r, r \in \{0, 1, \dots, M\}$, is calculated by

$$F_e(r) = \frac{1}{J} \sum_{v=0}^r \sum_{j=1}^J \binom{M}{v} (p_e^{[j]})^v (1 - p_e^{[j]})^{M-v}. \quad (5.19)$$

By converting $F_e(r)$ into the probability density function, we can obtain the estimated rank distribution $f_e(r)$ to ensure the successful decoding at the bottleneck vehicle. Note that with the same degree distribution, other vehicles are guaranteed to decode the file successfully since they receive more innovative packets.

5.6 Numerical Simulations and Discussions

In this section, numerical results are given to validate the analytical results and evaluate the performance of the proposed V2X content distribution scheme.

5.6.1 Simulation Settings

Our simulation environment is set up according to the content distribution system model described in Section 5.2 where a RSU is located at the entrance of campus, distributing digital maps to incoming vehicles. For simplicity, we consider a straight road consisting of two lanes with lane width of 3m. The RSU is 50m away from the centre of the nearest lane. The heights of the RSU and each vehicle are 8m and 1m. The communication range of the RSU as well as the vehicle is 200m. The large-scale path loss is characterized by the dual-slop model [87]:

$$PL = \begin{cases} PL_0 + 10\beta_1 \log_{10} \frac{d}{d_0}, & d_0 < d \leq d_c \\ PL_0 + 10\beta_1 \log_{10} \frac{d_c}{d_0} + 10\beta_2 \log_{10} \frac{d}{d_c}, & d > d_c \end{cases} \quad (5.20)$$

where PL_0 is the free space path loss at the reference distance $d_0 = 10\text{m}$, and the critical distance $d_c = 80\text{m}$. We assume the line-of-sight (LOS) is the dominant component in Phase 1. So we choose Nakagami fading factor $m_1 = 1.2$ for char-

Table 5.2: Parameter Settings in Simulations.

File size F	12000 packets
Packet length ℓ	1500 Bytes
Data transmission rate R_b	6 Mbps
Batch size M	16
Maximum random backoff delay	$50\mu s$
Transmission power P_t, P'_t	20 dBm, 20 dBm
Noise power P_N	-89 dBm
SNR threshold γ_{th}	10 dB
Carrier frequency f	5.9 GHz
Path loss model	Dual-slop model [87]: $\beta_1 = 2.3; \beta_2 = 2.7$
Fading model	Nakagami fading: $m_1 = 1.2; m_2 = 1.2, 0.75$
Height of RSU, vehicle	8m, 1m
Lane width	3m

acterizing the I2V channel. On the other hand, in V2V communication, vehicles encounter more signal reflections for the vehicles separated by longer distance. We choose m_2 to be 1.2 when the distance between any two vehicles is less than 90m whereas 0.75 for the distance beyond 90m. Other parameter values are shown in Table 5.2. Here, we directly use MATLAB tool to generate the network model and the traffic model because we mainly focus on the content downloading and sharing among a group of vehicles. Our proposed scheme has considered the variations of the inter-vehicle distances and speeds.

5.6.2 Simulation Results and Discussions

Phase 1 packet reception status and packet gain

We assume that the vehicles with relatively close moving speeds and within the same communication range form a group. Similar to [119], at any time instance, a typical vehicle V_i moves at v in kilometers per hour, with at most $\pm 5\text{km/h}$ variation. The horizontal separation between any two adjacent vehicles is randomly distributed. Fig. 5.2 and Fig. 5.3 verify the theoretical analysis of the packet

Figure 5.2: Impact of the average speed v on Phase 1 packet reception status.

reception status of Phase 1. In Fig. 5.2, eight vehicles form a group moving at different average speeds v and a variation up to $\pm 5\text{km/h}$. Based on the current simulation settings, when $v \leq 48 \text{ km/h}$, the cooperative sharing is not needed since each vehicle can receive a sufficient number of packets in phase 1. Fig. 5.3 is obtained when the vehicles move at $55\text{km/h} \pm 5\text{km/h}$. With more number of vehicles in the group, an individual vehicle can achieve a higher packet gain from the group.

Accuracy of the estimated rank distribution

The effectiveness of the estimated rank distributions which are derived in Section 5.5 is proved in Fig. 5.4 and Fig. 5.5 given two different average vehicle speeds. From the numerical results, vehicle V_1 is the bottleneck vehicle, hence the performance of V_1 is observed. The analytical rank CDF plotted in blue match the simulation results closely. Intuitively, we can learn that by adopting BATS code, it is not necessary for the vehicle to achieve the full rank of each batch so that the original file can be decoded. The slope of the curve in Fig. 5.5 is deeper than that in Fig. 5.4 because the packet gain from the group is less so more batches have to

Figure 5.3: Impact of the vehicle group size on Phase 1 packet reception status.

reach full rank for successful decoding. By converting the analytical CDF to the rank distribution, it is observed that the analytical distributions introduce only 5.3% and 5.4% coding overhead for the degree distribution optimization, which confirms the effectiveness of code design based on the analytical rank distribution.

Throughput of the proposed scheme

We consider a group of eight vehicles, namely V_1 to V_8 , according to the sequence of passing through the communication range of the RSU. Based on the numerical results, we find that vehicle V_1 is the bottleneck vehicle while vehicle V_5 is the first one to start decoding. The throughput performances of these two vehicles are shown in Fig. 5.6. Regarding the point that V_1 just enters the communication range of the RSU as the origin, the horizontal distances between V_1 and the origin are represented by the X-axis values. When the vehicle moves closer to the RSU, the throughput increases due to the shorter communication distance but decreases after passing by the RSU due to the larger communication distance. V_1 and V_5 are separated by a certain distance so an obvious throughput shift is observed in the

Figure 5.4: Rank CDF. Vehicle group size: 4. Speed: 55km/h $\pm$ 5km/h.

Figure 5.5: Rank CDF. Vehicle group size: 4. Speed: 60km/h $\pm$ 5km/h.

Figure 5.6: Throughput of vehicles V_1 and V_5 versus V_1 's moving distances. Vehicle group size: 8. Speed: $55\text{km/h} \pm 5\text{km/h}$.

figure. Note that when vehicles are conducting the second-phase communication by following the proposed V2V sharing scheme, the throughput will drastically increase, which validates the effectiveness of our proposed scheme.

Performance benchmarking

We compare our content distribution scheme with three data dissemination frameworks in the V2X communication. The first one is CodeTorrent [51], the pioneer work that combines file swarming with network coding. The second one is a popular scheme called CodeOnBasic [50] which is the packet-level version of CodeOn, and the other one is a network coded version of RLS-SNR [105] which is a centralized scheme that uses RLS for channel prediction and SNR-based utility for V2V scheduling. Generally, our scheme outperforms three benchmark schemes in three major aspects:

- Our proposed scheme exploits the rateless property of BATS code so the vehicle group is not required to collect all packets of each batch from the RSU. In contrast, the RSU in CodeTorrent, CodeOnBasic as well as NC-

based RLS-SNR divides the file into F/M blocks and performs RLNC within each block of M packets. The vehicle group is required to collect all the coded packets of each block for the next-phase V2V sharing.

- When vehicles work cooperatively to share the received content, without exchanging the reception status, the proposed scheme has a good total utility evaluation method that can be conducted distributedly at each vehicle. CodeTorrent is a pull-based scheme such that a vehicle requests peers to send the rarest block (containing the least number of received coded packets) first. CodeOnBasic relies on the frequent update of the rank of each block and selects a new transmitter based on the backoff delay up to $2ms$. NC-based RLS-SNR requires the update of decoding status of each vehicle to the central control after a round of transmissions and the scheduling decision is sent back from the control to vehicles. Both schemes introduce extra network overhead.
- To determine the transmission sequence, CodeOnBasic uses the rank difference between two vehicles as amount of innovative information. It may easily cause the wrong termination of the sharing phase when the number of coded packets of any block for two vehicles is the same but smaller than the block size. NC-based RLS-SNR ignores the impact of the fading channel on the packet reception at each vehicle thus the computation of the packet utility may not accurately reflect the decoding status. Therefore, these two schemes for transmission scheduling may end up with sub-optimal solutions. Our proposed scheme perfectly avoids above problems by using BATS code and taking both packet loss probability and utility of the coded packets into account.

We evaluate the delay performance of the content distribution using our proposed scheme and compare it with other benchmark schemes. The simulations are based on the following settings: the vehicle speed is $55km/h \pm 5km/h$ and the vehicle

Figure 5.7: Phase 2 delay for the proposed scheme, CodeOnBasic and CodeTorrent.

Figure 5.8: Phase 2 delay for the proposed scheme, NC-based RLS-SNR and CodeOnBasic.

Figure 5.9: Number of V2V transmissions for the proposed scheme, CodeOnBasic and CodeTorrent.

group size can vary from 4 to 24. To clearly show the difference between our proposed schemes and those benchmark schemes, we separately plot the results of CodeTorrent and NC-based RLS-SNR. First, the performance of the V2V sharing (cooperative sharing) delay using our proposed distribution scheme, CodeTorrent, CodeOnBasic and NC-based RLS-SNR have been shown in Fig. 5.7 and Fig. 5.8. When the group size expands from 4 to 24, the V2V transmission delay of the proposed scheme is observed to decline and get closer to the lower bound because more innovative packets that the vehicle group can obtain from the RSU. On the other hand, the benchmark schemes have an obvious delay increase because they are constrained by the requirement of receiving M coded packets per block for file decoding. The numbers of packet transmissions via the V2V communication that lead to the above delay results are given in Fig. 5.9 and Fig. 5.10, respectively.

Moreover, we depict the overall distribution delay for the four different schemes and the theoretical lower bound of the total delay in Fig. 5.11.

Fig. 5.12 shows the comparison between the proposed scheme and two benchmark schemes regarding the average downloading delay of a single vehicle, given

Figure 5.10: Number of V2V transmissions for the proposed scheme, NC-based RLS-SNR and CodeOnBasic.

