Video Streaming over Vehicular Networks Using Scalable Video Coding

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Abstract

Intelligent Transport System (ITS) is the next generation transport system, which is introduced to improve road safety, driving experience and efficiency, by employing vehicular networks on the road. The vehicular networks are consist of two kinds of communications, thus Vehicular-To-Infrastructure (V2I) and Vehicle-To-Vehicle (V2V). New information and communication technologies are applied in the scope of traffic configuring, road transport and mobility management, etc. Besides road safety, vehicular network communication is also a promising way to provide a lot of services, such as traffic monitoring, driving assistance and entertainment.

Video is an important medium for information sharing and entertainment (infotainment). In several years, video contents dissemination would extend 80%–90% of the entire Internet traffic load, referring to the recent CISCO report. Recently, more attention is caught for the video streaming in vehicular networks. Compared with smart phones, the car engine can provide ample power for intensive data computation and communication. Vehicles can also equip large on-board storage. As a result, the vehicles in the vehicular networks are powerful enough to transmit continuous video data among other vehicles or Road Side Units (RSUs). Furthermore, the recent vehicular communication standard can support up to 54 Mbps transmission rate. Even between high speed driving vehicles, it is reasonable to expect a 1Mbps data rate.

However, compared with the conventional networks, wireless communication in vehicular networks is challenged by the following problems. Firstly, the wireless channel suffers from the time-varying fading, shadowing and interference, which lead to high variation of link throughput. Secondly, vehicular communication is also affected by the high moving speed of vehicles. To accommodate the QoS constraints posed by video services in vehicular networks, the Scalable Video Coding (SVC) scheme in H.264/AVC standard family offers spatial and temporal scalabilities for video streaming.

We describe the scenario setting in this thesis as follows. While vehicles are

running on the highway road, RSUs deployed along the road provide video streaming services for all vehicular users. The videos are encoded into multiple layers with SVC mechanism. Besides the users who are using the video streaming services, vacant users are willing to help the communications between the RSUs and the video users, in a cooperative way.

In this thesis, SVC coded videos over cooperative vehicular networks are investigated to improve the performances of the video streaming services. We target the optimization problems of how many video layers should be transmitted for each vehicle, how to select the relay vehicular users to assist the receiver vehicles, and how to assign network resources to direct and cooperative communications.

The joint SVC layer selection and resource allocation for the multi-user video streaming over highway scenario was investigated at first. We proposed a Resource Allocation and Layer Selection (RALS) algorithm, which explicitly takes account of the utility value of each Group Of Picture (GOP) among all vehicular users. We decoupled this problem to two subproblems, i.e., the SVC layer selection subproblem and the resource allocation subproblem. The proposed RALS algorithm was designed to solve these subproblems separately. In RALS, we solved the SVC layer selection subproblem with dynamic programming method, and used a greedy based resource allocation scheme to deal with the resource allocation subproblem. The performance of RALS was evaluated by extensive simulations. Simulation results showed that RALS outperformed the comparison schemes in typical scenarios. Despite the system utility values, the GOP distributions of the comparison schemes were also shown in the simulation results section. The GOP distributions illustrated the detailed performance in the perspective of each user. As an extension of RALS, we designed RALS with Base layer Guarantee (BG) scheme to reduce the playback freeze. The performance of RALS with BG was also evaluated in the simulation results section and compared with RALS.

Then, we later investigated the joint SVC layer selection, resource allocation and relay assignment problem in cooperative vehicular networks. We formulated the relay assignment problem as a Maximum Weighted Bipartite Matching (MWBM) problem, and solved this problem with the proposed Maximum Utility Increment (MUI) algorithm. In MUI, we employed the Hungarian algorithm and Bellman-Ford algorithm to solve the MWBM problem. To solve the resource allocation and SVC layer selection problem, we explicitly considered the segment utility increment in MUI. The performance of MUI was evaluated by exploiting extensive simulations. Simulation results showed that MUI outperformed the comparison schemes in typical scenarios. In the perspective of each user, the GOP distributions of each comparison scheme were also shown in the simulation results section. In order to reduce the number of freezed GOPs in the playback, we extended the MUI to MUI with base layer guarantee scheme. According to the simulation results, MUI with base layer guarantee could eliminate playback freeze with quite little PSNR loss in most cases.

The limited network resources do not allow all vehicular users to receive the videos with the highest SVC layer levels simultaneously. However, the proposed scheduling algorithms have the ability to improve the system performance in the perspective of the quality of perceived videos, or the quality of experience. At the same time, proportional fairness is approximately achieved as well. As a result, the video streaming over vehicular networks is able to perform much better than before, and we are a small step forward to the bright future of in-vehicle infotainment.

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List of Abbrevations

ACR	Absolute Category Rating
BG	Base layer Guarantee
BS	Base Station
CT	Cooperative Transmission
D2D	Device-to-Device
DP	Dynamic Programming
DSRC	Dedicated Short Range Communications
DT	Direct Transmission
G/R coefficient	GOP playback time over Resource segment time coefficient
GOP	Group Of Picture
HCCA	Hybrid coordination function Controlled Channel Access
HetNet	Heterogeneous Network
ICN	Information Centric Network
ILP	Integer Linear Problem
ISP	Internet Services Provider
ITS	Intelligent Transport System
LTE	Long Term Evolution
MAC	Media Access Control

MDR	Maximum Data Rate
MEC	Mobile Edge Computing
MOS	Mean Opinion Score
MSE	Mean Square Error
MUI	Maximum Utility Increment
MUIB	Maximum Utility Increment with Base layer guarantee
MWBM	Maximum Weighted Bipartite Matching
OFMD	Orthogonal Frequency Division Multiplexing
OFMDA	Orthogonal Frequency Division Multiple Access
PSNR	Peak Signal to Noise Ratio
QoE	Quality of Experience
RALS	Resource Allocation and Layer Selection
RSU	Road Side Unit
SNR	Signal to Noise Ratio
STW	Scheduling Time Window
SVC	Scalable Video Coding
TDMA	Time Division Multiple Access
TXOP	Transmit OPportunities
V2I	Vehicle-To-Infrastructure
V2N	Vehicle-To-InterNet
V2P	Vehicle-To-Pedestrian
V2R	Vehicle-To-Road infrastructure
V2V	Vehicle-To-Vehicle
V2X	Vehicle-To-Everything
VANET	Vehicular Ad-hoc NETwork

WLAN	Wireless Local Area Network
WWAN	Wireless Wide Area Network

List of Notations

B	Number of Pre-buffer GOPs
$C(s,p)$	The capacity between s and p
$C_{AF}(s,r,p)$	The capacity between s and p in AF cooperative communication with relay r
$C_{DF}(s,r,p)$	The capacity between s and p in DF cooperative communication with relay r
E	The edge set between V_1 and V_2
I	Number of Video Users
J	Number of GOPs in each round
K	Number of resource segments in one round
L	The maximum number of SVC layer levels among all users
L_i	Number of SVC layer levels for video user i
M	The GOP playback time over resource segment time coefficient
N_0	Background noise
P	Transmission power
R	Number of relay users
$SNR_{s,p}$	The SNR value between s and p
T	The length of time for each round/STW

$V(j)$	Transform function from playback GOP index to resource assignment GOP index
V_1	Vertex set for all video users
V_2	Vertex set for all resource segments
Z	Bandwidth of the channel
$\Delta u_{i,k}$	The utility increment of user i if the resource segment k is assigned for it
$\Delta u_{i,r,k}$	The utility increment when assigning resource segment k for video user i, assisted by relay user r
γ	Path loss exponet
$\alpha_{i,k}$	Resource allocation 0-1 integer for video user i and resource segment k
$\bar{T}$	The time cost when one vehicle runs through the road with highest speed
$\bar{k}$	The resource segment located in the middle of T
$\bar{u}_i(d)$	The utility value when assigning as much as d data volume for video user i
$\beta_{i,r}$	Relay assignment 0-1 integer for video user i and relay user r
$\mathcal{E}$	The edge set for the relay assignment problem
$\mathcal{I}$	The set of video users
$\mathcal{I}_j^B$	The set of video users that have not received the base SVC layer for the next GOP j
$\mathcal{R}$	The set of relay users
$\bar{\mathcal{R}}$	The extended set of relay users
$\mid X_s - X_p \mid$	Euclidean distance between s and p

$\mu_i(j,d)$	Maximum system utility for j GOPs with given data volume d
ϕ	The transformed bipartite graph for the resource allocation subproblem
ψ	Subset of edge set E
$\vec{\alpha}$	Resource allocation vector
$\vec{\beta}$	Relay assignment vector
$\vec{d}_i^{rec}$	Received data vector for video user i
$\vec{l}$	SVC layer selection vector
$\vec{l}^{init}$	Initially received SVC layer levels vector
$d_{i,j}^{rec}$	The received data before the playback of GOP j
$d_{i,k}^{seg}$	The data volume of resource segment k if it is assigned for video user i
$d_{i@r,k}^{seg}$	The data volume of the resource segment k for user i assisted by relay user r
$d_{i,l}$	The data volume needed to playback one GOP from SVC layer level 1 to l for user i
i	Video user index i
j	GOP index j
k	Resource segment index k
l	SVC layer level
$l_{i,j}^{init}$	Initially received SVC layer level of user i about GOP j
$l_{i,j}$	SVC layer selection for user i about GOP j
p	Destination in cooperative network
r	Relay user index r
s	Sender in cooperative network

t_0	Start time of one round
t_{GOP}	The time duration of each GOP
$u_{i,l}$	The utility value of user i's GOP with the SVC layer level l
$w(e)$	The weight over edge e
$\vec{l}\,\|_i$	The SVC layer selection vector for video user i

Chapter 1

Introduction

1.1 Background

As one of the most important enabling technologies in the envisioned intelligent transportation system (ITS) [1][2], vehicular networks [3][4][5] are introduced to improve the road safety [6][7][8] by employing two transmission categories, i.e., Vehicle-To-Infrastructure (V2I) [9][10] communications which enable vehicles to communicate with Road Side Unit (RSU), and Vehicle-To-Vehicle (V2V) [11][12][13] communications which enable vehicles to communicate with each other. Nowadays, vehicles can exchange information with other vehicles (V2V), with the roadside infrastructure (V2I), with a backend server (e.g., from a vehicle manufacturer or other mobility service providers) or with the Internet, thus Vehicle-To-InterNet (V2N) [14][15], with a pedestrian, thus Vehicle-To-Pedestrian (V2P) [16][17], with road infrastructure, thus Vehicle-To-Road infrastructure (V2R) [18][19], etc. To refer to all these types of vehicular communication, the term Vehicle-To-Everything (V2X) [21] has been proposed.

Connected vehicle services have existed in the market for more than 10 years with the provision of automated crash notifications, vehicle breakdown notifications, traffic information and infotainment services, among others. With the explosive growth of information technology, vehicular networks [22][23] contribute to a more efficient driving experience by acting as a promising medium to provide a number of innovation applications, such as traffic monitoring, driving assistance, and multimedia services [24]. Recently, the development of cellular communication supported V2X services has received broad attention from both industry and academy. The cellular systems, such as Long Term Evolution (LTE) or 5G, are considered as a promising technique for vehicular communication due to its nice properties in terms of high data rate, low latency, large coverage area, high energy efficiency, robust interference control, high penetration rate, and high-speed terminal support [25]. In the near future, vehicular networks are promising to be integrated with cellular networks heterogeneously, for an example, 5G networks.

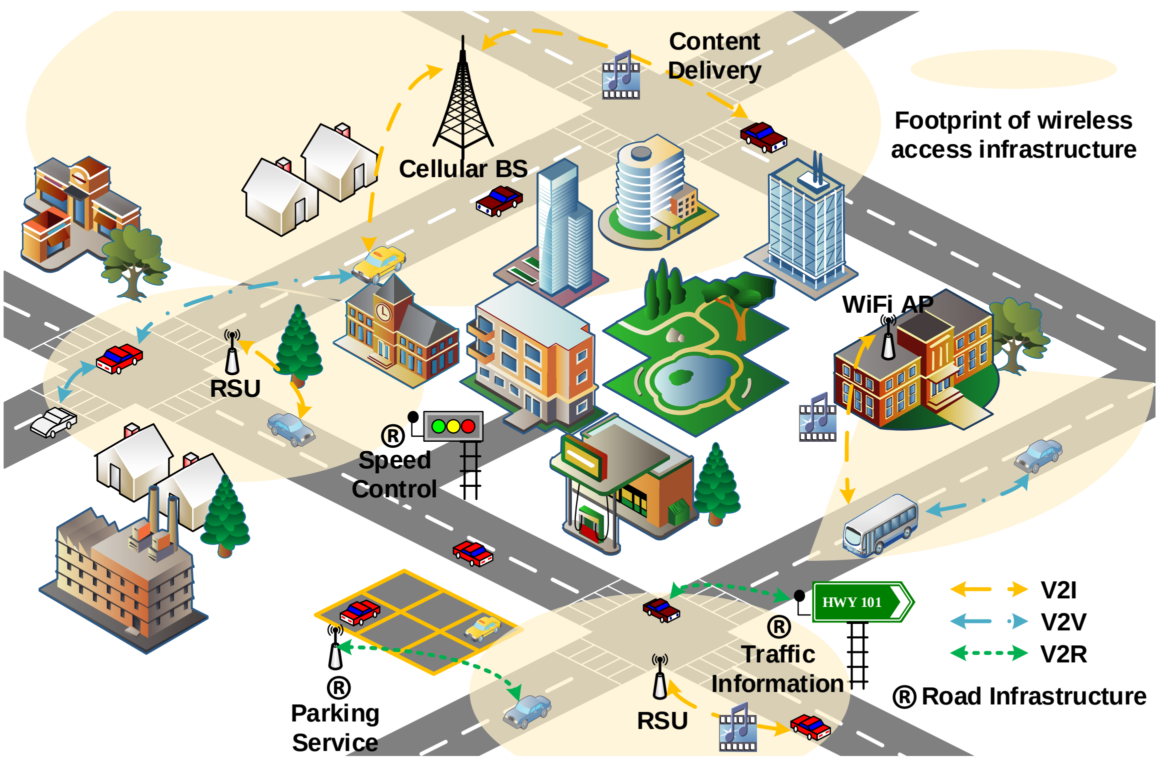

Figure 1-1: Cooperative Vehicular Networks.