Figure 5.11: Total delay for the content distribution with different schemes.

vehicle group size of 8 and speed at $55\text{km/h} \pm 5\text{km/h}$. Note that under the same simulation setting, CodeOnBasic and NC-based RLS-SNR cannot guarantee that the vehicle group can receive M coded packets for each block from the RSU due to the fading channel. So the RSU is adjusted to send one redundant coded packet per block in the favor of those benchmark schemes for comparison purpose. In contrast, our proposed scheme does not require the successful reception of M coded packets per batch. Therefore, the downloading rates of two benchmark schemes at the start of Phase 2 are lower than the proposed scheme. Moreover, the proposed scheme has a significant improvement in the delay in Phase 2. After disconnecting with the RSU for a certain period of time, some vehicles may leave the formed group to head for other directions. So the shorter the downloading delay is, the more reliable the V2V communication will be. Our proposed scheme performs well in enhancing the system reliability.

Note that with the moving speed at $55\text{km/h} \pm 5\text{km/h}$, we can see that in Phase 1, to achieve the same downloading percentage, the proposed scheme requires shorter time than the benchmark schemes. In Fig. 5.2, we know that when $v \leq 48 \text{ km/h}$, only the RSU broadcasting phase is needed. Therefore, it can be expected that even for a relatively lower moving speed such that the cooperative sharing is not necessary, the proposed scheme can also effectively help the vehicles reduce the total transmission delay.

Impact of network dynamics

In Fig. 5.13, we assume that after passing through the communication range of the RSU, 25% arbitrary vehicles will leave the vehicle group. Based on the simulation result shown in the figure, we can see that our proposed scheme is able to work effectively under this scenario, which needs on average 4% increase of the number of V2V transmissions for compensation.

Figure 5.12: Average downloading rate.

Figure 5.13: Impact of network dynamics on the number of P2P transmissions. Speed: 55km/h $\pm$ 5km/h.

5.7 Summary

In this chapter, we study a V2X content distribution scenario based on the DSRC technology, where a RSU actively distributes a large-size file to a group of vehicles that pass by in finite time. We propose an efficient and reliable V2X communication scheme that involves a joint I2V and V2V transmission phases, incorporating rateless-coded broadcast, network coded transmission and distributed transmission scheduling, to allow vehicles to successfully decode the file in shortest time, with least transmission overhead. Without requiring the exchange of reception status of the packets received in the first I2V broadcast phase, every vehicle distributedly computes the utility of its coded packets to prioritize the sequence of the second V2V transmission phase. The performance of the proposed scheme has been evaluated and validated by simulations. In comparison with the existing protocols such as NC-based RLS-SNR, CodeOnBasic and CodeTorrent, our proposed protocol significantly shortens the downloading delay at each vehicle. When the vehicle group size increases, by using our proposed protocol, the delay time can be reduced, while the existing protocols tend to suffer the opposite effect.

Chapter 6

V2X Multi-Hop Video Streaming Based on Network Coding with Optimal Scheduling

6.1 Introduction

In this chapter, the optimal scheduling scheme for multi-hop video streaming with generation-based random linear network coding in the C-V2X network is investigated. We enable the RF overhearing to allow every vehicle to receive the network coded packets from all its upstream vehicles. Then, we derive the explicit expression for the number of network coded packets that need to be generated at each vehicle to ensure successful decoding at its downstream vehicles. Moreover, to further enhance the network performance, we exploit the benefit of channel reuse to allow multiple vehicles to transmit simultaneously. Taking the co-channel interference into account, we derive the optimal channel reuse distance to maximize the normalized video generation rate by solving a convex optimization problem. Validated by the computer simulations, our proposed coding and scheduling scheme can gain higher end-to-end throughput and achieve the optimal normalized video generation rate compared with the conventional packet erasure correction coding

Figure 6.1: Multi-hop video streaming to vehicles in a platoon.

scheme that is only optimized for the one-hop communication.

6.2 Problem Formulation

6.2.1 System Model

As shown in Fig. 6.1, we consider a C-V2X network where a live video needs to be streamed from the front moving vehicle V_1 to all others in a platoon of n vehicles. We assume that the distance between adjacent vehicles V_i and V_{i+1} is constant and denoted by d_i . This is a reasonable approximation in practical scenarios when the vehicles are traveling with similar velocity. The live video is generated by the leading vehicle V_1 at a rate of R_s bits/second, and then partitioned into packets each of L bits. Thus, the packet generation rate is R_s/L in packets/second. The video streaming is supported by the C-V2X under the communication Mode 3 where the BS (eNodeB) as the central coordinator assigns the channel resource and gives the scheduling information to each vehicle. The C-V2X adopts the SC-FDMA with a resource pool for subchannel and subframe selection. We assume that with the channel transmission rate R_b bits/second, each packet transmission consumes exactly one time slot, the duration of which

Table 6.1: Related Notations in Chapter 6.

Notations	Definition
V_i	The i th vehicle in the platoon
n	Number of vehicles in a platoon
L	Packet length
R_s	Packet generation rate
T_s	One time slot duration
R_b	Transmission rate
$\bar{R}$	Normalized video generation rate
K	Number of original packets in a block (coding block size)
ϵ	The probability that a coding block failed to be decoded
s	Channel reuse distance
I_I	Indices of vehicles that transmit simultaneously when V_i transmits

is specified as $T_s = L/R_b$ second(s), equivalent to $1000 \cdot T_s$ adjacent subframes (one subframe is 1 ms). To avoid transmission collision, vehicles get access to the channel based on time-division method¹. The transmission sequence and duration (in time slots) are scheduled by the eNodeB according to the expected number of data packets generated by each vehicle. There is no feedback for the transmission in the network. In order to avoid buffer overflow and unbounded delay, the video should be properly compressed at V_1 so that all the packets can be delivered to the subsequent vehicles in time. We denote by $\bar{R} = R_s/R_b$ the maximum normalized video generation rate that can be supported by the network. Note that $\bar{R}$ depends on the channel statistics, the coding scheme, as well as the scheduling algorithm for all vehicles. Notations of the key parameters are summarized in Table 6.1.

6.2.2 Benchmark Coding Scheme

To combat against packet erasure introduced by the wireless channels, packet erasure correction code, e.g., Reed-Solomon (RS) code [120], can be applied for each

¹The scheduling scheme proposed in this chapter can also be applied in the V2X communication supported by the DSRC technology. The transmission coordination should be done by a coordinator in the platoon like the leading vehicle V_1 . To access the channel without inducing interfering signals, each vehicle can be assigned with a specific backoff time based on the scheduled transmission sequence.

block of K consecutive packets. With (N, K) RS code, K original packets can be recovered from any K out of N coded packets. Consider a channel where the packets are erased independently with probability p . The number of received packets out of N coded packets that have been sent out is a random variable distributed according to Binomial distribution $\mathcal{B}(N, 1-p)$, which can be approximated by the Gaussian distribution² $\mathcal{N}(\mu, \sigma^2)$, where $\mu = N(1-p)$ and $\sigma^2 = Np(1-p)$. To ensure that the coding block is decoded with probability $1 - \epsilon$, where ϵ is a small number, we should have

$$Q\left(\frac{K - \mu}{\sigma}\right) \geq 1 - \epsilon, \quad (6.1)$$

where $Q(x) \triangleq \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-u^2/2} du$ denotes the Gaussian Q function. By substituting μ and σ into (6.1), we have

$$N \geq \frac{2K + \alpha^2 p + \alpha \sqrt{4Kp + \alpha^2 p^2}}{2(1-p)}, \quad (6.2)$$

where $\alpha \triangleq |Q^{-1}(1 - \epsilon)|$, with $Q^{-1}(\cdot)$ denoting the inverse Q function.

To deliver a block of K packets from V_i to V_{i+1} with decoding probability no less than $(1 - \epsilon)$, the number of RS coded packets N_i to be sent by V_i should be no less than

$$N_i = \frac{2K + \alpha^2 p_{i(i+1)} + \alpha \sqrt{4Kp_{i(i+1)} + \alpha^2 p_{i(i+1)}^2}}{2(1 - p_{i(i+1)})}, \quad (6.3)$$

where $p_{i(i+1)}$ is the packet erasure probability for the wireless channel from V_i to V_{i+1} . Therefore, with the benchmark one-hop coding scheme, the achievable normalized video generation rate is given by

$$\bar{R}_{bm} = \frac{K}{\sum_{i=1}^{n-1} N_i}. \quad (6.4)$$

²The approximation error is negligible when $N(1-p) \geq 5$.

6.2.3 Proposed Coding and Scheduling

Besides the dedicated link for communication between two adjacent vehicles, the RF overhearing is enabled so that the vehicles several hops away can store the received packets for future decoding. For instance, in Fig. 6.1, V_3 overhears and stores the packets sent to V_2 by V_1 . To achieve this purpose, we propose to apply RLNC, instead of any deterministic coding scheme, over K consecutive packets to generate $Y > K$ coded packets. If the network coding coefficients are generated from a sufficiently large field, the original block can be decoded from any K network coded packets, regardless whether the packets are received by overhearing or dedicated transmissions. We assume that when a block of K packets are generated, as illustrated in Fig. 6.1, the front vehicle V_1 sends out Y_1 network coded packets, where Y_1 is optimized to ensure that the nearest vehicle V_2 can decode the block with high probability $1 - \epsilon$. If V_2 can successfully decode the block, it will re-generate and broadcast another Y_2 network coded packets from this block, where Y_2 is chosen to ensure that V_3 can decode the block with high probability, together with those overheard packets during the previous Y_1 transmissions from V_1 . If V_2 cannot decode the block, it will drop the whole block and remain silent since the probability that V_3 can decode the block, even with the help from V_2 , is negligible. Therefore, V_1 can proceed to the next information block directly. After V_3 decodes the block, it will re-generate Y_3 coded packets to help its subsequent vehicles.

Under the C-V2X network Mode 3, the eNodeB performs as a coordinator to assign the channel resource to vehicles in a centralized manner. With the basic safety messages received from vehicles, the eNodeB is able to learn the locations of vehicles and calculate the inter-vehicle distance. Therefore, when the platoon is long, two vehicles with sufficient distance separation can be scheduled to transmit simultaneously without causing too much interference to each other. For simplicity, we assume that two vehicles separated by $(s-1)$ vehicles in between will transmit simultaneously, where s is referred to as channel reuse distance. In other

words, when V_i is transmitting, the vehicles labeled by $\{V_{i \pm js}, j = 1, 2, \dots\}$ can transmit simultaneously, and the potential receivers for V_i include the subsequent $s - 1$ vehicles, i.e., $\{V_{i+u}, u = 1, \dots, s - 1\}$. For instance, in Fig. 6.1, given $s = 3$, as scheduled by the eNodeB, the red vehicles V_1 and V_4 can transmit in the same time slot. Denote by Y_i the number of transmissions from vehicle V_i to ensure high decoding probability at its next vehicle for each block. The delay (or end-to-end delay), which is defined as the time interval from the generation of the video block at V_1 until the last vehicle V_n can decode, is determined by the total number of time slots required, i.e.

$$D_n = T_s \sum_{i=1}^{n-1} Y_i. \quad (6.5)$$

With the proposed channel reuse, when V_{i+s} is sending the coded packets for j th video block, the vehicle V_i can send the packets for $(j + 1)$ th video block. Hence, the normalized video generation rate is determined by the segment that requires the most number of transmissions, which is given by

$$\bar{R} \triangleq \frac{R_s}{R_b} = \frac{K}{\max_i (\sum_{j=i}^{i+s-1} Y_j)}. \quad (6.6)$$

Note that the normalized video generation rate is also the normalized network throughput, which measures the number of packets received in the network in a unit time.

6.2.4 Packet Erasure Probabilities

Denote by p_{ji} the packet erasure probability experienced by the potential receiver V_j when V_i is transmitting. We assume that the packet is erased if the received signal-to-interference-plus-noise ratio (SINR) is lower than the receiving threshold γ_{th} . Otherwise, it is received successfully. Denote by I_i the indices of vehicles that are transmitting simultaneously when V_i transmits, i.e., $I_i \triangleq \{i \pm us, u = 0, 1, \dots\} \cap \{1, 2, \dots, n\}$ for $i = 1, 2, \dots, n$. The received signal at V_j can be expressed

as

$$y_j = \sum_{u \in I_i} h_{ju} x_u + w, \quad (6.7)$$

where h_{ju} is the channel gain from V_u to V_j , x_u is the signal sent by V_u and w is the Gaussian noise with variance σ_0^2 . Hence, the erasure probability can be calculated as

$$p_{ji} = \Pr \left(\frac{h_{ji}^2}{\sum_{u \in \{I_i \setminus i\}} h_{ju}^2 + \sigma_0^2} < \gamma_{th} \right) \quad (6.8)$$

All the vehicles are assumed to transmit at a constant power P_t . The averaged received power at V_j from transmitter V_u , is given by $\Omega_{ju} = \frac{P_t}{(4\pi f d_{ju}/c)^\beta}$, where f is the carrier frequency, $c = 3 \times 10^8 m/s$ is the speed of light in free space, β is a path loss exponent, and d_{ju} is the distance between the V_u and V_j . Evaluating the exact erasure probability between a pair of nodes given by (6.8) involves multiple integrations for instant channel gain of different links. For simplicity, we approximate the instant power of the interfering signal by its average power, denoted as P_I . Then, the packet erasure probability between the transmitter V_i and its potential receiver $V_j, j = i + 1, \dots, i + s - 1$ can be found as

$$p_{ij} \approx F(\gamma_{th}(P_I + \sigma_0^2)), \quad (6.9)$$

where γ_{th} is the receiving threshold, σ_0^2 is the noise power, $P_I = \sum_{u \in \{I_i \setminus i\}} \Omega_{ju}$, $F(\cdot)$ is the cumulative distributive function (CDF) of the small scale fading statistics.

As the reuse distance s reduces, more vehicles are allowed to transmit simultaneously. However, the packet erasure probability given by (6.9) will increase due to larger interference power. Hence, to maximize the video generation rate given by (6.6), the reuse distance should be carefully selected, as elaborated on in the following sections.

6.3 Performance Analysis

In this section, the number of transmissions for each vehicle in the platoon is derived as a function of the coding block size and reuse distance. Note that the normalized video generation rate and decoding delay are directly related to the number of transmissions at each vehicle, and hence the reuse distance, which is then optimized to maximize the achievable normalized video generation rate.

6.3.1 Scheduling Scheme without Channel Reuse

To gain some insights, we first consider the special case without channel reuse, which is applicable when the platoon is short and/or the inter-vehicle distances are small. In the absence of channel reuse, the video generation rate given by (6.6) is simply determined by the total number of transmissions for all vehicles. Hence, the optimal scheduling is determined by the minimum number of transmissions required for each vehicle to ensure that its downstream neighboring vehicle can decode the video block with probability $1 - \epsilon$. Assume that the source node V_1 sends out Y_1 network coded packets generated from a block with M video packets and the coding coefficients are randomly chosen from a finite field $\mathbb{F}_q$. Then, V_2 can decode the original block if it receives at least K innovative packets out of Y_1 transmissions, which is given by

$$P_{succ}^{(2)} = \sum_{t=K}^{Y_1} \binom{Y_1}{t} (1 - p_{21})^t p_{21}^{Y_1-t} \prod_{k=0}^{K-1} (1 - q^{-t+k}). \quad (6.10)$$

When the coding field size is sufficiently large, e.g., $q = 2^8$, $P_{succ}^{(2)}$ is simplified to Binomial distribution. By central limit theorem, this Binomial distribution can be approximated by Gaussian distribution with mean $\mu_{21} = Y_1(1 - p_{21})$ and variance $\sigma_{21}^2 = Y_1 p_{21}(1 - p_{21})$. Follow similar derivation in Section 6.2.2, to ensure

that $P_{succ}^{(2)} > 1 - \epsilon$, we should have

$$Y_1 \geq \frac{2K + \alpha^2 p_{21} + \alpha \sqrt{4K p_{21} + \alpha^2 p_{21}^2}}{2(1 - p_{21})}, \quad (6.11)$$

Note that $\alpha^2 = 5.4199$ with $\epsilon = 0.01$ and $p_{21} < 1$. Hence, we usually have $\alpha^2 p_{21} \ll K$ for moderate or large coding block size. Therefore, the number of transmissions by V_1 can be approximately set as

$$Y_1 = \left\lceil \frac{K + \alpha \sqrt{K p_{21}}}{1 - p_{21}} \right\rceil. \quad (6.12)$$

Among the Y_1 transmissions, the number of packets received by vehicle V_3 is a random variable distributed according to $\mathcal{B}(Y_1, 1 - p_{31})$, which can also be approximated by the Gaussian distribution. Therefore, the additional number of transmissions required by V_3 to decode the block from V_2 can be obtained from the following lemma.

Lemma 6.1. *Assume that a node has received $\mathbf{X}$ network coded packets generated from a block of K input packets, where $\mathbf{X} \sim \mathcal{N}(\mu, \sigma^2)$. With packet erasure probability p , the additional number of transmissions that are required for the node to decode the block with probability at least $(1 - \epsilon)$ is given by*

$$Y = \frac{2K - 2\mu + \alpha^2 p + \alpha \sqrt{4(K - \mu)p + \alpha^2 p^2 + 4\sigma^2}}{2(1 - p)} \quad (6.13)$$

$$\stackrel{(a)}{\approx} \frac{K - \mu + \alpha \sqrt{(K - \mu)p + \sigma^2}}{1 - p}, \quad (6.14)$$

where $\alpha \triangleq |Q^{-1}(1 - \epsilon)|$ and the approximation in (a) holds when $K \gg \alpha^2 p$.

Proof. Please refer to Appendix C.1. ■

Note that ϵ is made sufficiently small so that V_2 can decode the coding block with high probability. After V_2 decodes the video block, it should forward this video block to its downstream vehicles with RLNC. From Lemma 6.1, we can

obtain the number of transmissions required for node V_2 as

$$Y_2 = \left\lceil \frac{K - \mu_3 - \alpha \sqrt{(K - \mu_3)p_{32} + \sigma_3^2}}{1 - p_{32}} \right\rceil \quad (6.15)$$

where $\mu_3 = Y_1(1 - p_{31})$ and $\sigma_3^2 = Y_1 p_{31}(1 - p_{31})$.

Following similar analysis, the total number of packets overhead by V_i from the transmissions of $V_1, V_2, \dots, V_{i-2}$ is a random variable approximately distributed according to $\mathcal{N}(\mu_i, \sigma_i^2)$, where

$$\mu_i = \sum_{j=1}^{i-2} Y_j(1 - p_{ij}), \quad (6.16)$$

$$\sigma_i^2 = \sum_{j=1}^{i-2} Y_j p_{ij}(1 - p_{ij}). \quad (6.17)$$

The number of transmissions required for V_{i-1} to ensure V_i can decode the block is obtained from Lemma 6.1

$$Y_{i-1} = \left\lceil \frac{K - \mu_i - \alpha \sqrt{(K - \mu_i)p_{i(i-1)} + \sigma_i^2}}{1 - p_{i(i-1)}} \right\rceil, i = 2, \dots, n-1, \quad (6.18)$$

where μ_i and σ_i^2 are given in (6.16) and (6.17). Note that the value of Y_i can be computed from (6.18) in a recursive manner. Then, the video generation rate given in (6.6) can be expressed as

$$\bar{R} = \frac{K}{\sum_{i=1}^{n-1} Y_i}. \quad (6.19)$$

Due to the packet overhearing, the number transmissions required with the proposed RLNC scheme in (6.18) is usually much smaller than that required for the conventional deterministic one-hop erasure correction code in (6.3). Therefore, the proposed scheme is expected to achieve larger video generation rate than the benchmark scheme discussed in Section 6.2.2 even without channel reuse.