In Fig. 1-1, a well-developed street scenario enhanced by vehicular networks is shown. The vehicular networks integrated with cellular networks help to build the intelligent transport systems and become an important fraction of the smart city. The V2I communications provide vehicular users different kinds of services, including content delivery/video streaming, in the cellular base stations as well as other RSUs. The V2V communication let vehicular users communicate with each other and share local information. Also, V2V allows vehicular users to relay data for other vehicular users, as we discussed later in this thesis. The road infrastructures deployed on different locations provide different road services with V2R communication, like traffic information sharing, parking service, speed control and advertisement. The future vehicular networks are able to provide us a much safer road traveling experience and a more convenient life style.

The fast varying channel conditions and connectivity in vehicular networks lead to additional challenges compared with wireless communications in low mobility scenarios [26]. In fact, wireless communications in ITS systems should operate with minimal errors while reliably delivering vital data in real time. Hence, challenges imposed by the dynamic surroundings such as multi-path fading, shadowing, and path loss should be surmounted by the ITS system [27].

Due to maturity of multimedia processing and network technologies, i.e., H.264 codec and 3G/3.5G/4G wireless network, the demands of universal multimedia service are increased significantly. In future years, video contents dissemination would extend 80%–90% of the entire Internet traffic load, referring to the recent CISCO report [28]. More attention is caught for the video streaming in vehicular networks recently [29][30][31][32].

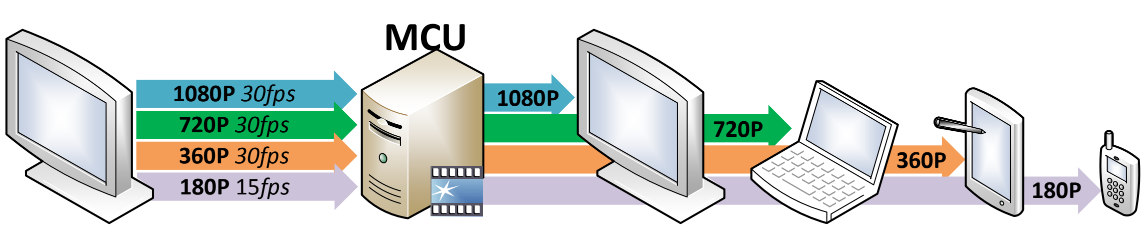

Figure 1-2: SVC coded video streaming.

Video streaming over vehicular networks has considerable benefit for both road safety and entertainment. However, high quality video streaming for fast-moving vehicles faces fundamental challenges attributed to the high mobility and dynamic nature of the network. To eliminate the negative impact of the wireless channel fading and exploit spatial diversity, we introduce SVC [33][34] over cooperative vehicular networks to improve the performance of the video streaming services. SVC is an attractive method to address the heterogeneity of networks and end-user capabilities. A SVC encoded video stream consists of one base layer that provides a minimum quality of the video, and multiple enhancement (also referred as higher) layers that represent the same video but with gradually increased quality, as shown in Fig. 1-2. The transmitter may send only a subset of layers according to the receiver's channel condition. The core idea of the cooperative communications in vehicular networks is that when the channel between the RSU and the receiver vehicle is unreliable, another vehicle that has much better channel conditions forwards the data to the receiver vehicle, and thus, a significant gain for the whole system is achieved.

1.2 Motivation

The video streaming over cellular networks has been well investigated in recent years, for an example, LTE networks. However, employing the same mechanisms of LTE networks in the vehicular environment instead of the general environment is not sufficient, due to the high mobility and dynamic nature of vehicular communication.

Compared with the LTE networks, vehicular networks are usually assumed to employ the license free frequency. Also, the new Mobile Edge Computing (MEC) technology enables the information sharing betweens RSUs. The current LTE networks assign the network resources based on the estimation of the channel condition. However, by utilizing the shared information like locations, velocities, buffer levels, video information etc., a smarter scheduling is possible when MEC is implemented in the RSU.

Research about comparing the performance of LTE networks and vehicular networks, like VANET, has been done by some researchers. Vinel investigates the abilities of LTE to support beaconing for vehicular safety applications in [35]. As a result, the LTE network easily becomes overloaded even under the idealistic assumptions. A detailed performance evaluation study of the IEEE 802.11p and LTE standards are given in terms of delay, reliability, scalability, and mobility support in the context of various application requirements in Mir et al.'s work [36]. The results indicate that IEEE 802.11p offers acceptable performance for sparse network topologies with limited mobility support. On the other hand, LTE meets most of the application requirements in terms of reliability, scalability, and mobility support; however, it is challenging to obtain stringent delay requirements in the presence of higher cellular network traffic load.

Meanwhile, employing SVC in vehicular networks has not been well investigated in literature [37][38][39]. There lies three challenges in the video streaming over cooperative vehicular networks issue, due to the limited network resource. The first is how to assign the limited network resource for multiple users, thus the resource allocation problem. The second is how to decide the SVC layer level for the received video, thus the layer selection problem. The last is how to assign proper relay users for video users, thus the relay assignment problem.

Regarding the resource allocation phase, each resource segment can be assigned for only one user. However, each user wants to get more resource segments to buffer enough number of GOPs for current/further playback. How to assign the limited number of resource segments for all the users to support a smooth playback is a great challenge.

Since the videos are encoded with H.264/SVC scheme, each GOP has multiple layer levels. With the limited network resource assigned by the RSU, the leverage between buffering more GOPs with lower SVC layer levels, and less GOPs with higher

SVC layer levels is a problem as well. The first choice promise a smooth playback for further GOPs, while the second will play the current GOP with better quality.

Cooperative communication could improve the network throughput by employing relay users in the communication range. However when there are multiple relay users to be assigned for multiple video users, the relay assignment mechanism should be designed carefully to cope with the main objective we want to achieve.

1.3 Application

The vehicular networks have many potential applications in public services as well as in the industry, like road safety services, automated parking system, emergency stop, adaptive cruise control, etc. In recent years, a lot of companies invested in the development of vehicular networks-related systems and applications. When 5G is implemented, video applications are able to support a more convenient and comfortable in-vehicle road trip. The applications of video streaming over vehicular networks are discussed in four instances.

Improving Road Safety: Overtaking Assistance

In the overtaking assistance application, a video stream captured by a windshield-mounted camera in a vehicle is compressed, broadcast to the vehicle driving behind it, and displayed to its driver. Such a "see-through" system is aimed at helping drivers overtake long and vision-obstructing vehicles, such as trucks on rural roads using the oncoming lane. Moreover, dangerous road situations or even rear-end collisions can be avoided when information about the obstacle is provided to the driver well in advance, following observation from the vision-obstructing vehicle [40][41].

Improving Public Security: In-vehicle Video Surveillance

The in-vehicle video surveillance application captures video data by means of an internal cabin-mounted camera in a vehicle. After compression, this information is transmitted to the emergency security services such as the police and ambulance. The application will allow real-time monitoring of public transportation to help counteract terrorism, vandalism and other crimes. The efficiency of in-vehicle video surveillance can be enhanced by means of video data analysis and the detection of criminal activity using the state-of-the-art video analytics methods [42].

Traffic Control: Traffic Conditions Video Surveillance

For traffic control purposes it might be necessary to ascertain the current situation at a given road section, intersection or even lane. Thanks to the benefits of global positioning systems, traffic management center can activate the external cameras of vehicles located in the geographical area of interest. Video information with the current road views is then compressed at the vehicle side and transmitted back to the management center. Real-time reaction to traffic jams caused by accidents can be achieved if the video surveillance system of traffic conditions is combined with the eCall [43] or a similar system, which automatically notifies the emergency services of the crash.

Infotainment

Of course video streaming provides in-vehicle passengers information as well as entertainment services. For a long travel on the road, how to spend the time becomes a problem for the passengers who do not need to care much about driving the vehicle. In the future, when auto-mobile vehicles are widely used, there will be no more drivers. The infotainment services are becoming the most important use cases in video streaming over vehicular networks scenario.

In this thesis, we investigate the downlink video streaming for vehicular video users, which is more likely related to infotainment services. However, the proposed schemes are not limited to provide only infotainment services, depending on different application scenarios.

1.4 Related Work

1.4.1 Cooperative network and relay assignment

There were some researches concentrating on the idea of cooperative downloading [44][45]. In [46], the authors proposed a cooperative strategy for content delivery and sharing in vehicular networks, in which the proposed strategy did not focus on streaming and is designed to gather part of the data from one-hop helpers only. In [47], authors proposed a system for mobile devices that receive the same video stream and thus can share received video data over Wireless Local Area Network (WLAN). In their algorithm for the cooperative system, and analytically showed that the proposed system is outstanding in terms of energy consumption and channel switching delay. However, in the vehicular network environment, the considered mobile nodes are unlike the traditional mobile devices in two aspects: (1) the power consumption is no longer the main issue and (2) the computing capability is more powerful to run complicated tasks. Regarding the cooperative streaming scenario, a collaborative downloading system called COMBINE was designed by Ananthanarayanan et al. [48]. COMBINE integrates neighboring nodes' Wireless Wide Area Network (WWAN) interfaces to download resources for an active node. Then, neighboring nodes deliver data to the active node using their WLAN links. Furthermore, the cooperative streaming scenario may adopt different codecs to encode video data. For example, Leung and Chen proposed a protocol called Collaborative Streaming among Mobiles (COSMOS) using the MDC codec in wireless networks [49]. On the other hand, Fan et al. described a joint session scheduling (JOSCH) mechanism using layer-encoded streaming in heterogeneous wireless networks [50]. In [51], Guan et al. proposed a cross layer scheme using rate control, relay selection and power control for video streaming. However, their proposed system considered single hop network and the scenario is for multimedia sensor network. Our proposed system considers multiple hop network and the corresponding scenario is for the vehicular networks.

Thus, the considered technical issues are different.

Except those one-hop cooperative helpers, a helper may use multiple routing paths to send the data to the requester. In [52], the authors presented an architecture supporting transmission of multiple video streams in ad-hoc networks by establishing multiple routing paths to provide extra video coding and transport schemes. In [53], the proposed multi-path transmission control scheme not only aggregates the available bandwidth of multiple paths, but also reduces the unnecessary time of packet reordering at the receiver. In [54], authors proposed a protocol that selects multiple maximally disjointed paths without causing flow congestion. Although a lot of researches have addressed the problem of multi-path routing, most of them concentrated on how to find paths providing good quality to send data back, but how to find appropriate cooperative helpers is left without answers.

1.4.2 Resource allocation schemes in cooperative vehicular networks

The authors in [55] proposed a downlink resource allocation scheme in vehicular networks where both an infrastructure and a vehicle can form multiple direction beams via smart antenna in order to transmit multiple data streams simultaneously. The work was focused on how to avoid the co-channel interference between V2I/V2V links, and did not consider the issue of relay selection. A cooperative social network and its dynamic bandwidth allocation algorithm were proposed in [56] where the closest relay station was selected to forward data without consideration of link quality. The authors in [57] considered the scenario where the long range transmission is based on LTE and the short range transmission is based on IEEE 802.11p. The resource allocation process was focused on LTE links and the V2V links adopted multicast. Zheng et.al. proposed a scheme to allocate the V2I and V2V links for both one-hop and two-hop communications by solving the maximum weighted matching of the constructed bipartite graph of the vehicular networks through Kukn-Munkres algorithm [58]. The scheme was suboptimal because the radio resources are equally allocated to each link. In [59], the authors proposed a two-dimensional-multi-choice knapsack problem (2D-MCKP) based scheduling scheme to select the coordinator vehicles for the destination vehicle and allocation radio resource to V2V/V2I links to maximize sum utility of the networks. However, these schemes are designed for data transmission in vehicular networks, and cannot be directly applied for the SVC streaming services.

1.4.3 Video streaming in vehicular networks

There are dozens of researches about video streaming in conventional networks, including resource allocation for video over network [60], energy aware video streaming [61][62]. However, less work have been done investigating the video streaming over vehicular networks. Yan *et al.* [63] proposed an analytical model to utilize the multihop throughput over vehicular highway networks. Zhang *et al.* [64] developed a platoon-based content replication algorithms to improve the data access. Li *et al.* [65] focused on multicasting video contents on the highway by employing symbol-level network coding scheme. A density-aware relay selection scheme, VIRTUS, was developed by Rezende *et al.* [66] as to provide a reactive and scalable unicast solution for video streaming over vehicular networks. Rezende et al. proposed a VIdeo Reactive Tracking based UnicastSt (VIRTUS) protocol for unicast streaming over vehicular networks [67][66]. The work focused on the suitability of a node to relay packets based on balance between geographic advancement and link stability. Asefi et al. proposed an adaptive retransmission limit selection scheme to improve the performance of IEEE 802.11p protocol for video streaming applications over vehicular networks [68].

Due to the characteristics of IEEE 802.11p standard, these schemes cannot be directly applied to the cellular communication-supported vehicular networks. However, video streaming in cellular communication supported vehicular networks has not been well investigated in literature. An et al. considered the SVC video streaming scheduling problem over vehicular networks in the perspective of only one user [69]. The scheme proposed by Yaacoub et al. was based on grouping the moving vehicles into cooperative clusters [70]. Within each cluster, the LTE system was used to send the data over long range cellular links to a selected cluster head, which multicasts the received video over IEEE 802.11p links to vehicles in its cluster.

In our perspective, SVC could offer us a new point of view of the video streaming issue over vehicular networks. In the literature, SVC coding scheme is well investigated by researchers, focusing on conventional networks. Schaar *et al.* [72] developed the cross-layer optimization strategies for HCCA-based video streaming using SVC. Ji *et al.* [73] investigated the problem of scheduling and resource allocation for multiuser video streaming over downlink Orthogonal Frequency Division Multiplexing (OFMD) channels, in which the video is encoded by SVC.

Although SVC coding scheme has been introduced to the conventional networks, employing H.264/SVC for video streaming in vehicular networks is not trivial in literature. Xing *et al.* [74] proposed relay selection and adaptive SVC layer selection schemes over the highway Vehicular Ad-hoc NETwork (VANET) scenario. Xu *et al.* [71] developed a dynamic programming based algorithm for the resource allocation problem of scalable video streaming over VANETs [75]. They focus on a small window size of GOPs and one user cannot buffer more video data when this window size is full, even though the network resource is redundant. Belyaev *et al.* [76] proposed a low-complexity unequal packet loss protection and rate control algorithm for scalable video coding for road surveillance applications.

1.5 Contribution

The contributions of this thesis is two-fold. As first we target the resource allocation and SVC layer selection problem in SVC video streaming over one-hop vehicular networks in Chapter 2.

- We investigated the resource allocation and layer selection problem for the multi-user SVC video streaming over highway scenario. A centralized network in RSU was assumed, and the network resources were shared by all video users on the road. Such network resources, in the form of resource segments were used to watch realtime video encoded with SVC.

- We proposed a Resource Allocation and Layer Selection (RALS) algorithm to cope with the problem. Specifically, we decouple the optimization problem into two subproblems, i.e., the SVC layer selection subproblem as the lower layer subproblem, and the resource allocation subproblem as the upper layer subproblem. We solved the SVC layer selection subproblem with dynamic programming method, and used a greedy based resource allocation scheme to deal with the resource allocation subproblem.

- In order to reduce the playback freeze, we extended RALS to RALS with base layer guarantee algorithm, and explained the detailed steps to execute the base layer guarantee scheme.

- Simulation results showed that the proposed RALS algorithm outperformed the comparison schemes in typical scenarios. We also analyzed the SVC layer distributions of different comparison schemes to show how the video would be like while users were running through the RSU coverage. At last, the performance of RALS with base layer guarantee is shown.

In Chapter 3, the resource allocation, SVC layer selection and relay selection problem over the SVC video streaming in cooperative vehicular networks environment is discussed, the contributions of this chapter is as follows,

- The resource allocation, SVC layer selection and relay assignment problem for SVC video streaming over cooperative vehicular networks scenario is investigated. We follow the resource model and video model as introduced in Chapter 2. For the relay assignment problem, we assumed that the relay users and video users were one to one matches.

- We proposed a Maximum Utility Increment (MUI) algorithm to solve the aforementioned problem. In MUI, we explicitly took account of the utility value increment of resource segment among all video users. We formulated the relay assignment problem as a Maximum Weighted Bipartite Matching problem, and solved this problem using Hungarian and Bellman–Ford algorithms.

- Similar with Chapter 2, we designed the Maximum Utility Increment with Base layer guarantee (MUIB) scheme to reduce the playback freeze.

- The proposed MUI algorithm was evaluated in extensive simulations. Simulation results showed that not only MUI outperformed other comparison schemes with the objective to maximize the system utility value, MUI also prevented playback freeze in most of time, by comparing with the performance of MUIB.

1.6 Organization

The outline of this thesis is shown as follows:

We first presented the background, motivation, application, related work and contribution of this thesis in Chapter 1.

In Chapter 2, we introduced the resource allocation and layer selection problem for the multi-user SVC video streaming over highway scenario. The RALS algorithm was designed to solve this problem, and evaluated according to the simulation results. We also designed RALS with BG algorithm to reduce the playback freeze of RALS in this chapter.

As an extension of Chapter 2, Chapter 3 described the resource allocation, SVC layer selection and relay assignment problem for SVC video streaming over cooperative vehicular networks scenario. Such problem was solved with the proposed MUI algorithm. Simulations were done to evaluate the performance of MUI. In order to reduce the playback freeze, MUI with base layer guarantee scheme was investigated as well.

Chapter 4 concluded this thesis, discussed the solutions proposed and introduced some research issues that had not been well addressed.

Chapter 2

Video Streaming over Vehicular Networks: Resource Allocation and SVC Layer Selection

2.1 Introduction

Before we investigate the video streaming over cooperative vehicular networks, we start with one-hop video streaming scenario [77][78][79]. The video streaming issue over one-hop vehicular networks issue can be considered as preliminary work. But the research about this issue is also quite meaningful when dealing with the one-hop scenario, which is also very common in reality.

In this chapter, we discuss the video streaming over vehicular networks in highway scenario. Refer to Fig. 2-1, when several vehicles running on the highway road, some of the passengers want to watch realtime videos through the vehicular networks. In this case, video streaming over vehicular networks would make it possible for the video playback.

Due to the limited network resource, there are two challenges in the video streaming over vehicular networks issue as explained as follows. The first is about how to

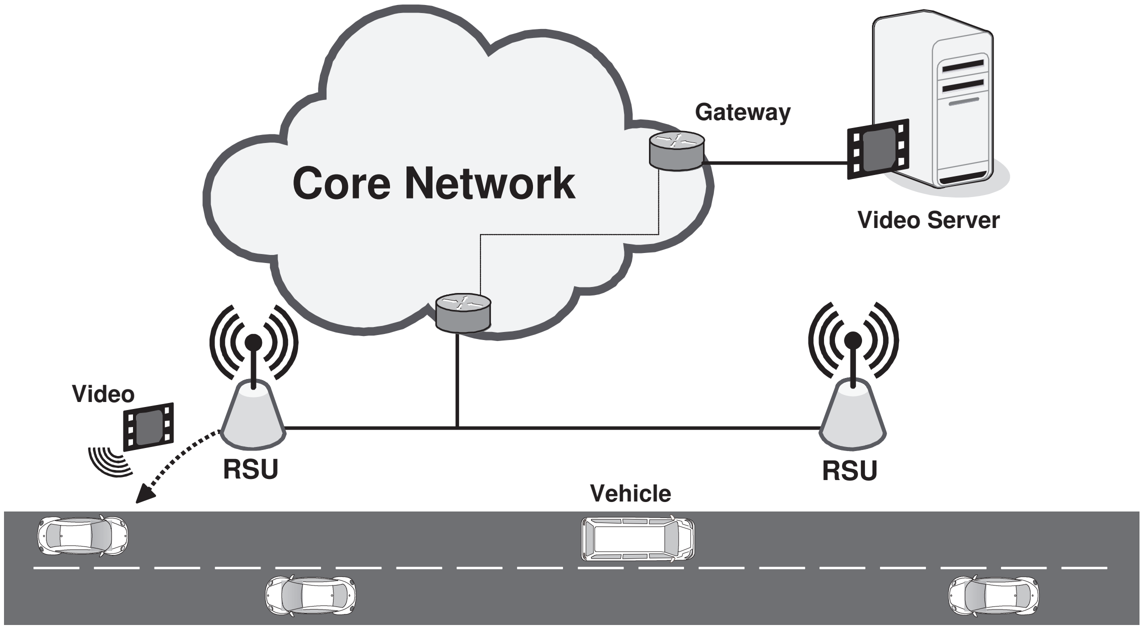

Figure 2-1: Video streaming over vehicular networks.

assign the limited network resource for multiple users, i.e., the resource allocation problem. The second one is how to decide the SVC layer level for the received video, i.e., the layer selection problem.

In the resource allocation phase, each resource segment can be assigned for no more than one user. However, each user wants to receive more resource segments to buffer more SVC layers for current/further playback. As a result, the problem of how to assign the limited network resource for all users is a great challenge.

As a property of SVC scheme, each GOP is encoded with multiple SVC layers. Constrained by the limited network resource assigned by the RSU, the leverage between receiving more GOPs with lower SVC layer levels, and receiving less GOPs with higher SVC layer levels is a problem as well. Usually, the first choice promise a smooth playback for more GOPs, while the second choice may let users play the current GOP with much better quality.

The contributions of this chapter are listed as follows. At first, we investigate the resource allocation and layer selection problem for the multi-user SVC video streaming over highway scenario. Secondly, we propose a Resource Allocation and Layer Selection (RALS) algorithm to cope with the problem. Thirdly, simulation results show that the proposed RALS algorithm outperforms the comparison schemes in typical scenarios. At last, we extend RALS to RALS with base layer guarantee scheme to reduce the playback freeze.

The organization of this chapter is shown as below. Section 2.2 presents the system model and Section 2.3 illustrates the formulation of the resource allocation and layer selection problem. In Section 2.4, we decouple this problem to two subproblems and propose the RALS algorithm with or without the base SVC layer level guarantee. Section 2.5 shows the setup of the simulations and the analysis of the simulation results. At last, the chapter is concluded in Section 2.6.

2.2 System Model

2.2.1 System Architecture

We establish our highway scenario as follows. The highway road is bidirectional, straight and has multiple tracks. RSUs are located along the road. Assume that the information of the vehicular users in each RSU's coverage, such as locations and velocities, is shared by the adjacent RSUs. We focus on the video streaming problem for the vehicular users in one RSU coverage.

Our algorithm executes in a round-by-round fashion. The length of time for each round is T. For each highway road, usually there is a speed limit for the vehicles running on it. We let T be the length of time that is needed for one vehicle to go through the RSU coverage with the highest speed. Suppose t_0 is the start time of one round. Denote I as the number of users that can communicate with the RSU in the time period $[t_0, t_0+T]$, and want to watch realtime videos via the vehicular networks. The network resource provided by the RSU is shared by all these users.

2.2.2 Video Coding Model

In our system model, the videos are encoded by the H.264/SVC scheme. The videos are encoded in the unit of GOP. Each GOP contains a fix number of frames. Each GOP has multiple layers.

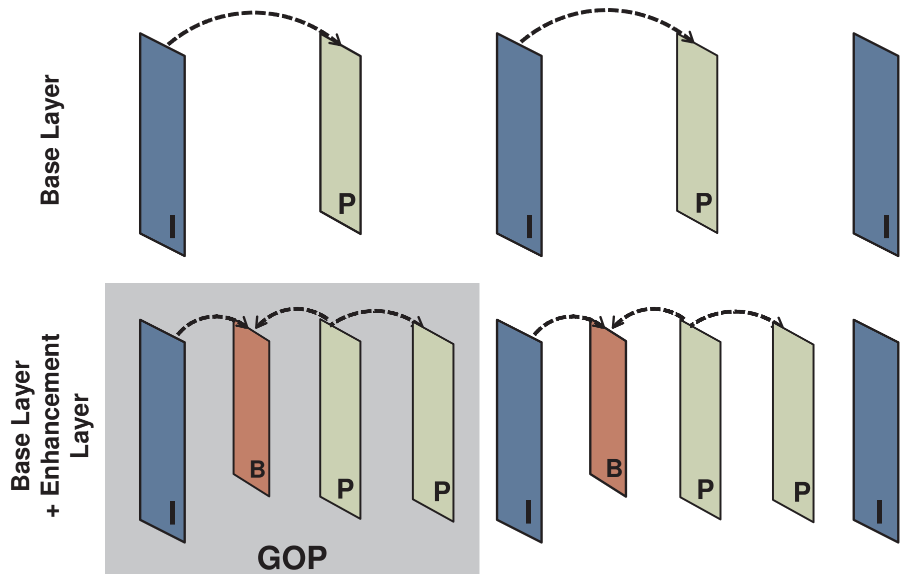

Figure 2-2: SVC coding scheme for two layers with I-frames (blue), P-frames (green) and B-frames (red).

To introduce the H.264/SVC scheme, Fig. 2-2 shows an example with two SVC layers, thus one base layer and one enhancement layer. There are three kind of frames shown in the figure: I-frame (blue), P-frame (green) and B-frame (red). The P-frame can only be decoded with the previous I/P-frame. The B-frame can only be decoded with the previous and the next frames. In the example, each GOP contains one I-frame, two P-frames and one B-frame. The base layer contains I-frame and P-frame. While the enhancement layer contains the P-frame and the B-frame. Dislike the base layer, the enhancement layer cannot be decoded by itself. With the aid of the enhancement layer, the frequency of the video is doubled. The more enhancement layers are decoded, the higher video quality is achieved.

Denote the number of SVC layers for user i as L_i. Let L be the maximum number of layers among all users, thus $L = \max\{L_i \mid 1 \leq i \leq I\}$. If we want to decode one GOP with layer level l, we need to receive all the layers from layer 1 to layer l. Due to the nested dependency among layers, we define the data volume of one GOP from layer 1 to layer l as $d_{i,l}$. Remark that the layer level 0 stands for freeze.

During the time period $[t_0, t_0 + T]$, J GOPs will be played by each user, where $J = \lceil T/t_{GOP} \rceil$. Furthermore, we also pre-buffer a few number of GOPs, in order to support a smooth playback after one user runs out of the communication range. The number of pre-buffered GOPs is denoted as B. The value of B is usually constrained by user's buffer size or the length of realtime video that is already generated in the server.

We assume the duration of each GOP is uniform for all users, and the playback of each GOP is synchronized. This is reasonable when the SVC coding scheme is performed by the same video providers, like YouTube, Netflix, etc.