6.3.2 Scheduling Scheme with Channel Reuse

In this subsection, we consider the general scheme with channel reuse, where the group of vehicles $\{V_j, j \in I_i\}$, for $i = 1, \dots, s$, transmit simultaneously by sharing the same channel. The number of time slots allocated for the group of concurrent transmitters is determined by the bottleneck user that requires the most number of transmissions. In the preceding subsection, the number of transmissions required for each vehicle is determined in a recursive manner in (6.18). However, if $Y_{i+s} > Y_i$ as determined from (6.18), we need to allocate Y_{i+s} time slots for that group of concurrent transmitters and it is a waste of channel resource if V_i only sends Y_i number of coded packets. By increasing the number of transmissions at V_i to the Y_{i+s} , the receiving status of the subsequent vehicles will be affected, and so does the required number of transmissions.

Considering the bottleneck user, the time slots allocated for the group of vehicles that simultaneously transmit with V_i , $i = 1, 2, \dots, s$, is assumed to be $\bar{Y}_i$. For a receiving vehicle V_j , it may receive useful packets from the $(s-1)$ front vehicles, i.e., $V_{j-s+1}, \dots, V_{j-1}$. The number of received packets by V_j can be modeled by a Gaussian random variable with mean and variance given by

$$\bar{\mu}_j = \sum_{u=j-s+1}^{j-1} \bar{Y}_u (1 - p_{ju}), \quad (6.20)$$

$$\bar{\sigma}_j^2 = \sum_{u=j-s+1}^{j-1} \bar{Y}_u p_{ju} (1 - p_{ju}), \quad (6.21)$$

where $\bar{Y}_u$ is the number of coded packets sent by V_u and p_{ju} is the erasure probability from V_u to V_j given by (6.9).

To maximize the channel utilization, we have assumed that the concurrent vehicles will transmit the same number of packets. Then, the minimum number of transmissions at each vehicle can be obtained by solving the following problem.

$$\mathbf{P1:} \quad \min_{\{\bar{Y}_i, i=1, \dots, s\}} \sum_{i=1}^s \bar{Y}_i \quad (6.22a)$$

$$\text{s.t.} \quad \bar{\mu}_j \geq \bar{\sigma}_j |Q^{-1}(1 - \epsilon)| + K, j = 2, 3, \dots, n, \quad (6.22b)$$

$$\bar{Y}_u = \bar{Y}_{u-\theta s}, \theta = \lceil u/s \rceil - 1, u = s + 1, \dots, n, \quad (6.22c)$$

where $\bar{\mu}_j$ and $\bar{\sigma}_j$ are given by (6.20) and (6.21), respectively. The first constraint in (6.22b) specifies the decoding condition for V_j and the second constraint in (6.22c) states that the concurrent transmitters should send the same number of packets.

P1 is a non-convex optimization problem due to the non-convex constraint (6.22b). However, since $\bar{\sigma}_j$ on the right hand side of (6.22b) is a concave function with respect to $\bar{Y}_u$, the successive convex optimization technique can be applied to find an efficient local optimal solution to **P1**. Denote by $\bar{R}(s)$ the normalized video generation rate with reuse distance s . According to (6.6), we have

$$\bar{R}(s) = \frac{K}{\sum_{i=1}^{s-1} Y_i} \quad (6.23)$$

where $Y_i, i = 1, \dots, s-1$ are solved from **P1**. Since the erasure probabilities between pairs of vehicles are complex functions of reuse distance, it is difficult to directly optimize the reuse distance that maximizes the video generation rate. However, since the reuse distance must be an integer ranging from 2 to $n-1$, we can find the optimal value by exhaustive search, which involves solving **P1** for at most $n-2$ times with different reuse distances.

6.4 Numerical Simulations and Discussions

In this section, numerical examples are presented to verify the analytical results derived in the preceding sections. The setup of the system is described in Table 6.2, where the neighboring vehicles are separated by equal distance d . We assume that

Table 6.2: System Setup

Transmission power P_t	20 dBm
Receiving sensitivity γ_{th}	15 dB
Path loss exponent β	2.3
Number of vehicles n	15/30
Inter-vehicle distance d	50 m
Nakagami fading shaping factor m	2
Carrier frequency f	5.9 GHz [63]
MCS	7

the inter-vehicle channels follow the Nakagami fading with shaping factor 2.

6.4.1 Performance without Channel Reuse

In the case where there is no channel reuse, the signal is received without interference, i.e., $P_I = 0$ in (6.9). The packet erasure probabilities can be calculated from the CDF of Nakagami fading and we have

$$p_{ij} = \begin{cases} 0.0642, & |i - j| = 1 \\ 0.5987, & |i - j| = 2 \\ 0.9636, & |i - j| = 3 \\ 1, & |i - j| \geq 4 \end{cases} \quad (6.24)$$

We first consider video streaming in a short platoon with number of vehicles $n = 15$. The scheduling scheme is designed such that a coding block is decoded by V_{i+1} with probability greater than 0.99 if it is successfully decoded by its upstream neighbor V_i , i.e., we have per hop failure probability $\epsilon = 0.01$. The numbers of transmissions at each vehicle for different coding block size are plotted in Fig. 6.2 for different coding block size. It is observed that the front vehicle V_1 needs to transmit the most number of packets to ensure that V_2 can decode the video block. Since V_3 can overhear a certain number of packets from the transmissions by V_1 , the number of packets sent by V_2 is the least. The number of transmissions

Figure 6.2: Number of transmissions by each vehicle to guarantee downstream vehicles can successfully decode the coded block.

converges quickly, which implies that almost the same number of transmissions required for the subsequent vehicles in the platoon. Furthermore, as expected, the number of transmissions required with the proposed scheme is much less than the benchmark scheme where packet overhearing is not properly utilized.

The throughput, end-to-end delay, and normalized video generation rate for different coding block sizes are plotted in Fig. 6.3, Fig. 6.4 and Fig. 6.5, respectively. It is observed that a longer delay is incurred when the coding block size grows. Moreover, the achievable video generation rate as well as the throughput increases slowly with the coding block size. When K is sufficiently large, the achievable rate approaches its limit, which is given by $\frac{\sum_i (1-p_{i1})}{n-1}$. To have a good trade-off between the achievable rate (throughput) and delay, we assume a small coding block size $K = 30$ in the following context, at which 14.73% performance gap from the upper limit is expected.

In practice, the inter-vehicle distance may change due to the variation of velocity. When the inter-vehicle distance is larger than the designed parameter, the packets will suffer more loss and the decoding probability will degrade. We test the robustness of the scheme by choosing between each pair of neighboring vehicles randomly and uniformly from $[(1-\eta)d, (1+\eta)d]$ and the resulting decoding

Figure 6.3: Throughput for different coding block sizes.

Figure 6.4: End-to-end delay for different coding block sizes.

Figure 6.5: Normalized video generation rate for different coding block sizes.

Figure 6.6: Normalized video generation rate and the corresponding delay at each vehicle.

Figure 6.7: Successful decoding probability at different vehicles with distance variations.

probabilities for different vehicles are plotted in Fig. 6.7. The simulation results are obtained by averaging 100 runs. Note that the design target is the minimum successful decoding probability to be achieved for given inter-vehicle distances and it is computed as $(1-\epsilon)^{i-1}$, where i is the vehicle index. It is observed from Fig. 6.7 that we can still achieve the design target when the variation of inter-vehicle distance is within 10%. As expected, the decoding probability decreases when the inter-vehicle distance is far from the design values.

6.4.2 Performance with Channel Reuse

Next, we consider multi-hop video streaming with channel reuse over a longer platoon with $n = 30$ vehicles. The rest network settings follow Table 6.2. In the case of channel reuse, the packet erasures are caused by both the channel fading and the interfering signal. Fig. 6.8 shows the erasure probabilities observed by the subsequent vehicles when V_1 is broadcasting, under the scenarios of different reuse distances. When $s = 30$, there is no channel reuse and the erasure probabilities are identical to the case without interference. As the channel reuse distance reduces, the number of interfering sources and the average interference power increases,

Figure 6.8: Packet erasure probabilities with different reuse distance.

which leads to larger packet erasure probabilities.

To find the optimal reuse distance, we plot the achievable video generation rates for all possible reuse distance ranging from 5 to 30 in this example. It is clear from Fig. 6.9 that the maximal video generation rate can be achieved with reuse distance 13. Compared with the case without reuse, which corresponds to reuse distance 30, the achievable rate is improved by 63.59%. Furthermore, compared with the benchmark scheme, the achievable rate is improved by 129.63%. As the length of the platoon increases, higher rate gain is expected since more channel reuse is possible.

6.5 Summary

In this chapter, we have proposed to apply generation-based RLNC to improve the throughput of multi-hop video streaming protocol in the C-V2X network. With the proposed scheme, the number of transmissions by each vehicle is significantly reduced by enabling the RF overhearing. Furthermore, we have derived the explicit number of transmissions required at each vehicle to ensure that its downstream vehicles can successfully decode the video block for any coding block size.

Figure 6.9: Normalized video generation rates with different reuse distance.

The tradeoff between the achievable video generation rate and decoding delay by varying the coding block size has been investigated. Furthermore, for a given coding block size, the optimal channel reuse distance that maximizes the achievable video generation rate is obtained by repetitively solving a non-convex optimization problem. The simulation results show that the achievable video generation rate can be significantly improved with packet overhearing and proper channel reuse.