Before we execute our algorithm regarding time interval $[t_0, t_0 + T]$, the users may have already buffered some SVC layers of different GOPs in the previous round. Denote $\vec{l}^{init} := \{l_{i,j}^{init} \in \{0, 1, 2, ..., L_i\} \mid 1 \leq i \leq I, 1 \leq j \leq J + B\}$ as the initial received layer status vector. $l_{i,j}^{init}$ is the initially received SVC layer level of GOP j for user i. After the execution of our algorithm, the layer selection vector $\vec{l} = \{l_{i,j} \in \{l_{i,j}^{init}, ..., L_i\} \mid 1 \leq i \leq I, 1 \leq j \leq J+B\}$ represents the expected received layer status at $t_0 + T$.

2.2.3 Resource Model

In this chapter, we employ centralized Media Access Control (MAC) layer control over the vehicular networks. The access to the medium is divided into small resource segments. Such resource segments can be comprehended similarly as the resource blocks employed in the OFDM networks, the Transmit OPportunities (TXOP) allocated by Hybrid coordination function Controlled Channel Access (HCCA) in 802.11e, or time slots given by Time Division Multiple Access (TDMA). For simplification, we assume that all the resource segments are derived from the time domain.

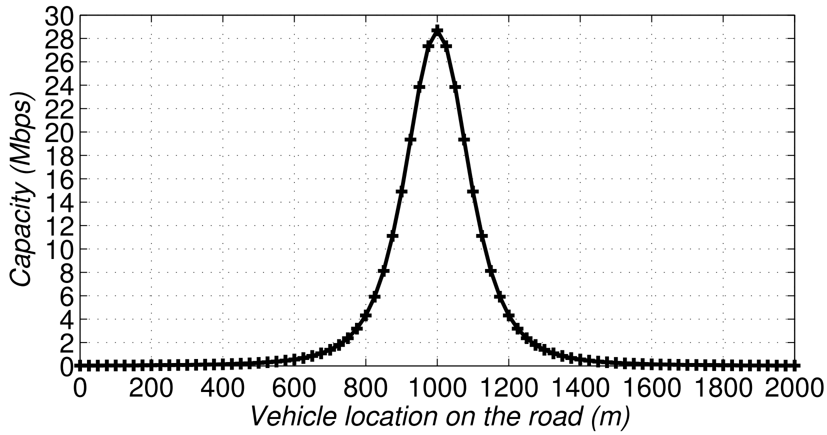

Figure 2-3: The capacity of the link between the RSU and a vehicle.

We assume the time duration of each resource segment is fixed and there are M resource segments in the duration of one GOP. The integer constant M is defined as the GOP playback time over Resource segment time coefficient (G/R coefficient). Thus the number of resource segments is $K = MJ$.

The data volume contained in each resource segment depends on the data rate between the RSU and the user. The distance from the RSU to the user is one of the most important factor to affect the data rate. The Signal to Noise Ratio (SNR) [24][80] of the link between the RSU s and a vehicular user p is shown as below.

$$SNR_{s,p} = \frac{P}{\mid X_s - X_p \mid^{\gamma} \cdot N_0}, \tag{2.1}$$

where P is the transmission power, $\mid X_s - X_p \mid$ stands for the Euclidean distance between the RSU (source s) and the video user (destination p), and γ is the path loss exponent. The noise is denoted as N_0. Given the SNR value, we can calculate the link capacity as follows [81][44],

$$C(s,p) = Z \log_2(1 + SNR_{s,p}), \tag{2.2}$$

where Z stands for the bandwidth.

In Fig. 2-3, the capacity of the link between the RSU and a vehicle user is varying according to the different locations on the road. In this figure, the length of the highway is set as 2000 meters. The RSU is located along the road, the vertical distance to the middle point (1000 m point) of the road is 30 m. We set Z as 10 MHz, P as 10 dBm, α as 3 and N_0 as 10^{-10} W.

Assume that the SNR values between the users and the RSU at each time are already known. The data volume contained in each resource segment can be obtained from the Shannon capacity formula. Define the data volume of the resource segment k for user i as $d_{i,k}^{seg}$.

Even though the handover between RSUs are not considered in this thesis, we assume that the user informations are shared by adjacent RSUs using the MEC technologies. The user informations contain the locations, velocities, directions etc. As a result, the data volume contained in each resource segment can be precisely calculated even though the user has not entered the RSU coverage. By this way, the resource allocation can be done seamlessly for the users that go through different RSU coverages.

Denote $\vec{\alpha} := \{\alpha_{i,k} \in \{0,1\} \mid 1 \leq i \leq I, 1 \leq k \leq K\}$ as the resource allocation vector. We assign the resource segment k for the user i when $\alpha_{i,k}$ equals one and vice versa.

Figure 2-4 shows a valid SVC layer selection and resource allocation result for a simple scenario. The G/R coefficient M is 2. There are 8 resource segments, in which the first 5 resource segments are assigned for A. The layer selection results are $\{1, 2, 3, 3, 1\}$ for these GOPs.

2.2.4 Utility Model

We define the utility of user i's GOP with the SVC layer level l as $u_{i,l}$. Assume that $u_{i,l}$ is non-decreasing and concave over the discrete $\{1, 2, ..., L_i\}$ values for user i.

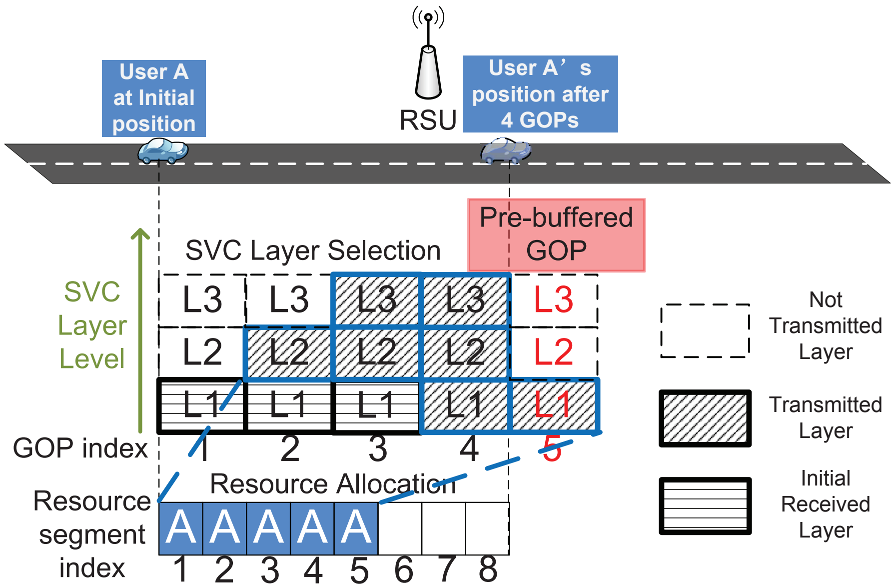

Figure 2-4: SVC layer selection and resource allocation for user A in 5 GOPs ($J = 4$ and $B = 1$), 3 SVC layer levels, 8 resource segments and $M = 2$ scenario.

These properties of $u_{i,l}$ help us to solve the resource allocation problem in the latter part of this chapter.

The utility $u_{i,l}$ can be expressed in another form $\bar{u}_i(d)$, where d stands for the data volume. $\bar{u}_i(d)$ is the utility value when user i gets data volume d to buffer one GOP. We have $\bar{u}_i(d) = u_{i,l}$, when $d \in [d_{i,l}, d_{i,l+1})$. Then $\bar{u}_i(\cdot)$ is a staircase function over a continuous value.

The utility values can be comprehended as the quality of the videos, or the quality of human experience when watching these videos, etc. For an example, we can use the Peak Signal to Noise Ratio (PSNR) value of each GOP as the utility value, which is a commonly used metric to depict the similarity of the decoded video compared with the original video.

The definition of the utility function is very important, since it directly affects the properties of the optimization process. For an example, the fairness of the scheduling. In the field of wired/wireless communication, usually three kinds of scheduling mechanisms are considered, each of which stands for a different fairness level, shown as below:

Maximum C/I

In wired communication, the maximum C/I scheduling finds a user which maximize the system throughput instantly. This offers excellent throughput but it is not fair. Because the users with poor channel quality will not be served until the channel quality of one of these users becomes the highest. The fairness of the system is often unachievable.

Max-Min

The max-min scheduling in wireless communication always assigns the network resources for the users with less channel gain, regardless of the system throughput. By this way, the absolute fairness is achieved. However, the throughput is sacrificed.

Proportional Fair

The proportional fair mechanism in wireless communication can be considered as a compromise between the maximum C/I (not fair) and max-min (absolute fair). In this scheduling mechanism, the scheduler assigns more resources to a user with relatively better average throughput, based on the history information of the average throughput. This offers a better trade off of the throughput as well as fairness satisfactorily.

The proportional fairness will be achieved if and only if the utility function is a logarithm function [82][83]. Following the thought of proportional fairness, we seek for a log-like utility function to approximately achieve the proportional fairness. PSNR is a log scaled function. The utility function itself is a staircase function as we explained before. If we fit the PSNR utility function to a logarithm function, we find that the PSNR utility function is close to the fitted function, shown in Fig. 2-5. As a result, the proposed PSNR utility function can be considered as a proportional fairness based utility function, approximately.

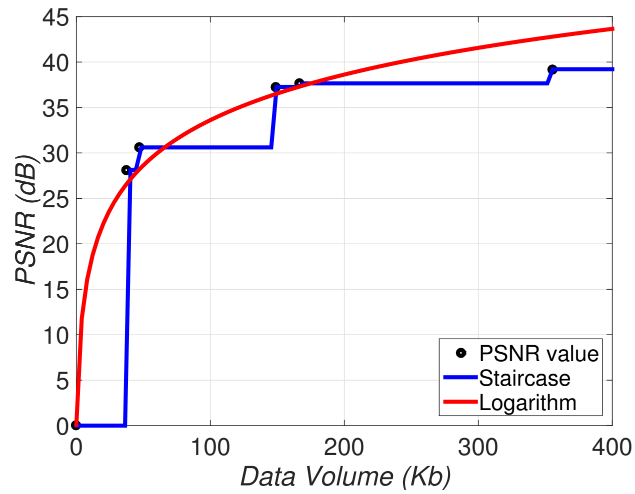

Figure 2-5: Comparison of staircase PSNR utility function and fitted logarithm function, generated with real video data.

Our objective is to maximize the system utility, i.e., $\sum_{i=1}^{I}\sum_{j=1}^{J+B}(u_{i,l_{i,j}} - u_{i,l_{i,j}^{init}})$. Since $l_{i,j}^{init}$ is a fixed value, we can eliminate $u_{i,l_{i,j}^{init}}$ in the expression. In the objective function, the GOP number of each user is the same and each GOP of each user is calculated only once in the objective function. Moreover, the function to calculate the utility value, like PSNR value, of each GOP is usually a log-like function, i.e., as the SVC layer level increases, the increment of the utility value is becoming smaller.

2.3 Formulation

We define $d_{i,j}^{rec}$ as the received data before the playback of GOP j, i.e.,

$$d_{i,j}^{rec} := \sum_{k=1}^{MV_j} \alpha_{i,k} d_{i,k}^{seg}, \quad 1 \leq i \leq I, 1 \leq j \leq J+B, \tag{2.3}$$

where V_j is defined as

$$V_j := \begin{cases} j, & 1 \leq j \leq J; \\ J, & J < j \leq J + B. \end{cases} \tag{2.4}$$

The meaning of $V(j)$ is that, since $\{J+1, ..., J+B\}$ are pre-buffered GOPs and there is no more resource segment to assign by the RSU after GOP J, the received data before the playback of the pre-buffered GOPs is equal to the received data before the playback of GOP J. We define $\vec{d_i^{rec}} := \{d_{i,j}^{rec} \mid 1 \leq j \leq J+B\}$ as the received data vector for user i.

The problem formulation is shown as follows,

$$\max_{\{\vec{\alpha},\vec{l}\}} \sum_{i=1}^{I} \sum_{j=1}^{J+B} u_{i,l_{i,j}}, \tag{2.5}$$

subject to

$$\sum_{j=1}^{\tau} (d_{i,l_{i,j}} - d_{i,l_{i,j}^{init}}) \leq d_{i,\tau}^{rec}, \quad 1 \leq i \leq I,$$
$$1 \leq \tau \leq J+B, \tag{2.5C1}$$

$$l_{i,j}^{init} \leq l_{i,j} \leq L_i, \quad 1 \leq i \leq I, 1 \leq j \leq J+B, \tag{2.5C2}$$

$$\alpha_{i,k} \in \{0,1\}, \quad 1 \leq i \leq I, 1 \leq k \leq K, \tag{2.5C3}$$

$$\sum_{i=1}^{I} \alpha_{i,k} \leq 1, \quad 1 \leq k \leq K. \tag{2.5C4}$$

Constraint (2.5C4) shows the constraint that each resource segment cannot be assigned for more than one user. Constraint (2.5C1) shows the network resource constraint for the SVC video playback. Before the playback of GOP j, the user should have already received enough data to playback the GOPs $\{1, ..., j\}$ with the selected SVC layer level $l_{i,j}$.

We found that the problem shown in Eq. 2.5 is an Integer Linear Problem (ILP) and is NP-hard [84]. In order to get a solution that has comparable utility value with the optimal solution, and can be computed in polynomial time, we introduce the decoupling of this problem.

2.4 Problem Decoupling and Algorithms

2.4.1 Problem Decoupling

We observe that the total utility of user i's GOPs is only constrained by the received data before the playback of each GOP, i.e., $\vec{d}_i^{rec}$. Therefore, we can decouple the original problem to two subproblems: the SVC layer selection subproblem as the lower layer subproblem, and the resource allocation subproblem as the upper subproblem.

1) Lower layer subproblem: SVC layer selection

Let $G_i(\vec{d}_i^{rec})$ be user i's maximum total utility with a given $\vec{d}_i^{rec}$. We have

$$G_i(\vec{d}_i^{rec}) := \max_{\vec{l}|_i} \sum_{j=1}^{J+B} u_{i,l_{i,j}}, \tag{2.6}$$

subject to

$$\sum_{j=1}^{\tau}(d_{i,l_{i,j}} - d_{i,l_{i,j}^{init}}) \leq d_{i,\tau}^{rec},\ 1 \leq \tau \leq J+B, \tag{2.6C1}$$

$$l_{i,j} \in \{l_{i,j}^{init}, ..., L_i\},\quad 1 \leq j \leq J+B. \tag{2.6C2}$$

where $\vec{l}\,|_i$ is the SVC layer selection vector for user i.

2) Upper layer subproblem: resource allocation

The maximum system utility can be expressed as

$$\max_{\vec{\alpha}} h(\vec{\alpha}) = \max_{\vec{\alpha}} \sum_{i=1}^{I} G_i(\vec{d}_i^{rec})$$
$$= \max_{\vec{\alpha}} \sum_{i=1}^{I} G_i(d_{i,1}^{rec}, d_{i,2}^{rec}, ..., d_{i,J+B}^{rec}) \tag{2.7}$$

subject to

$$\alpha_{i,k} \in \{0, 1\}, \quad 1 \leq i \leq I, 1 \leq k \leq K, \tag{2.7C1}$$
$$\sum_{i=1}^{I} \alpha_{i,k} \leq 1, \quad 1 \leq k \leq K. \tag{2.7C2}$$

In Section 2.4.2 and 2.4.3, we design the Resource Allocation and Layer Selection (RALS) algorithm to solve these two subproblems. The optimal solution of the SVC layer selection subproblem is given by the Dynamic Programming (DP) [85][86] method with a given $\vec{d}_i^{rec}$. For the resource allocation subproblem, we prove that the greedy algorithm yields a $(1 - 1/e)$-approximation of the optimal solution.

2.4.2 SVC Layer Selection Subproblem

Dynamic programming (also known as dynamic optimization) is a method for solving a complex problem by breaking it down into a collection of simpler subproblems, solving each of those subproblems just once, and storing their solutions ideally, using a memory-based data structure. The next time the same subproblem occurs, instead of recomputing its solution, one simply looks up the previously computed solution, thereby saving computation time at the expense of a modest expenditure in storage space. For an example, the knapsack problem [87] can be solved by DP in pseudo-polynomial time.

To use DP, the problem itself should have the characteristics of overlapping subproblems and optimal substructure. A problem is said to have overlapping subproblems if it can be broken down into subproblems which are reused multiple times, which is closely related to recursion. The SVC layer selection for J GOPs can be considered as the same problem for $J-1$ GOPs plus one more GOP. A problem is said to have optimal substructure if the globally optimal solution can be constructed from locally optimal solutions to subproblems. We have optimal substructure in the SVC layer selection problem since at any point we only need information about the choices we have already made.

The SVC layer selection subproblem can be solved using the DP method . At first, we define an auxiliary function $\mu_i(j,d)$ as the maximum system utility when we conduct the SVC layer selection over j GOPs, limited by d bits resource budget. When j equals $J+B$ and d equals the maximum received data $d_{i,J+B}^{rec}$, we have $\mu_i(J+B, d_{i,J+B}^{rec}) = G_i(\vec{d}_i^{rec})$. We start the recursion from $\mu_i(0,d)$. We have

$$\mu_i(0,d) = 0, \quad \forall d. \tag{2.8}$$

The recursion function from $\mu_i(j,d)$ to $\mu_i(j+1,d)$ is defined as

$$\mu_i(j+1,d) := \max\{\mu_i(j,d), \mu_i(j, d-d_{used}) + \bar{u}_i(d_{used})\}, \tag{2.9}$$

where $\bar{u}_i(d_{used})$, defined in Section 2.2.4, is the utility gain by assigning data d_{used} for one GOP. When the SVC layer selection problem of j GOPs constrained by d bits data is solved, we can further solve the problem of $j+1$ GOPs constrained by the same d with regard to the recursion function. With the definitions given in Eqs. (2.8) and (2.9), the DP can be easily implemented. We omit the details herein due to lack of space.

The computation complexity of the SVC layer selection subproblem is $O(NJL)$, where N is the maximum number of bits regarding the possible values of d in $\mu_i(J+B,d)$. However, if we substitute N with the maximum number of data units, we can further reduce the complexity of the SVC layer selection subproblem. Remark that the data unit is defined as the greatest common divisor of the data volume among all layers.

2.4.3 Resource Allocation Subproblem

In this subsection, we introduce the relaxation of the utility function at first. Secondly, we convert the resource allocation subproblem to the problem that how to choose a subset of edges over a bipartite graph. Then we prove that this problem belongs to the set of problems that maximize a monotone submodular function subject to a matroid constraint. At last we propose a greedy based algorithm to solve this subproblem.

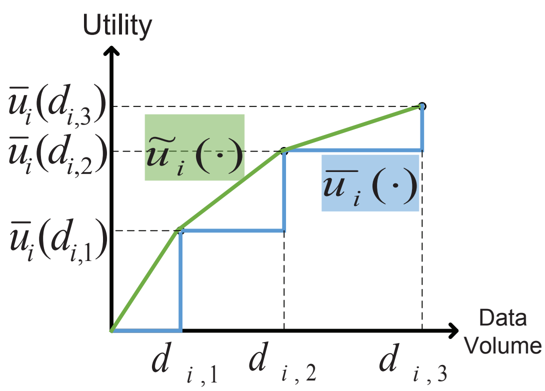

Figure 2-6: The curves of $\tilde{u}_i(\cdot)$ and $\bar{u}_i(\cdot)$ over 3 SVC layers.

As we explained before, $\bar{u}_i(\cdot)$ is a staircase function over a continuous value. We relax the staircase function $\bar{u}_i(\cdot)$ to a continuous utility function $\tilde{u}_i(\cdot)$ as follows,

$$\tilde{u}_i(d) := \bar{u}_i(d_{i,l}) + \frac{d - d_{i,l}}{d_{i,l+1} - d_{i,l}}(\bar{u}_i(d_{i,l+1}) - \bar{u}_i(d_{i,l})), \tag{2.10}$$

for $\forall d \in [d_{i,l}, d_{i,l+1})$. The relationship between $\tilde{u}_i(\cdot)$ and $\bar{u}_i(\cdot)$ is depicted in Fig. 2-6. It is obvious that $\tilde{u}_i(\cdot)$ is non-decreasing and concave.

We define a bipartite graph $\phi = (V_1, V_2, E)$. Define the vertex sets V_1 and V_2, and the edge set E as

$$V_1 := \{i \mid 1 \le i \le I\},$$
$$V_2 := \{k \mid 1 \le k \le K\},$$
$$E := \{(i,k) \mid i \in V_1, k \in V_2\}.$$

The resource allocation subproblem is equivalent to find a subset ψ of the edge set E, which has the property that each vertex k in V_2 cannot be connected to more than one vertex i in V_1. It is obvious that there exits a one to one mapping between ψ and $\vec{\alpha}$. In the rest of this section, we use ψ to substitute the resource allocation $\vec{\alpha}$. The system utility can be expressed as $h(\psi)$.

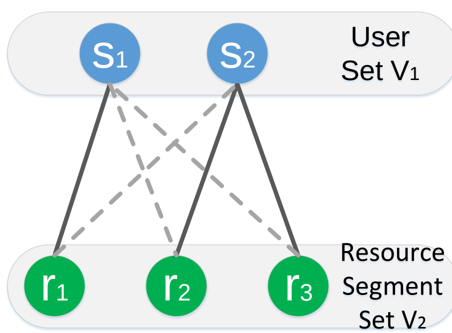

Figure 2-7: Example of resource allocation graph. (2 users, 3 resource segments)

Figure 2-7 shows an example of ϕ when there are 2 users and 3 resource segments. The solid lines in the figure form a valid ψ, i.e., resource segment r_1 is assigned for user s_1, and $\{r_2, r_3\}$ are assigned for user s_2.

Theorem 2.4.1 *(ψ, ϕ) is a matroid for valid ψ.*

Proof: In a bipartite graph $\phi = (V_1, V_2, E)$, if there is a set E', $E' \subseteq E$, and the elements in E' are the vertices on one side of the bipartition, (E', ϕ) is a matroid [88]. Since in a valid ψ, there is no common vertex in V_2 for any two edges, we proved that (ψ, ϕ) is a matroid. ■

Theorem 2.4.2 *$h(\psi)$ is a monotone submodular set function for ψ.*

Proof: Let $\psi^X \subseteq \psi^Y \subseteq E$, and one edge $e \in E \setminus \psi^Y$. Assume that e is an edge between user i' and one resource segment that is allocated for GOP j'. The data volume contained in e is d_e. We have

$$
\begin{aligned}
& h(\psi^X \cup e) - h(\psi^X) \\
& = (\sum_{i \neq i'} \sum_{1}^{J+B} \tilde{u}_i(d^X_{i,l_{i,j}}) + \sum_{j \neq j'} \tilde{u}_{i'}(d^X_{i',l_{i',j}}) \\
& + \tilde{u}_{i'}(d^X_{i',l_{i',j'}} + d_e)) - \sum_{1}^{I} \sum_{1}^{J+B} \tilde{u}(d^X_{i,l_{i,j}}) \\
& = \tilde{u}_{i'}(d^X_{i',l_{i',j'}} + d_e) - \tilde{u}_{i'}(d^X_{i',l_{i',j'}}) \\
& \geq \tilde{u}_{i'}(d^Y_{i',l_{i',j'}} + d_e) - \tilde{u}_{i'}(d^Y_{i',l_{i',j'}}) \\
& = h(\psi^Y \cup e) - h(\psi^Y).
\end{aligned}
$$

The third inequality is true because $\tilde{u}_i(\cdot)$ is non-decreasing and concave as we shown in Section 2.2.4. Therefore, the theorem is proved regarding the definition of the monotone submodular set function [89]. ■

For the problems that maximize a monotone submodular function subject to a matroid constraint, the greedy algorithm achieves an approximation factor of 1/2. When the matroid is uniform, which means the problem is $\max\{f(S) :\mid S \mid\leq H\}$, the greedy algorithm yields a $(1 - 1/e)$-approximation [90][91].

With respect to Theorems 1 and 2, the resource allocation subproblem belongs to such problem set. We have $\mid \psi \mid\leq K$ for any valid ψ. Therefore, a greedy based algorithm could provide a $(1 - 1/e)$-approximation of the resource allocation subproblem. In each step, we choose one edge e with the maximum improvement of $h(\psi \cup e) - h(\psi)$ into the edge set ψ. We omit the details of the greedy algorithm due to the lack of space.

The time complexity of the proposed greedy algorithm is $O(KI)$. Since the time complexity of the SVC layer selection subproblem is $O(NJL)$ for each user. We conclude that the time complexity of RALS is $O(KI + NJLI)$.

2.4.4 RALS with Base Layer Guarantee

The objective of this chapter is to maximize the system utility values. For an example, when we define the utility value as the PSNR value of each GOP, we take the quality of the playback GOPs as our objective to maximize. However, besides the quality of each GOP, the video users may also concern about the playback freeze. Freeze happens when the data of the current playback GOP is not received, even for the base SVC layer. As an extension our previous work [92], we introduce the joint resource allocation and SVC layer selection problem with base SVC layer guarantee as follows.

$$\max_{\{\vec{\alpha},\vec{l}\}} \sum_{i=1}^{I} \sum_{j=1}^{J+B} u_{i,l_{i,j}}, \tag{2.11}$$

subject to

$$\sum_{j=1}^{\tau} (d_{i,l_{i,j}} - d_{i,l_{i,j}^{init}}) \leq d_{i,\tau}^{rec}, \quad 1 \leq i \leq I,$$

$$1 \leq \tau \leq J + B, \tag{2.11C1}$$

$$\max\{l_{i,j}^{init}, 1\} \leq l_{i,j} \leq L_i, \quad 1 \leq i \leq I, 1 \leq j \leq J + B, \tag{2.11C2}$$

$$\alpha_{i,k} \in \{0, 1\}, \quad 1 \leq i \leq I, 1 \leq k \leq K, \tag{2.11C3}$$

$$\sum_{i=1}^{I} \alpha_{i,k} \leq 1, \quad 1 \leq k \leq K. \tag{2.11C4}$$

We extend the optimization problem presented in Eq. (2.5) to a new problem as presented in Eq. (2.11). The objective function and most of the constraints, thus (2.11C1)(2.11C3)(2.11C4) are same. In constraint (2.11C2), notice that the SVC layer selection $l_{i,j}$ for any user i and any GOP j should be no less than 1, thus the base SVC layer level.

The new problem is much harder to solve compared with the original one, since the base layer guarantee is an extremely strong constraint. For most of the cases, there is no solution at all. The reason is that for the video users far from the RSU, it is impossible to let all these users receive all the base layer level GOPs. This will happen even we assign all the resource segments for them, with the poor data rate.

Even though we cannot find any feasible solution for this problem sometimes, we can target this problem and try to reduce the freeze GOP numbers in the proposed RALS algorithm. As an extension of RALS, we present the Resource Allocation and Layer Selection with Base layer Guarantee algorithm (RALS with BG).

The RALS with BG is executed in three steps, thus the base layer guarantee step, the resource allocation step and the SVC layer selection step. For the last two steps, we follow the same scheme as we employed in RALS. We explain the base layer guarantee process as follows.