Chapter 7

Conclusion and Recommendations

7.1 Conclusion

In this thesis, we have studied V2X data dissemination schemes for both safety and non-safety related ITS applications under realistic vehicular communication scenarios. We focused on the optimization of MAC layer and transmission scheduling with the objectives to mitigate packet erasure introduced by vehicular channel impairments, to improve system reliability, and to reduce communication latency. Applying RLNC, BATS coding techniques, and Markov chain modeling, the achievements of different novel data dissemination schemes are summarized as follows.

We studied the throughput maximization for periodic-broadcast applications by optimizing the contention window of the IEEE 802.11p DSRC MAC layer standard. To this end, we analyzed the DSRC V2V broadcast performance by introducing a simple yet accurate Markov chain model, which effectively characterized the MAC protocol for periodic broadcast for both saturated and unsaturated network loads. By exploiting the CBR of each vehicle, we proposed a distributed method to allow vehicles to locally estimate the vehicle density in the realistic op-

erating scenarios. We explicitly established the relationship between the system throughput and the contention window size, and developed an analytical framework to obtain the optimal contention window size for V2V broadcast throughput maximization in accordance with varying vehicle densities caused by the dynamic vehicular topology on the road. The proposed analytical scheme with optimal contention window size was validated by computer simulations and proved to significantly outperform the current standard using fixed window sizes.

We next studied the periodic broadcast of short messages in the V2X network but focused on the enhancement of BSM dissemination reliability at the NLOS intersections. The signal degradation caused by the blockage of buildings, and the strict delay requirement of the BSM posed challenges to the information exchange among vehicles at NLOS road intersections. To alleviate the packet loss due to the NLOS condition, we adopted the packet relaying strategy and a controlled repetitive transmission (RT) pattern. We also applied RLNC and combined the RLNC with relaying. Specifically, two network coding assisted relaying schemes, RT-NCI and RT-NCA, were proposed. On top of the RT pattern, the relaying schemes were modeled based on a Markov chain framework. The superiorities of the proposed schemes RT-NCI and RT-NCA over the relaying at a single node, in terms of the BSM dissemination success probability, were validated through numerical simulations. These two schemes were proved to significantly enhance the system reliability and scalability while meeting the latency requirement of BSMS at the same time, and hence offered promising solutions to mitigate the effects of NLOS intersection.

We extended our research to the V2X content distribution scenario where a RSU actively distributed large-size content (related to the safety information or commercial materials) to vehicles. We divided the data dissemination protocol into I2V broadcasting phase and V2V cooperative sharing phase, and provided an efficient and delay-reduced dissemination protocol. We applied the BATS code, a rateless RLNC, to reinforce the usefulness of each coded packet in the lossy vehic-

ular environment. We proposed a distributed utility-based scheduling such that each vehicle could prioritize the sequence of the coded packets to be transmitted. The proposed scheduling and BATS-coding based transmission contributed to shorten the total dissemination delay and reduce the communication overhead. Moreover, to design the optimal BATS code, a closed-form expression for the expected rank distribution was derived. The performance of the proposed protocol was compared with existing benchmark schemes, NC-based RLS-SNR, CodeTorrent and CodeOnBasic. The results confirmed the effectiveness, scalability and robustness of the proposed protocol. The delay time was found to be further reduced with the increasing vehicle group size.

Last, optimal scheduling for V2X video streaming in a vehicle platoon was investigated by adopting the C-V2X technology instead of DSRC V2X. Different from V2X content distribution, video streaming could involve multiple hops and the streaming content might propagate from a leading vehicle to the subsequent vehicles. We applied the generation-based RLNC to combat the exponential throughput drop in this multi-hop network. Taking RF overhearing into account, we derived an explicit expression for the number of transmissions scheduled at each vehicle such that its downstream vehicle would be able to successfully decode the video. For a given coding block size, the achievable video generation rate with minimum end-to-end delay for block transmission was analyzed. To further enhance the channel utilization while maintaining the video decoding probability, channel reuse was exploited. We formulated and solved the non-convex optimization problem to obtain the optimal reuse distance for video generation rate maximization. According to numerical results, our proposed scheduling protocol was shown to provide substantial performance gain over the benchmark scheme, e.g., Reed-Solomon (RS) code.

7.2 Recommendations for Future Research

There are several potential research directions to advance the V2X communication based on the future 5G network and the DSRC. Firstly, the release of LTE sidelink and two communication modes (Mode 3 and Mode 4) provide advances to the realization of new V2X services, like autonomous driving. As the baseline of the direct V2V communication, vehicles under Mode 4 follow the sensing-based semi-persist scheduling (SPS) to select the subchannel in a distributed manner. However, there is a tradeoff between the packet reception ratio and the time interval before a next message can be correctly decoded [121]. These two metrics may be affected by the transmission power, subchannel selection frequency and the vehicle density. To balance the tradeoff between the two metrics, a joint optimization is needed to be investigated.

Secondly, the network coding assisted relaying at NLOS road intersections discussed in Chapter 4 utilizes the controlled repetitive transmission (RT) pattern in a distributed transmission manner. To address the NLOS condition and the lossy environment, Mode 4 with retransmission is a potential solution. Distinct from the proposed controlled RT where all vehicles randomly pick time slots for broadcast, the selection of the retransmitting node, subframe and subchannel can be systematically designed based on a certain criterion. Therefore, some redundant transmissions can be avoided. Furthermore, relying on the sensing-based SPS, mode 4 can reduce packet collisions to some degree. Thus, the combination of RLNC and C-V2X mode 4 is expected to be useful for the NLOS intersection case with more performance gain.

Thirdly, the proposed scheduling of V2V cooperative transmission achieves its efficiency based on a distributed utility-computation in Chapter 5. Such V2V scheduling is performed when the vehicles disconnect with the RSU. Different from DSRC, the LTE network has a larger communication range so that most of the main roads in the urban area are covered by the connected cells. Then new scheduling problems with the assistance of eNodeB can be foreseen. Due to the

limited channel bandwidth available to the eNodeB in a large vehicular network, the direct V2V channel is yet an option to serve the content recovery, as what we have studied in this thesis. Therefore, an appropriate channel selection among the I2V and V2V channels deserves more attention.

Furthermore, in Chapter 3, our work on the enhancement of the DSRC throughput focuses on the periodic broadcast applications. The proposed solution may not be applicable if some messages that belong to the higher-priority access categories are also waiting in the queue for transmission [40]. To solve this problem, taking the internal collision and the backoff process of all access categories into account, a more general solution to the optimal contention window size for maximizing the throughput needs to be carefully studied.

Lastly, Chapter 6 has proposed a video streaming protocol in which the file is divided into blocks and the RLNC is applied within each block for mitigating the throughput drop in the multi-hop network. Advances can be added to the proposed protocol by adopting the multi-layer scalable video coding concept such that different video layers have unequal error protection. Motivated by the expanding-window (EW) fountain code [122], a EW-RLNC provides a promising solution to enhance the network throughput and alleviate packet loss in the multi-hop video streaming network. To maximize the peak SNR of the video and meet the end-to-end delay constraint in the platooning applications, an appropriate design of the expanding window is needed.

Appendix A

Proofs of Lemmas in Chapter 3

A.1 Proof of Lemma 3.1

Substitute (3.10) into (3.11), the CBR_t is expressed as

$$\text{CBR}_0 = \text{CBR}_t = \frac{P_c \times t_p}{(1 - P_c)t_s + P_c t_r}. \quad (\text{A.1})$$

Hence we have the following relationship between the local perceived CBR_0 and the channel occupied probability P_c

$$P_c = \frac{\text{CBR}_0 t_s}{t_p - \text{CBR}_0 t_r + \text{CBR}_0 t_s}. \quad (\text{A.2})$$

By substituting (3.9) into the above equation, we have

$$(1 - \tau)^N = \frac{t_p - \text{CBR}_0 \cdot t_r}{t_p - \text{CBR}_0 (t_r - t_s)}. \quad (\text{A.3})$$

Since $N = 2\beta R_{cs}$, the vehicle density β can be calculated by

$$\beta \approx \frac{1}{2R_{cs}} \left[\log_{(1-\tau)} \frac{t_p - \text{CBR}_0 \cdot t_r}{t_p - \text{CBR}_0 (t_r - t_s)} \right]. \quad (\text{A.4})$$

A.2 Proof of Lemma 3.2

Let $y(\tau)$ be the numerator of $S'(\tau)$. So $y(\tau) = 1 - \alpha(1 - \tau)^N - N\tau$. First, we prove the existence of a unique τ to make $S'(\tau) = 0$, which can be transformed to prove the existence of τ_o to satisfy $y(\tau_o) = 0$. Since $y'(\tau) = N[\alpha(1 - \tau)^{N-1} - 1]$, and $\alpha < 1$, obviously, $y'(\tau) < 0$. Therefore, $y(\tau)$ is monotonically decreasing in the given domain. Hence, $y(\tau)$ is bounded by $y(0)$ and $y(1)$, i.e., $y(0) > y(\tau) > y(1)$. As $y(0) = 1 - \alpha > 0$ and $y(1) = 1 - N < 0$, there must be a unique solution τ_o to make $y(\tau_o) = 0$. So τ_o is the unique solution such that $S(\tau_o)$ is the extremum value.

Given the domain $\tau \in (0, 1)$, the denominator of $S'(\tau)$ in (eqn:Sprime) is larger than 0. When $0 < \tau < \tau_o$, $y(\tau) > y(\tau_o) = 0$, hence, $S'(\tau) > 0$. On the contrary, when $\tau_o < \tau < 1$, $S'(\tau) < 0$. Therefore, $S(\tau_o)$ is the maximum value in the given domain.

Appendix B

Proofs of Lemmas in Chapter 4

B.1 Proof of Lemma 4.1

We take the first derivative of p_t with respect to p from (4.4). p'_t is given by

$$p'_t = (1 - p)^{n-1} - p(n - 1)(1 - p)^{n-2} \quad (\text{B.1})$$

Let $p'_t = 0$. Then the values of p are $p = 1$ or $p = \frac{1}{n}$. Since $p_t = 0$ when $p = 1$, is not the appropriate solution to this question, the maximum p_t can be obtained when p is equal to $\frac{1}{n}$.

Appendix C

Proofs of Lemmas in Chapter 6

C.1 Proof of Lemma 6.1

Since each packet is erased independently with probability p , the number of packets received by the node, out of the additional Y transmissions, can be approximately modeled by a Gaussian random variable $\mathbf{Z} \sim \mathcal{N}(Y(1-p), Yp(1-p))$. The total number of packets received at the node is thus given by $\mathbf{X} + \mathbf{Z}$, which is distributed according to $\mathcal{N}(\mu + Y(1-p), \sigma^2 + Yp(1-p))$. Provided that the network coding coefficients are chosen from a sufficiently large field, the source block can be recovered if $\mathbf{X} + \mathbf{Z} \geq K$. By solving the equation $\Pr(\mathbf{X} + \mathbf{Z} \geq K) \geq 1 - \epsilon$, we can obtain the additional number of transmissions required as given in (6.13).

Author's Publications

Journals Papers

1. **Y. Gao**, X. Xu, Y. L. Guan, and P. H. J. Chong, "V2X content distribution based on batched network coding with distributed scheduling," *IEEE Access*, vol. 6, pp. 59449-59461, 2018.
2. **Y. Gao**, X. Xu, Y. L. Guan, K. K. Leung, and P. H. J. Chong, "Throughput enhancement by contention window optimization for periodic V2V broadcast," *IEEE Transactions on Intelligent Transportation Systems* under review.
3. **Y. Gao**, X. Xu, Y. L. Guan, "Optimal scheduling for scalable video transmission with expanding-window network code in the multi-hop vehicular networks," *IEEE Transactions on Multimedia* under review.

Conference Papers

1. **Y. Gao**, X. Xu, Y. Zeng, and Y. L. Guan, "Optimal scheduling for multi-hop video streaming with network coding in vehicular networks," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, 2018.
2. X. Xu, **Y. Gao**, and Y. L. Guan, "Applications of temporal network coding in V2X communications," in *International Conference on Smart Grid Inspired Future Technologies*, Springer, 2018, pp. 53-63.
3. **Y. Gao**, P. H. J. Chong, and Y. L. Guan, "BSM dissemination with network coded relaying in VANETs at NLOS intersections," in *2017 IEEE International Conference on Communications (ICC)*, 2017.

4. **Y. Gao**, G. G. M. N. Ali, P. H. J. Chong, and Y. L. Guan, "Network coding based BSM broadcasting at road intersection in V2V communication," in *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*, 2016.
5. G. N. Ali, M. A. Rahman, S. K. Samantha, **Y. Gao**, P. H. Chong, and Y. L. Guan, "Efficient coding based heterogeneous data access in vehicular networks," in *2017 IEEE International Conference on Communications (ICC)*, 2017.
6. M. A. Rahman, G. M. N. Ali, **Y. Gao**, S. K. Samantha, and P. H. Chong, "On accessing heterogeneous data items using network coding in wireless broadcast," in *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*, 2016.

Bibliography

- [1] T. Ho, M. Médard, R. Koetter, D. R. Karger, M. Effros, J. Shi, and B. Leong, “A random linear network coding approach to multicast,” *IEEE Transactions on Information Theory*, vol. 52, no. 10, pp. 4413–4430, 2006.
- [2] W. H. O. Violence, I. Prevention, and W. H. Organization, *Global status report on road safety 2018*. World Health Organization, 2018.
- [3] L. Figueiredo, I. Jesus, J. T. Machado, J. R. Ferreira, and J. M. De Carvalho, “Towards the development of intelligent transportation systems,” in *Proceedings of the IEEE Intelligent Transportation Systems, 2001*. IEEE, 2001, pp. 1206–1211.
- [4] W. Goodall, T. Dovey, J. Bornstein, and B. Bonthron, “The rise of mobility as a service,” *Deloitte Rev*, vol. 20, pp. 112–129, 2017.
- [5] T. Lozano-Perez, *Autonomous robot vehicles*. Springer Science & Business Media, 2012.
- [6] P. Papadimitratos, A. De La Fortelle, K. Evenssen, R. Brignolo, and S. Cosenza, “Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation,” *IEEE communications magazine*, vol. 47, no. 11, 2009.
- [7] “ITS standards program.” [Online]. Available: <https://standards.its.dot.gov/LearnAboutStandards/ResearchInitiatives>
- [8] N. Liu, M. Liu, J. Cao, G. Chen, and W. Lou, “When transportation meets communication: V2P over VANETs,” in *2010 IEEE 30th International Conference on Distributed Computing Systems (ICDCS)*. IEEE, 2010, pp. 567–576.
- [9] A. Lewandowski, S. Bocker, V. Koster, and C. Wietfeld, “Design and performance analysis of an IEEE 802.15.4 V2P pedestrian protection system,” in *2013 IEEE 5th International Symposium on Wireless Vehicular Communications (WiVeC)*. IEEE, 2013, pp. 1–6.
- [10] M. Bagheri, M. Siekkinen, and J. K. Nurminen, “Cellular-based vehicle to pedestrian (V2P) adaptive communication for collision avoidance,” in *2014 International Conference on Connected Vehicles and Expo (ICCVE)*. IEEE, 2014, pp. 450–456.

- [11] A. Hussein, F. García, J. M. Armingol, and C. Olaverri-Monreal, "P2V and V2P communication for pedestrian warning on the basis of autonomous vehicles," in *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2016, pp. 2034–2039.
- [12] L. Hobert, A. Festag, I. Llatser, L. Altomare, F. Visintainer, and A. Kovacs, "Enhancements of V2X communication in support of cooperative autonomous driving," *IEEE communications magazine*, vol. 53, no. 12, pp. 64–70, 2015.
- [13] A. Hosseini, T. Wiedemann, and M. Lienkamp, "Interactive path planning for teleoperated road vehicles in urban environments," in *2014 IEEE 17th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2014, pp. 400–405.
- [14] M. Boban, A. Kousaridas, K. Manolakis, J. Eichinger, and W. Xu, "Connected roads of the future: Use cases, requirements, and design considerations for vehicle-to-everything communications," *IEEE Vehicular Technology Magazine*, vol. 13, no. 3, pp. 110–123, 2018.
- [15] H. Hartenstein and L. Laberteaux, "A tutorial survey on vehicular ad hoc networks," *IEEE Communications magazine*, vol. 46, no. 6, pp. 164–171, 2008.
- [16] F. J. Martinez, C.-K. Toh, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Emergency services in future intelligent transportation systems based on vehicular communication networks," *IEEE Intelligent Transportation Systems Magazine*, vol. 2, no. 2, pp. 6–20, 2010.
- [17] H. Hartenstein and K. Laberteaux, *VANET: vehicular applications and inter-networking technologies*. John Wiley & Sons, 2009, vol. 1.
- [18] J. B. Kenney, "Dedicated short-range communications (DSRC) standards in the United States," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1162–1182, 2011.
- [19] E. ETSI, "302 637-2 v1. 3.1-Intelligent Transport Systems (ITS); vehicular communications; basic set of applications; part 2: Specification of cooperative awareness basic service," *ETSI, Sept*, 2014.
- [20] F. C. Commission *et al.*, "FCC allocates spectrum in 5.9 GHz range for intelligent transportation systems uses," *Report No. ET*, pp. 99–5, 1999.
- [21] Final Report, U.S. Dept. Trans., National Highway Traffic Safety Admin., "Vehicular safety communications project," *Rep. DOT HS 810 591*, Apr. 2006.
- [22] Y. L. Morgan, "Notes on DSRC & WAVE standards suite: Its architecture, design, and characteristics," *IEEE Communications Surveys & Tutorials*, vol. 12, no. 4, pp. 504–518, 2010.

- [23] W. Xiang, P. Richardson, and J. Guo, "Introduction and preliminary experimental results of wireless access for vehicular environments (WAVE) systems," in *3rd Annual International Conference on Mobile and Ubiquitous Systems-Workshops, 2006*. IEEE, 2006, pp. 1–8.
- [24] R. A. Uzcátegui, A. J. De Sucre, and G. Acosta-Marum, "WAVE: A tutorial," *IEEE Communications magazine*, vol. 47, no. 5, 2009.
- [25] I. . W. Group *et al.*, "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 amendment 6: Wireless access in vehicular environments," *IEEE Std*, vol. 802, no. 11, 2010.
- [26] 3GPP TR 36.885, v.14.0.0, "Study on LTE-based V2X services," July, 2016.
- [27] 3GPP TR 22.185, "Service requirements for V2X services," Nov, 2016.
- [28] 3GPP TR 36.213, "Physical layer procedures," Sept, 2016.
- [29] 3GPP TR 23.285, "Architecture enhancements for V2X services," Dec, 2016.
- [30] 5G Automotive Association, "Experience the future of mobility." [Online]. Available: <http://5gaa.org/5g-technology/experience-the-future/>
- [31] H. Seo, K. Lee, S. Yasukawa, Y. Peng, and P. Sartori, "LTE evolution for vehicle-to-everything services," *IEEE Communications Magazine*, vol. 54, no. 6, pp. 22–28, June 2016.
- [32] S. Sun, J. Hu, Y. Peng, X. Pan, L. Zhao, and J. Fang, "Support for vehicle-to-everything services based on LTE," *IEEE Wireless Communications*, vol. 23, no. 3, pp. 4–8, June 2016.
- [33] R. Molina-Masegosa and J. Gozalvez, "LTE-V for sidelink 5G V2X vehicular communications: a new 5G technology for short-range vehicle-to-everything communications," *IEEE Vehicular Technology Magazine*, vol. 12, no. 4, pp. 30–39, 2017.
- [34] S. Chen, J. Hu, Y. Shi, Y. Peng, J. Fang, R. Zhao, and L. Zhao, "Vehicle-to-everything (v2x) services supported by lte-based systems and 5G," *IEEE Communications Standards Magazine*, vol. 1, no. 2, pp. 70–76, 2017.
- [35] K. Wevers and M. Lu, "V2X communication for ITS-from IEEE 802.11p towards 5G," *IEEE 5G Tech Focus*, vol. 1, no. 2, 2017.
- [36] K. Abboud, H. A. Omar, and W. Zhuang, "Interworking of DSRC and cellular network technologies for V2X communications: A survey," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 12, pp. 9457–9470, 2016.
- [37] S. Ucar, S. C. Ergen, and O. Ozkasap, "Multihop-cluster-based IEEE 802.11p and LTE hybrid architecture for VANET safety message dissemination," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 4, pp. 2621–2636, 2016.