For a GOP j, the data used to playback this GOP should be already received before the playback. In order to let all video users have enough data to play j with at least base SVC layer level, we should let the users who have not received the base layer data get the resource segments with higher priority. Denote the set of users that have not received the base layer data for GOP j as $\mathcal{I}_j^B$, thus $\mathcal{I}_j^B = \{i \mid l_{i,j} = 0,\ 1 \leq i \leq I, 1 < j \leq J\}$. For one of the resource segments that should be assigned during the playback time of GOP $j-1$, denoted as k, we assign k for the user $i^\star$ in $\mathcal{I}_j^B$ who has the highest data volume contained in k. Thus we have

$$i^\star = \arg\max\{d_{i,k}^{seg} \mid i \in \mathcal{I}_j^B\}, \tag{2.12}$$

where $d_{i,k}^{seg}$ is the data volume contained in k for user i, which is defined in Section 2.2.2.

The base layer guarantee will continue to assign resource segments for users in $\mathcal{I}_j^B$

Table 2.1: Parameter Setting of Video Sequences

Sequence	Layer	Resolution@FPS	Datarate	PSNR
Kendo	1	256×192@8	74.468	28.1496
	2	512×384@32	297.652	37.2694
	3	1024×768@32	710.404	39.2136
Pantomime	1	320×240@8	154.9760	20.1870
	2	640×480@16	590.3520	24.3703
	3	1280×960@32	1755.0160	40.8527

until all users have buffered the base layers for GOP j. The first step of RALS with BG will be finished in two cases. The first case is that all users have buffered the first SVC layer levels as mentioned, and the rest resource segments will be used to assign for other users as the same manner as RALS. The second case is that even all resource segments are assigned for users in $\mathcal{I}_j^B$, the base layers cannot be guaranteed for some users though. In this case, the playback freeze cannot be prevented.

The performance of RALS with BG is shown in Section 2.5.5, and compared with RALS without BG.

2.5 Simulation Results

2.5.1 Simulation Setup

In the simulation, we use JSVM [93] as the SVC encoder. We encoded two video sequences, thus *Kendo* and *Pantomime* [94] in our simulation. The parameters related to the video sequences can be found in TABLE 2.1. We use the PSNR value as the utility value. The PSNR value is calculated between the video received and decoded at the user side and the ground truth (original video) at the server side. We explain the PSNR calculation method in the Section 2.5.2.

A 2000-meter-long highway with multiple lanes in each direction is deployed in the simulation. The RSU is at the middle point of the road, refer to Fig. 2-4. The

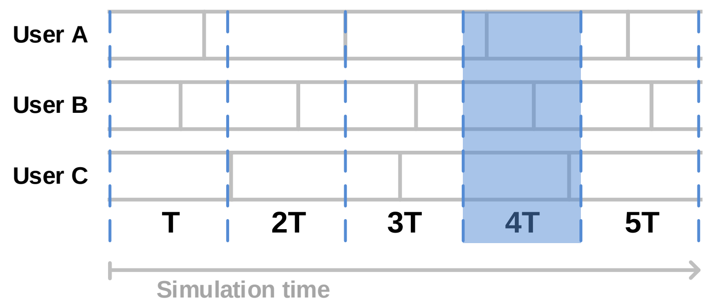

Figure 2-8: Simulation time and sampling interval.

distance from the RSU to the road is 10 m. TABLE 2.2 shows the detailed parameter settings of the highway vehicular network scenario. In the simulation, vehicles are randomly distributed upon the road following the uniform distribution. The velocities of the vehicles are ranging from 80 kmph to 120 kmph. Assume that there are enough lanes to allow all vehicles to run with different velocities without crash.

As defined in the system model section, we let T be the time cost when one vehicle runs through the 2000 m road with the highest speed limit 120 kmph. We have $T = 60$ s. Refer to the definition of J, the number of GOPs J is 120. Moreover, each vehicle has pre-buffered 10 GOPs before we run the simulations. Each buffered GOP has the base SVC layer level. Notice that these initially buffered GOPs are employed to support a smooth playback at the beginning stages of the simulation, and relevant statics are not counted in the simulation results.

We conduct the simulation for as long as $5T$, thus 5 rounds. Suppose we begin the simulation at time 0, we collect the data in $4T$. A simple three-user scenario is shown in Fig. 2-8. When vehicular user A runs out of the range, we assume that a new vehicle $\bar{A}$ runs into the range on the other side of the road. $\bar{A}$ wants to watch the same video as A and has already pre-buffered at most 10 GOPs with the same SVC layer levels as in A's buffer before A runs out. By this way, we generate the traffic on the road with a fixed vehicle number. For simplification, we use the same index A to denote the trace of users $\{A, \bar{A}\}$ and go on in Fig. 2-8. Each block in the figure stands for the time needed to go through the road. Each user enters the road at the beginning of the block and goes out at the end. While at the middle of the block, the user is closest to the RSU. Even though the user number is fixed, the locations of the users are different in each T, because the velocities are randomly generated for the users. By this way we simulate the fixed-user-number road traffic without repeat for each T. Remark that user B is synchronized with T, because we let B has the highest speed.

Note that we conduct the simulation for 5 rounds in order to evaluate the performance of RALS with a more convincing pre-buffered GOP levels, since the SVC layer levels in each user's buffer at the beginning of the fifth round is given by the results of the fourth round.

In the simulation, we initialize the data volume $d_{i,k}^{seg}$ of the resource segment k for user i based on the Shannon capacity equation in Eqs. (2.1)(2.2) with a given distance from i to the RSU. Remark that the location of each vehicle at the time when k is assigned can be calculated when we know the initial location and the velocity of this vehicle.

2.5.2 PSNR Calculation

We discuss the PSNR calculation between the received video with different SVC layer levels and the original uncompressed video in two cases. The first case is when the received video has the same resolution and frame rate with the original video. The PSNR value between each corresponding frame is calculated as follows,

$$PSNR = 10 \log_{10} \frac{255 \times 255}{MSE}, \tag{2.13}$$

where Mean Square Error (MSE) is calculated among all pixels in this frame. Remark that the PSNR value shown in TABLE 2.1 is the average PSNR value among all frames.

The second case is when the resolution or the frame rate of the received video is

Table 2.2: Parameter Setting for the Highway Scenario

Road length (m)	2000
#vehicles on the road I	[20,40,60,80]
Velocity of vehicles (kmph)	random in [80, 120]
RSU location on the road (m)	0
Distance from RSU to the road (m)	10
Bandwidth Z (MHz)	10
Transmission power (mW)	100
Noise (W)	10^{-9}
Pass loss exponent α	3.0
G/R coefficient M	1000
Duration of each round T (s)	60
Duration of GOP t_{GOP}(s)	0.5
Duration of resource segment (ms)	0.5
GOP number J	120
#Pre-buffer GOPs B	10

smaller than the original video. In this case we will up-sample the received video to a reconstructed video with the same resolution and frame rate with the original video at first, then calculate the PSNR between the reconstructed video and the original video.

Denote the original video as V, which has the video setting as $X \times Y@Z$, where X and Y are the length and width of each frame in pixels, and Z is the frame rate. V is encoded into multiple SVC layers with different resolution degrees and frame rate degrees, denoted as D_r and D_f. D_r and D_f are with non-negative integer values. The definitions are given as below. Denote the received video with the resolution degree D_r and the frame rate degree D_f as $\hat{V}$, which has the setting as $\hat{X} \times \hat{Y}@\hat{Z}$, then we have

$$\begin{cases} \hat{X} = 2^{-D_r} X, \\ \hat{Y} = 2^{-D_r} Y, \\ \hat{Z} = 2^{-D_f} Z. \end{cases} \tag{2.14}$$

We use a naive but straightforward up-sampling method to build the reconstructed video, denoted as $\bar{V}$, from the received video $\hat{V}$. The up-sampling method and the calculation of the PSNR value are introduced in three steps shown as follows,

Step 1: In the first step, we raise the frame rate of the received video $\hat{V}$ from $\hat{Z}$ to Z. After this step, we get a reconstructed video, denoted as $\bar{V}_{frame}$, which has the setting as $\hat{X} \times \hat{Y}@Z$. For each frame $\bar{F}_z \in \bar{V}_{frame}, z > 0$, let

$$\bar{F}_z = \hat{F}_{\lceil 2^{-D_f} z \rceil}, \tag{2.15}$$

where $\hat{F}_z$ is a frame in the received video $\hat{V}$.

Step 2: In this step, we do the resolution up-sampling of each frame in $\bar{V}_{frame}$ from $\hat{X} \times \hat{Y}$ to $X \times Y$, then we can get the reconstructed video $\bar{V}$. For each pixel $\bar{P}_{x,y}$ in $\bar{V}$, let

$$\bar{P}_{x,y} = \bar{P}^{frame}_{\lfloor 2^{-D_r} x \rfloor, \lfloor 2^{-D_r} y \rfloor}, \tag{2.16}$$

where (x, y), $x \geq 0, y \geq 0$, is the location of the pixel, and $\bar{P}^{frame}_{x,y}$ is a pixel in $\bar{V}_{frame}$. By this way, $\bar{V}$ with video setting $X \times Y@Z$ is built.

Step 3: Calculate the PSNR values between the reconstructed video $\bar{V}$ and the original video V via Eq. (2.13) frame by frame, and calculate the average PSNR at last.

2.5.3 Comparison Schemes

To better evaluate the performance of the proposed scheme, we compare the result of RALS with Optimal, Maximum Data Rate (MDR) and MUI schemes.

Optimal

The optimal result regarding Eq. (2.5) is calculated by CPLEX [95].

MDR

In the MDR scheme, the resource allocation is conducted in the same way with the proposed RALS algorithm. After the resource is assigned, MDR selects the SVC layer levels for the GOPs one by one. For each GOP, MDR uses all resource segments that received before the playback of this GOP to assign the SVC layer level as high as possible.

MUI

We develop the MUI algorithm as a multi-user version of OSA, proposed in our previous work [69]. Before assigning one resource segment k, MUI calculates the utility increment for each user and assigns this resource segment for the user with the biggest utility increment value. Denote $\Delta u_{i,k}$ as the utility increment of user i, there is

$$\Delta u_{i,k} := \frac{d_{i,k}^{seg}}{d_{i,l} - d_{i,l-1}} \cdot (u_{i,l} - u_{i,l-1}), \tag{2.17}$$

where $d_{i,k}^{seg}$ is the data volume contained in resource segment k for user i, defined in Section 2.2.3. Denote $l-1$ as the current SVC layer level. MUI will upgrade the SVC layer level using the received resource segment from the next GOP to the last GOP one by one.

2.5.4 Analysis

The simulation results are shown in Figs. 2-9 and 2-10. The average values calculated from 10 runs and the maximum and minimum values are shown in the figures. The performances of RALS in different scenarios are presented.

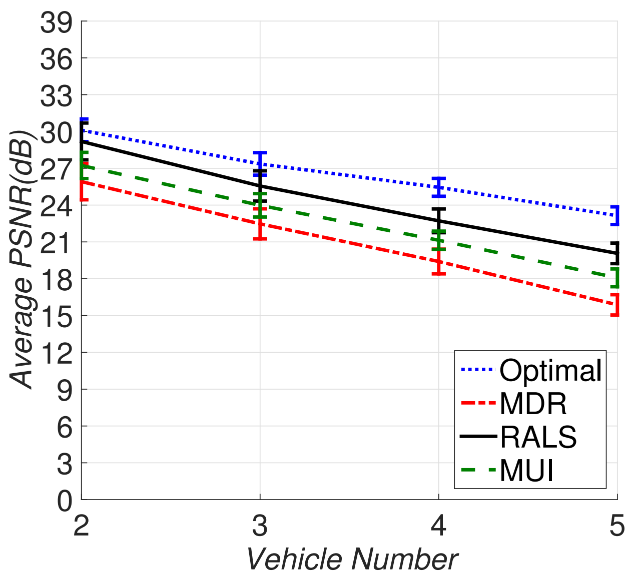

Figure 2-9: Performance comparison with Optimal, MDR and MUI.

At first, we compare the average PSNRs given by RALS with Optimal, MDR and MUI schemes with different vehicle numbers in Fig. 2-9. In this part of simulation, we employ a different parameter setting from TABLE 2.2. Since the computation time of Optimal is extremely long, we degrade the original setting to a much smaller scale. We set the vehicle numbers as [2, 3, 4, 5], the duration of T as 10 s, the number of pre-buffer GOPs as 5, the duration of resource segment as 25 ms and the G/R coefficient M as 20. In order to build a similar load condition with more users' scenarios, the transmission power is decreased from 100 mW to 10 mW. We found that RALS is closer to the optimal solution compared with MDR and MUI.

The average PSNRs for all GOPs regarding the parameters given by TABLE 2.2 are shown in Fig. 2-10. Notice that the average PSNRs keep decreasing when more vehicles are deployed on the road, which is caused by the limited channel capacity. RALS outperforms MDR and MUI in all scenarios. The average PSNR values given by different schemes are closer to each other in 20 users scenario than that in 80 users scenario. The reason is that when there is only a small number of users sharing

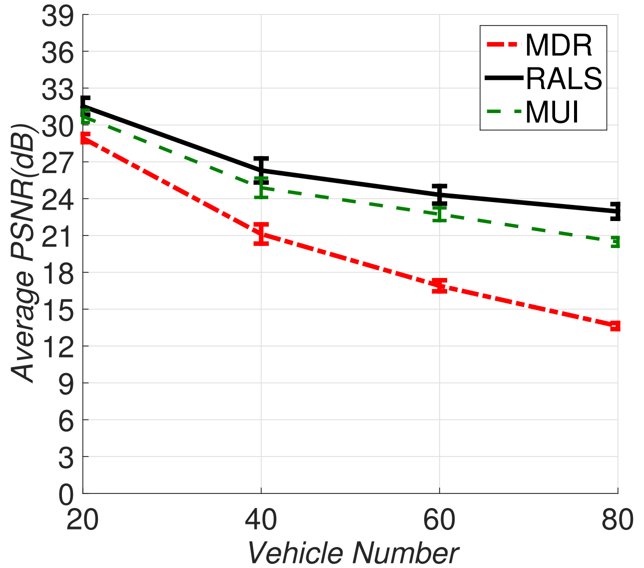

Figure 2-10: Performance comparison with MDR and MUI.

the network resource, usually every user could receive a high quality video, and the performance difference between different schemes is not much.