- [38] K. Kosek-Szott, M. Natkaniec, and A. R. Pach, "A simple but accurate throughput model for IEEE 802.11 EDCA in saturation and non-saturation conditions," *Computer Networks*, vol. 55, no. 3, pp. 622–635, 2011.
- [39] M. I. Hassan, H. L. Vu, and T. Sakurai, "Performance analysis of the IEEE 802.11 MAC protocol for DSRC safety applications," *IEEE Transactions on vehicular technology*, vol. 60, no. 8, pp. 3882–3896, 2011.
- [40] Y. Yao, L. Rao, and X. Liu, "Performance and reliability analysis of IEEE 802.11p safety communication in a highway environment," *IEEE Transactions on vehicular technology*, vol. 62, no. 9, pp. 4198–4212, 2013.
- [41] X. Ma, X. Chen, and H. H. Refai, "Performance and reliability of DSRC vehicular safety communication: a formal analysis," *EURASIP Journal on Wireless Communications and Networking*, vol. 2009, no. 1, p. 969164, 2009.
- [42] Y. P. Fallah, C.-L. Huang, R. Sengupta, and H. Krishnan, "Analysis of information dissemination in vehicular ad-hoc networks with application to cooperative vehicle safety systems," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 1, pp. 233–247, 2011.
- [43] K. A. Hafeez, L. Zhao, B. Ma, and J. W. Mark, "Performance analysis and enhancement of the DSRC for VANET's safety applications," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 7, pp. 3069–3083, 2013.
- [44] J. Zheng and Q. Wu, "Performance modeling and analysis of the IEEE 802.11p EDCA mechanism for VANET," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 4, pp. 2673–2687, 2016.
- [45] G. V. Rossi and K. K. Leung, "Optimised CSMA/CA protocol for safety messages in vehicular ad-hoc networks," in *2017 IEEE Symposium on Computers and Communications (ISCC)*. IEEE, 2017, pp. 689–696.
- [46] W. H. O. Violence, I. Prevention, and W. H. Organization, *Global status report on road safety 2015*. World Health Organization, 2015.
- [47] T. Mangel, O. Klemp, and H. Hartenstein, "5.9 GHz inter-vehicle communication at intersections: a validated non-line-of-sight path-loss and fading model," *EURASIP Journal on Wireless Communications and Networking*, vol. 2011, no. 1, p. 182, 2011.
- [48] B. Hassanabadi and S. Valaee, "Reliable periodic safety message broadcasting in VANETs using network coding," *IEEE Transactions on Wireless Communications*, vol. 13, no. 3, pp. 1284–1297, 2014.
- [49] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Transaction on Information Theory*, vol. 46, no. 4, pp. 1204–1216, 2000.
- [50] M. Li, Z. Yang, and W. Lou, "CodeOn: Cooperative popular content distribution for vehicular networks using symbol level network coding," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 1, pp. 223–235, 2011.

- [51] U. Lee, J.-S. Park, J. Yeh, G. Pau, and M. Gerla, "Code torrent: content distribution using network coding in VANET," in *Proceedings of the 1st international workshop on decentralized resource sharing in mobile computing and networking*. ACM, 2006, pp. 1–5.
- [52] F. Ye, S. Roy, and H. Wang, "Efficient data dissemination in vehicular ad hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 4, pp. 769–779, 2012.
- [53] K. Liu, J. K.-Y. Ng, J. Wang, V. C. Lee, W. Wu, and S. H. Son, "Network-coding-assisted data dissemination via cooperative vehicle-to-vehicle/-infrastructure communications," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 6, pp. 1509–1520, 2016.
- [54] T.-X. Yu, C.-W. Yi, and S.-L. Tsao, "Rank-based network coding for content distribution in vehicular networks," *IEEE Wireless Communications Letters*, vol. 1, no. 4, pp. 368–371, 2012.
- [55] S. Yang and R. W. Yeung, "Batched sparse codes," *IEEE Transactions on Information Theory*, vol. 60, no. 9, pp. 5322–5346, 2014.
- [56] T.-C. Ng and S. Yang, "Finite-length analysis of BATS codes," in *2013 International Symposium on Network Coding (NetCod)*. IEEE, 2013, pp. 1–6.
- [57] K. Sjoberg and A. Vinel, "Pre-study: Real-time video streaming over VANETs for increased road traffic efficiency and safety," *Project within FFI Transport Efficiency*, 2013.
- [58] E. Belyaev, K. Egiazarian, and M. Gabbouj, "A low-complexity bit-plane entropy coding and rate control for 3-d dwf based video coding," *IEEE Trans. on Multimedia*, vol. 15, no. 8, pp. 1786–1799, 2013.
- [59] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, "Design of 5.9 GHz DSRC-based vehicular safety communication," *IEEE Wireless Communications*, vol. 13, no. 5, 2006.
- [60] "U-NII-4-TO-DSRC EMC TEST AND MEASUREMENT PLAN PHASE I: FCC LABORATORY TESTS," *Federal Communications Commission Office of Engineering and Technology Laboratory Division, Tech. Rep. ET Docket*, pp. 13–49, October 2016.
- [61] "Dedicated short range communications (DSRC) message set dictionary," Nov, 2009.
- [62] J.-B. Seo and V. C. Leung, "Performance modeling and stability of semi-persistent scheduling with initial random access in lte," *IEEE Transactions on Wireless Communications*, vol. 11, no. 12, pp. 4446–4456, 2012.
- [63] R. Molina-Masegosa and J. Gozalvez, "System level evaluation of LTE-V2V Mode 4 communications and its distributed scheduling," in *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*. IEEE, 2017, pp. 1–5.

- [64] S.-Y. Li, R. W. Yeung, and N. Cai, "Linear network coding," *IEEE transactions on information theory*, vol. 49, no. 2, pp. 371–381, 2003.
- [65] R. Koetter and M. Médard, "An algebraic approach to network coding," *IEEE/ACM Transactions on Networking (TON)*, vol. 11, no. 5, pp. 782–795, 2003.
- [66] S. Jaggi, P. Sanders, P. A. Chou, M. Effros, S. Egner, K. Jain, and L. M. Tolhuizen, "Polynomial time algorithms for multicast network code construction," *IEEE Transactions on Information Theory*, vol. 51, no. 6, pp. 1973–1982, 2005.
- [67] G. L. Mullen and D. Panario, *Handbook of finite fields*. CRC Press, 2013.
- [68] K. E. Atkinson, *An introduction to numerical analysis*. John Wiley & Sons, 2008.
- [69] N. Cai and R. W. Yeung, "Secure network coding on a wiretap network," *IEEE Transactions on Information Theory*, vol. 57, no. 1, pp. 424–435, 2011.
- [70] T. Ho, B. Leong, R. Koetter, M. Médard, M. Effros, and D. R. Karger, "Byzantine modification detection in multicast networks with random network coding," *IEEE Transactions on Information Theory*, vol. 54, no. 6, pp. 2798–2803, 2008.
- [71] S. Jaggi, M. Langberg, S. Katti, T. Ho, D. Katabi, and M. Médard, "Resilient network coding in the presence of byzantine adversaries," in *IEEE International Conference on Computer Communications*. IEEE, 2007, pp. 616–624.
- [72] N. Cai and R. W. Yeung, "Network coding and error correction," in *in Proc. 2002 IEEE Inform. Theory Workshop*, 2002, pp. 119–122.
- [73] R. Koetter and F. R. Kschischang, "Coding for errors and erasures in random network coding," *IEEE Transactions on Information Theory*, vol. 54, no. 8, pp. 3579–3591, 2008.
- [74] T. C. Ng and S. Yang, "Finite-length analysis of bats codes," in *2013 International Symposium on Network Coding (NetCod)*, Calgary, AB, Jun. 2013, pp. 1–6.
- [75] Bats code for network transmission. Available online: <http://www.inc.cuhk.edu.hk/research/bats>.
- [76] D. J. MacKay, "Fountain codes," 2004.
- [77] Y. Xiao, "Performance analysis of IEEE 802.11e EDCF under saturation condition," in *2004 IEEE International Conference on Communications*, vol. 1. IEEE, 2004, pp. 170–174.
- [78] J. Y. Lee and H. S. Lee, "A performance analysis model for IEEE 802.11e EDCA under saturation condition," *IEEE Transactions on Communications*, vol. 57, no. 1, pp. 56–63, 2009.