Figures 2-11 to 2-16 show the layer distributions and average PSNRs when vehicles running through the 2000-meter-long road for 20 and 80 users scenarios. Remark that the SVC layer level 0 stands for the playback freeze.

In Figs. 2-11 and 2-12, we found that the performances of RALS and MDR are similar in [600, 1500] m interval, due to the same resource allocation scheme they employed. Even though RALS and MDR have the same assigned resource segments, RALS could use these resource segments to buffer more GOPs with SVC layer level 3 than MDR. Remark that the first 10 GOPs are pre-buffered GOPs, which are given by the layer selection results in the last running through process.

For RALS in 80 users scenario, shown in Fig. 2-14, we divide the 2000-meter-long road into 4 intervals, [0, 100], [100, 700], [700, 1400] and [1400, 2000]. In [0, 100], the users will play the pre-buffered GOPs. For the GOPs played in [100, 700], all of them are level 0. Users in [100, 700] usually have lower data rates than users in [700, 1400]. As a result, it is hard for these users to receive much resource segments, regarding

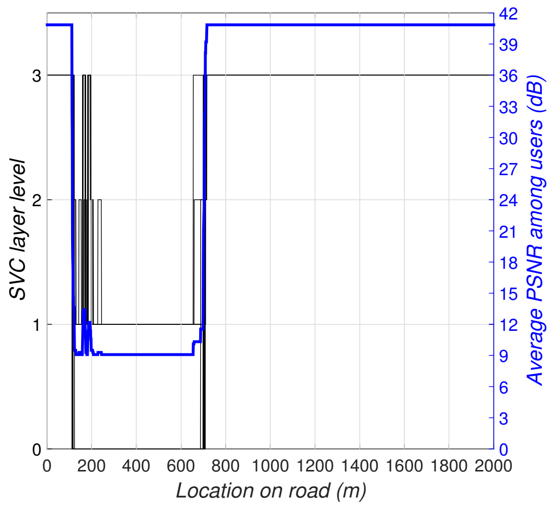

Figure 2-11: RALS for 20 users scenario.

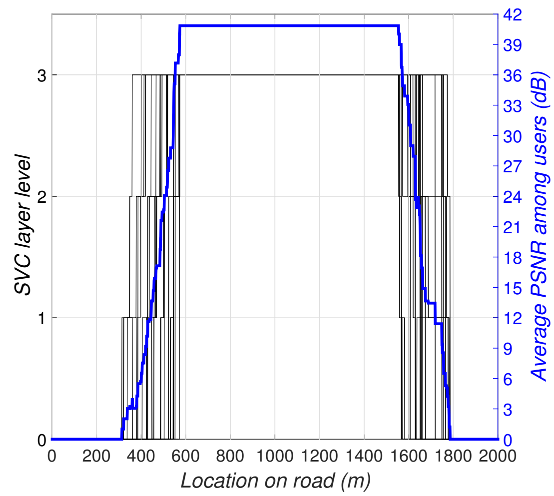

Figure 2-12: MDR for 20 users scenario.

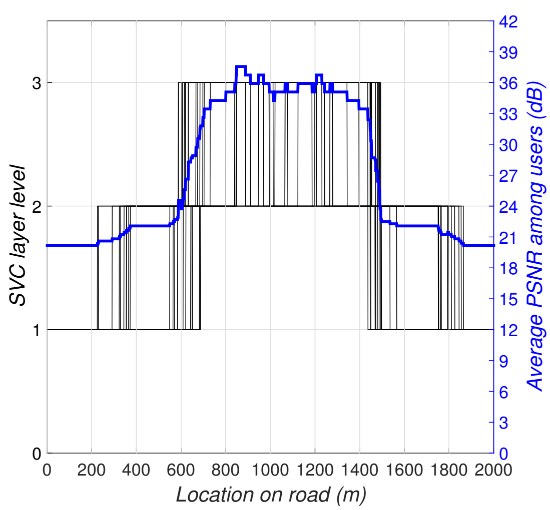

Figure 2-13: MUI for 20 users scenario.

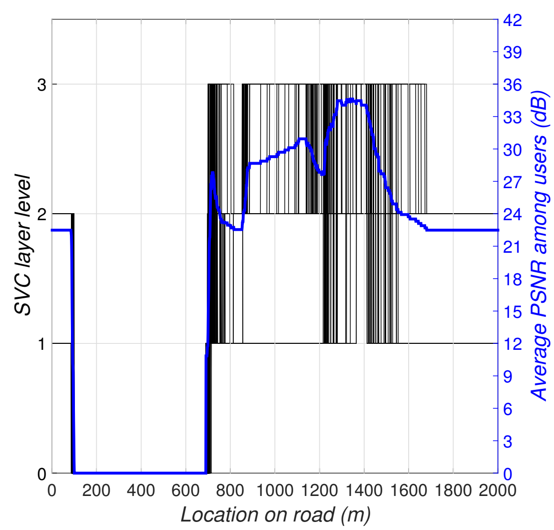

Figure 2-14: RALS for 80 users scenario.

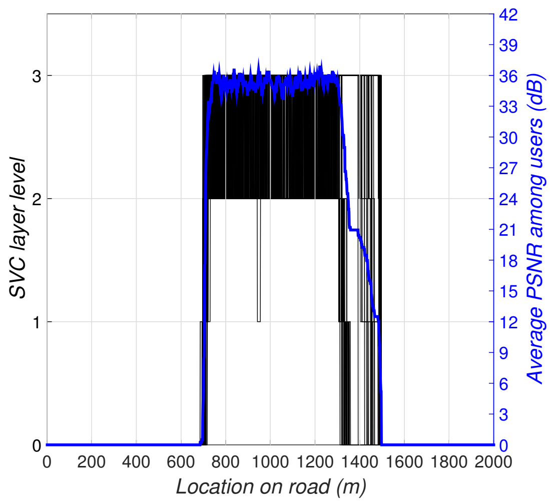

Figure 2-15: MDR for 80 users scenario.

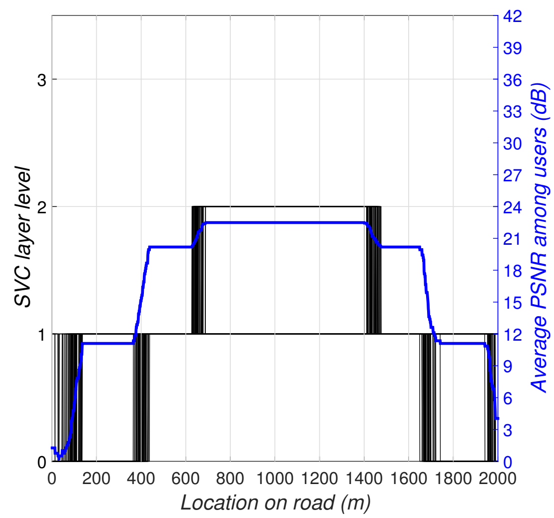

Figure 2-16: MUI for 80 users scenario.

the greedy resource allocation method in RALS. The same situation happens in the interval [1400, 2000]. While in [700, 1400], the users could get enough data to buffer the GOPs that would be played in [700, 1400] plus the pre-buffer GOPs with quite higher SVC layer levels.

For MDR in 80 users scenario, shown in Fig. 2-15, the GOPs played in the interval [0, 700] and [1800, 2000] always have SVC layer level 0, thus freeze. While the GOPs in the interval [700, 1400] usually have higher SVC layer levels compared with RALS. At last, some of the GOPs played in the interval [1400, 1800] are not freeze because the data needed to playback these GOPs may have been already buffered when the users are running in the interval [700, 1400].

For MUI in both 20 and 80 users scenarios, shown in Fig. 2-13 and 2-16, the SVC layer levels are more "flat" than other schemes. Regarding the same resource segment, the utility increment provided by the users that are not close to the RSU may be bigger than the users near the RSU in some cases. For an example, when user X near the RSU has got all GOPs with layer level 1 and user Y which is far from the RSU has got nothing, in this case, Y will probably get the resource segment.

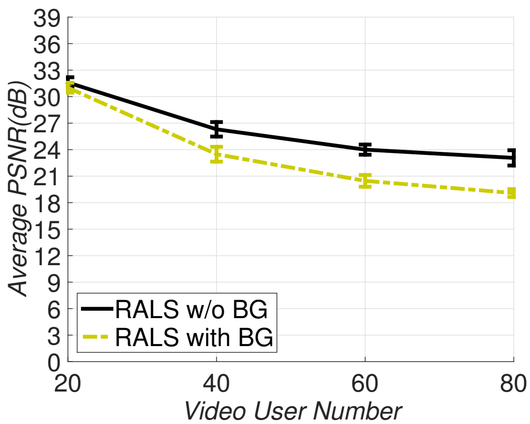

Figure 2-17: The average PSNR values varying the number of video users.

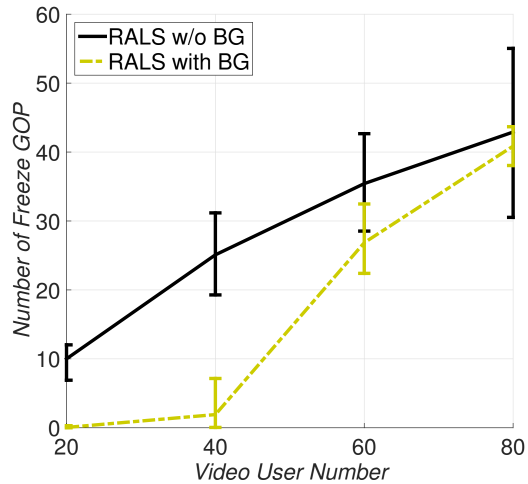

Figure 2-18: The average playback freeze GOP number varying the number of video users.

2.5.5 Base Layer Guarantee

In this section, we present the performance of RALS with BG and compare with the proposed RALS algorithm, thus RALS w/o BG.

At first, we investigated the average PSNR value over each video user and each GOP in Fig. 2-17. Although RALS w/o BG had better performance for all 4 scenarios than RALS with BG obviously, we found that when the number of video users were not much, thus for 20 video users scenario, the average PSNR values were quite close. The reason was already explained in Section 2.5.4, when explaining Fig. 2-10.

Figure 2-18 shows the number of freeze GOPs for 20, 40, 60 and 80 video users scenarios. It is easy to tell that RALS with BG has fewer freeze GOPs than RALS w/o BG. When the video users are not many, like in 20 and 40 users scenarios, the base layer guarantee scheme worked quite well. However, when the video users were many, like 60 and 80 video users, RALS with BG would consume a lot of resource segments to reduce the number of freeze GOPs. But the limited network resource did not allow all users receive all base layer data. As a result, a lot of freeze happened in RALS with BG, and the freeze GOP number when there were 80 users was similar

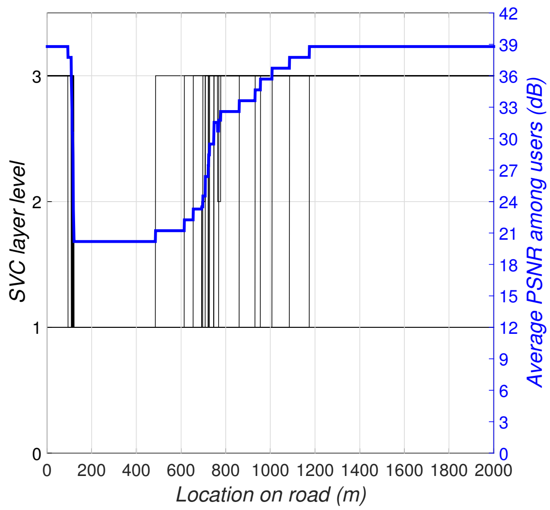

Figure 2-19: RALS with base layer guarantee for 20 users scenario.

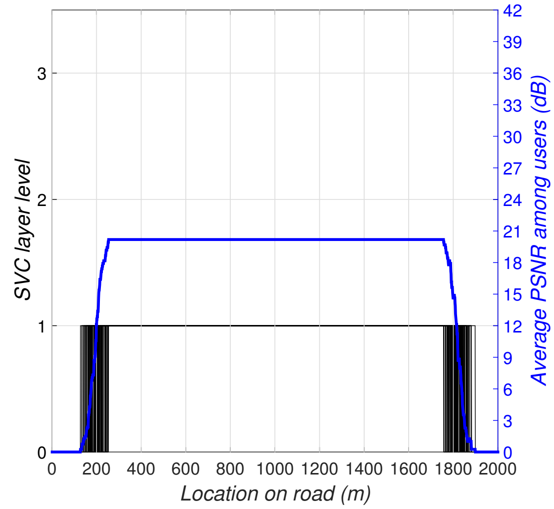

Figure 2-20: RALS with base layer guarantee for 80 users scenario.

to that of RALS w/o BG.

Figures 2-19 and 2-20 showed the SVC layer level distribution and average PSNR value curve of RALS with BG for 20 and 80 video users scenario. In 20 users scenario, we found that RALS with BG had no freeze GOPs in [100, 600] m interval, but the average PSNR value in [600, 1200] was lower than that of RALS w/o BG, which is shown in Fig. 2-11. For 80 users scenario, we notice that almost all users had the base layer level GOP in the interval [200, 1800] m. However, higher SVC layer levels were not found, and the freeze was not evitable in [0, 200] m and [1800, 2000] m.