- [79] M. Gas, K. Kosek-Szott, M. Natkaniec, and A. Pach, "3D Markov chain-based saturation throughput model of IEEE 802.11 EDCA," *Electronics letters*, vol. 47, no. 14, pp. 826–827, 2011.
- [80] D.-J. Deng, C.-H. Ke, H.-H. Chen, Y.-M. Huang *et al.*, "Contention window optimization for IEEE 802.11 DCF access control," *IEEE Transactions on wireless communications*, vol. 7, no. 12, p. 5129, 2008.
- [81] K. Hong, S. Lee, K. Kim, and Y. Kim, "Channel condition based contention window adaptation in IEEE 802.11 WLANs," *IEEE Transactions on Communications*, vol. 60, no. 2, pp. 469–478, 2012.
- [82] M. Khatua and S. Misra, "D2D: Delay-aware distributed dynamic adaptation of contention window in wireless networks," *IEEE Transactions on Mobile Computing*, vol. 15, no. 2, pp. 322–335, 2016.
- [83] R. Reinders, M. van Eenennaam, G. Karagiannis, and G. Heijenk, "Contention window analysis for beaconing in VANETs," in *7th International Wireless Communications and Mobile Computing Conference (IWCMC)*. IEEE, 2011, pp. 1481–1487.
- [84] T. ETSI, "Intelligent Transport Systems (ITS); Cross Layer DCC Management Entity for operation in the ITS G5A and ITS G5B medium; Report on Cross layer DCC algorithms and performance evaluation," ETSI TR 101 612 V1, Tech. Rep., 2014.
- [85] A. Autolitano, M. Reineri, R. M. Scopigno, C. Campolo, and A. Molinaro, "Understanding the channel busy ratio metrics for decentralized congestion control in VANETs," in *2014 International Conference on Connected Vehicles and Expo (ICCVE)*. IEEE, 2014, pp. 717–722.
- [86] M. Sepulcre, J. Gozalvez, O. Altintas, and H. Kremo, "Integration of congestion and awareness control in vehicular networks," *Ad Hoc Networks*, vol. 37, pp. 29–43, 2016.
- [87] L. Cheng, B. E. Henty, D. D. Stancil, F. Bai, and P. Mudalige, "Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communication (DSRC) frequency band," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 8, pp. 1501–1516, 2007.
- [88] T. Abbas, K. Sjöberg, J. Karedal, and F. Tufvesson, "A measurement based shadow fading model for vehicle-to-vehicle network simulations," *International Journal of Antennas and Propagation*, vol. 2015, 2015.
- [89] F. Ahmed-Zaid, F. Bai, S. Bai, C. Basnayake, B. Bellur, S. Brovold, G. Brown, L. Caminiti, D. Cunningham, H. Elzein *et al.*, "Vehicle safety communications—applications (vsc-a) final report: Appendix volume 2 communications and positioning," Tech. Rep., 2011.
- [90] M. Sepulcre, J. Gozalvez, and J. Hernandez, "Cooperative vehicle-to-vehicle active safety testing under challenging conditions," *Transportation research part C: emerging technologies*, vol. 26, pp. 233–255, 2013.

- [91] H. Nguyen, Z. Liu, D. Jamaludin, Y. Guan *et al.*, “A semi-empirical performance study of two-hop DSRC message relaying at road intersections,” *Information*, vol. 9, no. 6, p. 147, 2018.
- [92] M. Noor-A-Rahim, G. M. N. Ali, H. Nguyen, and Y. L. Guan, “Performance analysis of IEEE 802.11p safety message broadcast with and without relaying at road intersection,” *IEEE Access*, vol. 6, pp. 23 786–23 799, 2018.
- [93] X. Ma, G. Butron, and K. Trivedi, “Modeling of VANET for BSM safety messaging at intersections with non-homogeneous node distribution,” in *International Workshop on Communication Technologies for Vehicles*. Springer, 2016, pp. 149–162.
- [94] L. Le, A. Festag, R. Baldessari, and W. Zhang, “Vehicular wireless short-range communication for improving intersection safety,” *IEEE Communications Magazine*, vol. 47, no. 11, pp. 104–110, November 2009.
- [95] H. Cheng and Y. Yamao, “Reliable inter-vehicle broadcast communication with sectorized roadside relay station,” in *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*. IEEE, 2013, pp. 1–5.
- [96] Y. Yamao *et al.*, “An investigation of network coding relay in its V2V communication at intersections,” in *2014 4th IEEE International Conference on Network Infrastructure and Digital Content (IC-NIDC)*. IEEE, 2014, pp. 297–301.
- [97] G. M. N. Ali, M. N. A. Rahim, P. H. J. Chong, and Y. L. Guan, “Analysis and improvement of reliability through coding for safety message broadcasting in urban vehicular networks,” *IEEE Transactions on Vehicular Technology*, 2018.
- [98] S.-J. Lee, W. Su, and M. Gerla, “On-demand multicast routing protocol in multihop wireless mobile networks,” *Mobile networks and applications*, vol. 7, no. 6, pp. 441–453, 2002.
- [99] A. Nandan, S. Das, G. Pau, M. Gerla, and M. Sanadidi, “Co-operative downloading in vehicular ad-hoc wireless networks,” in *Second Annual Conference on Wireless On-demand Network Systems and Services, 2005*. IEEE, 2005, pp. 32–41.
- [100] K. C. Lee, S.-H. Lee, R. Cheung, U. Lee, and M. Gerla, “First experience with cartorrent in a real vehicular ad hoc network testbed,” in *2007 Mobile Networking for Vehicular Environments*. IEEE, 2007, pp. 109–114.
- [101] S. Ahmed and S. S. Kanhere, “VANETCODE: network coding to enhance cooperative downloading in vehicular ad-hoc networks,” in *Proceedings of the 2006 international conference on wireless communications and mobile computing*. ACM, 2006, pp. 527–532.
- [102] M. H. Firooz and S. Roy, “Collaborative downloading in VANET using network coding,” in *IEEE International Conference on Communications (ICC), 2012*. IEEE, 2012, pp. 4584–4588.

- [103] W. Zhu, D. Li, and W. Saad, "Multiple vehicles collaborative data download protocol via network coding." *IEEE Transactions on Vehicular Technology*, vol. 64, no. 4, pp. 1607–1619, 2015.
- [104] W. Xing, F. Liu, C. Wang, and P. Wang, "Stochastic analysis of network coding based relay-assisted I2V communications in intelligent transportation systems," *Wireless Communications and Mobile Computing*, vol. 2017, 2017.
- [105] F. Zeng, R. Zhang, X. Cheng, and L. Yang, "Channel prediction based scheduling for data dissemination in VANETs," *IEEE Communications Letters*, vol. 21, no. 6, pp. 1409–1412, 2017.
- [106] R. Zhang, X. Cheng, L. Yang, X. Shen, B. Jiao *et al.*, "A novel centralized TDMA-based scheduling protocol for vehicular networks." *IEEE Transaction on Intelligent Transportation Systems*, vol. 16, no. 1, pp. 411–416, 2015.
- [107] X. Xu, M. S. G. P. Kumar, Y. L. Guan, and P. H. J. Chong, "Two-phase cooperative broadcasting based on batched network code," *IEEE Transactions on Communications*, vol. 64, no. 2, pp. 706–714, 2016.
- [108] M. A. Bonuccelli, G. G. T+, F. Lonetti, F. Martelli *et al.*, "Real-time video transmission in vehicular networks," in *2007 Mobile Networking for Vehicular Environments*. IEEE, 2007, pp. 115–120.
- [109] M. Asefi, J. W. Mark, and X. S. Shen, "A mobility-aware and quality-driven retransmission limit adaptation scheme for video streaming over VANETs," *IEEE Transactions on Wireless Communications*, vol. 11, no. 5, pp. 1817–1827, 2012.
- [110] J.-S. Park, U. Lee, S. Y. Oh, M. Gerla, and D. S. Lun, "Emergency related video streaming in VANET using network coding," in *Proceedings of the 3rd international workshop on Vehicular ad hoc networks*. ACM, 2006, pp. 102–103.
- [111] Z. Yang, M. Li, and W. Lou, "Codeplay: Live multimedia streaming in VANETs using symbol-level network coding," in *2010 18th IEEE International Conference on Network Protocols (ICNP)*. IEEE, 2010, pp. 223–232.
- [112] F. Ye, S. Roy, and H. Wang, "Efficient data dissemination in vehicular ad hoc networks," *IEEE Journal on Selected Areas in Commun.*, vol. 30, no. 4, pp. 769–779, May 2012.
- [113] C. Jiang, H. Zhang, Z. Han, Y. Ren, V. C. Leung, and L. Hanzo, "Information-sharing outage-probability analysis of vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 12, pp. 9479–9492, 2016.
- [114] W. Li, J. Wu, X. Ma, and Z. Zhang, "On reliability requirement for bsm broadcast for safety applications in dsrc system," in *2014 IEEE Intelligent Vehicles Symposium Proceedings*. IEEE, 2014, pp. 946–950.

- [115] A. S. Alfa and M. F. Neuts, "Modelling vehicular traffic using the discrete time markovian arrival process," *Transportation Science*, vol. 29, no. 2, pp. 109–117, 1995.
- [116] T. Guo, C. Li, W. Dong, Z. Miao, and X. Su, "Enabling efficient content dissemination for cooperative vehicular networks," in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. IEEE, 2017, pp. 1–5.
- [117] G. V. Rossi, Z. Fan, W. H. Chin, and K. K. Leung, "Stable clustering for ad-hoc vehicle networking," in *2017 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2017, pp. 1–6.
- [118] X. Xu, Y. L. Guan, Y. Zeng, and C.-C. Chui, "Quasi-universal BATS code," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 4, pp. 3497–3501, 2017.
- [119] Q. Wang, P. Fan, and K. B. Letaief, "On the joint V2I and V2V scheduling for cooperative VANETs with network coding," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 1, pp. 62–73, 2012.
- [120] I. S. Reed and G. Solomon, "Polynomial codes over certain finite fields," *Journal of the society for industrial and applied mathematics*, vol. 8, no. 2, pp. 300–304, 1960.
- [121] A. Bazzi, G. Cecchini, A. Zanella, and B. M. Masini, "Study of the impact of PHY and MAC parameters in 3gpp c-v2v mode 4," *IEEE Access*, vol. 6, pp. 71 685–71 698, 2018.
- [122] D. Sejdinovic, D. Vukobratovic, A. Doufexi, V. Senk, and R. J. Piechocki, "Expanding window fountain codes for unequal error protection," *IEEE Transactions on Communications*, vol. 57, no. 9, 2009.