The base layer guarantee scheme does not work quite well in the current problem, because when we try to let the users that far from the RSU receive enough data for the base layer level playback, we need to assign many resource segments for them due to the poor channel condition. Considering this, we also investigated the similar base layer guarantee scheme in the next chapter Section 3.5.4 in the cooperative vehicular network scenario.

2.5.6 Quality of Experience Evaluation

Unlike PSNR, which explicitly shows the quality of perceived video compared with the original video, Quality of Experience (QoE) refers to how well the perceived video satisfies users' expectations. To evaluate the QoE, most of the researchers use the Mean Opinion Score (MOS). Measuring the MOS was usually done by subjective testing. In order to quantify the MOS, we introduce the ITU-T 5 point Absolute Category Rating (ACR) scale [96], in TABLE. 2.3.

Table 2.3: The ITU-T 5 point ACR scale

MOS	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible but not annoying
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

We discuss the MOS values of the perceived video in two key factors, thus the average video quality and the freeze, denoted as MOS^q and MOS^f. The weighted sum of these two MOS values is evaluated as the MOS value of the perceived video, denoted as MOS.

Average quality

As we know, the PSNR is a well known and commonly used metric to show the quality of perceived video by comparing the differences of each frame with the original video (ground through). We follow the definition of MOS of video quality in [97], which converses the PSNR values to the MOS values according to TABLE. 2.4.

In Section 2.5.2, we already explained how to calculate the PSNR value of each GOP. Denote the video quality MOS value of user i's GOP j is $MOS^q_{i,j}$. Then we have

Table 2.4: PSNR to MOS conversion

PSNR (dB)	MOS
>37	5(Excellent)
31-37	4(Good)
25-31	3(Fair)
20-25	2(Poor)
<20	1(Bad)

$$MOS^q := \frac{\sum_{i=1}^{I}\sum_{j=1}^{J+B} MOS^q_{i,j}}{I(J+B)}. \tag{2.18}$$

Freeze

For the freeze factor, we take the freeze GOP number into consideration. Assume that the freeze GOP number of user i is N. Refer to [98], we define the freeze MOS of user i, thus MOS^f_i, as

$$MOS^f_i := 4.3971 - \frac{6.3484}{1 + (\frac{4400}{Nt_{GOP}})^{0.72134}}. \tag{2.19}$$

The MOS model of playback freeze given by Eq. (2.19) is fitted according to the subjective tests conducted over 23 test persons and 52 test videos. The average MOS among all users is calculated as MOS^f. There is

$$MOS^f := \frac{\sum_{i=1}^{I} MOS^f_i}{I}. \tag{2.20}$$

At last, the MOS of the perceived video MOS is defined as the weighted sum of MOS^q and MOS^f, thus

$$MOS := \lambda MOS^q + (1-\lambda) MOS^f. \tag{2.21}$$

The weight of MOS^q λ is a real number, where $\lambda \in [0, 1]$. Since QoE is a subjective evaluation of the perceived video by humans, how to leverage the weights of different key factors depends on the users' requirements and expectations. We follow the idea that let the penalty of one GOP's freeze equal to a MOS reduction of one GOP's layer level from the highest level to level 0 [99][100]. According to Eqs. (2.18)-(2.21), we have $\lambda = 0.3581$.

Now we evaluate the performances of the proposed RALS and RALS with BG schemes with the MOS values. The MOS values are shown in Fig. 2-21.

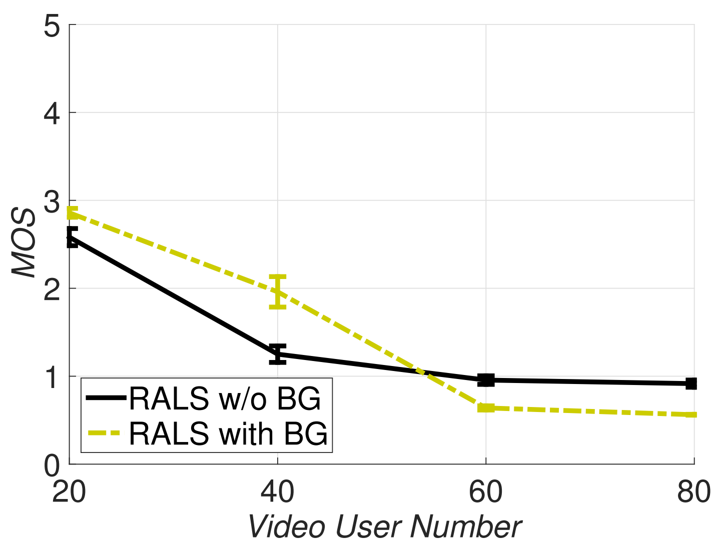

Figure 2-21: MOS comparison of RALS and RALS with BG.

We find that when there are 20 users or 40 users, the MOS values of RALS with BG is better than RALS w/o BG. In this cases, the average qualities of the perceived videos of both schemes are not varying a lot. The key factor the leads to such difference is the freeze GOP number, refer to Figs. 2-17 and 2-18. However, for 60 and 80 users scenarios, many freeze GOPs are found in both schemes. The MOS^f values of both schemes are almost 0. RALS w/o BG is better since it has better average quality MOS.

2.6 Summary

In this chapter, we investigated the multi-user video streaming problem in highway vehicular networks. Our objective is to maximize the system utility values of all video users and all GOPs. The system architecture, video coding model, resource model and utility model are introduced in our system model section. The problem is formulated and decoupled to two subproblems, i.e., the SVC layer selection subproblem and the resource allocation subproblem. The proportional fairness is shown as well. We design the RALS algorithm to solve these two subproblems separately. In RALS, we used the dynamic programing method to solve the SVC layer selection subproblem, and solved the resource allocation subproblem with greedy based resource allocation scheme. The performance of RALS was evaluated by extensive simulations. As shown in the simulation results, the proposed RALS algorithm outperformed other schemes in typical scenarios. Despite the system utility values, the GOP distributions were also shown in the simulation results. The GOP distributions presented the detailed performance in the perspective of each user. As an extension RALS, we designed another algorithm in order to reduce the freeze GOPs number in the playback process, thus RALS with BG. The performance of RALS with BG was shown as well, and compared with RALS w/o BG. The base layer guarantee scheme worked fine when there were not much video users in the communication range.

Chapter 3

Video Streaming over Cooperative Vehicular Networks: Resource Allocation, SVC Layer Selection and Relay Assignment

3.1 Introduction

As an extension of the previous chapter of our work in [101], we focus on the video streaming over cooperative vehicular networks, instead of one-hop scenario. As shown in Fig. 3-1, while the video users want to watch realtime videos on the road, the relay users could not only help the video users located in the direct transmission area improve their data rate, but also enable the video users in the cooperative transmission area to download video data as well, who are out of the RSU coverage with one-hop communication.

There are three challenges in the cooperative video streaming over the vehicular networks issue, due to the limited network resource. The first one is how to assign the limited network resource for multiple users, thus the resource allocation problem.

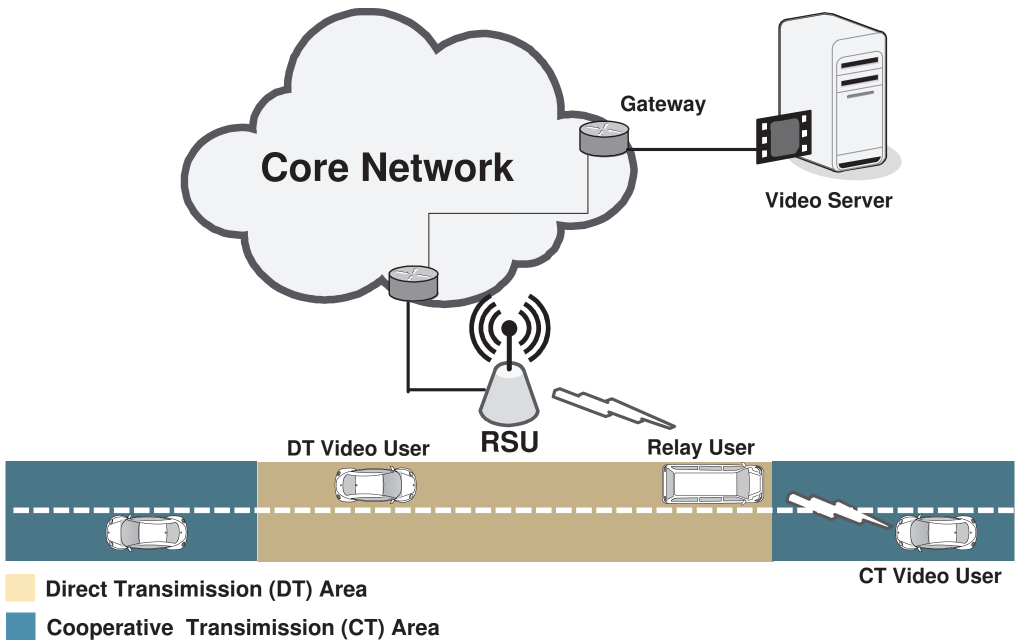

Figure 3-1: Cooperative video streaming over vehicular networks.

The second one is how to decide the SVC layer level for the received video, thus the layer selection problem. The last one is how to assign the relay users for video users, thus the relay assignment problem.

We target the cooperative video streaming over highway vehicular networks problem in this chapter. The core idea of the cooperative communications in vehicular networks is that when the channel between RSU and destination vehicle is unreliable, another vehicle that has much better channel conditions forwards the packets to the destination vehicle, and thus, a significant gain for the whole system is achieved.

The contributions of this chapter are shown as follows:

- The SVC-based video streaming over cooperative vehicular networks is investigated, and we formulate the joint resource allocation, SVC layer selection and relay assignment problem to an integer linear optimization problem.

- We propose a Maximum Utility Increment (MUI) algorithm to solve this problem in two phases: Relay Assignment (RA) phase and Resource allocation and

SVC layer selection (RS) phase. In MUI, we formulate the relay assignment as a Maximum Weighted Bipartite Matching (MWBM) problem, and solve it using Hungarian and Bellman-Ford algorithms in RA. We explicitly take account of the utility value increment of each resource segment among all video users in RS.

- In order to provide a freeze-free playback for each video user, the base layer guarantee mechanism is designed.

- MUI algorithm is evaluated in extensive simulations. Simulation results show that the proposed MUI outperforms all comparison schemes in typical scenarios. Moreover, the Quality of Experience (QoE) of MUI is evaluated as well.

As a reminder of this chapter, Section 3.2 builds up the system model. Formulation of the cooperative SVC video streaming over highway vehicular networks is presented in Section 3.3. In Section 3.4, we describe the proposed MUI algorithm in details, and designed MUI with base layer guarantee scheme to reduce playback freeze. Section 3.5 shows the setup of the simulations and evaluates the performance of the proposed schemes. At last, the chapter is concluded in Section 3.6.

3.2 System Model

3.2.1 System Architecture

In this chapter, we extend the multiple users scenario as we introduced in Chapter 2 to the cooperative scenario. As shown in Fig. 3-1.

We consider a cooperative vehicular network with one RSU and multiple vehicular users on the road. We follow the highway model as mentioned in Section 2.2.1 and the video setting as mentioned in Section 2.2.2. Denote the part of the road in the communication range of the RSU as the Direct Transmission (DT) area. The part of the road on which the users can communicate with the RSU through at most one-hop relay as the Cooperative Transmission (CT) area. While some users in either DT or CT area want to watch realtime videos through the RSU, some users in DT area perform as voluntary relay users. Denote the users who require SVC encoded videos in the DT range and do not need relay user to assist them as direct video users. Correspondingly, denote the users that assisted by relay users as the cooperative video users. Remark that the users in the DT area could be cooperative video users as well, if they are assisted by relay users.

The proposed scheduling algorithm is executed at the RSU or at a specific scheduling center, in a round-by-round fashion once and again after a certain time period. We call this scheduling time period as the Scheduling Time Window (STW), and the duration of each STW is denoted as T. Generally speaking, a shorter STW could give us more accurate results, in the sense of higher throughput, better received video quality, etc. However the STW length is limited by how frequent we can change the relay assignment. When one relay is assigned for one video user, it cannot be switched/reassigned for another video user in a short time period shorter than STW.

Suppose t_0 is the start time of one round. Denote I as the number of video users that can communicate with the RSU, directly or cooperatively, in the time period $[t_0, t_0 + T]$, and want to watch realtime videos via the vehicular networks. The number of relay users are R. The network resource provided by the RSU is shared by all these users. In the rest of this chapter, we use the index of each user i to represent the user itself.

3.2.2 Relay Assignment Model

When the RSU is transmitting data to one video user, relay users in the RSU coverage can overhear the data as well, due to the broadcast nature of wireless communication, as demonstrated in a three users example in Fig. 3-2(a). This property gives relay users the chance to help video users improve the quality of communication. The co-

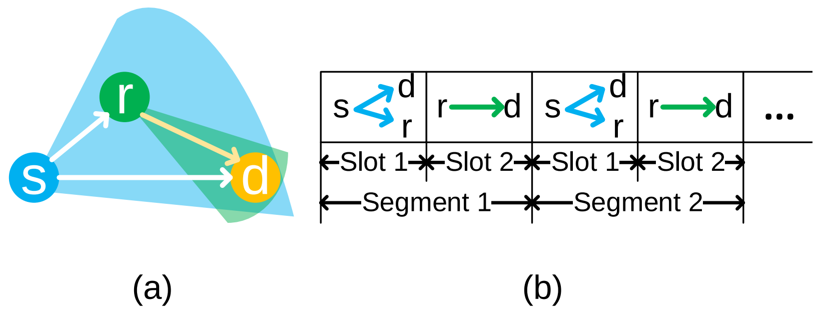

Figure 3-2: A three users example of cooperative communication.

operative communication proceeds in a segment-by-segment fashion. Each resource segment is divided into two time slots. The RSU transmits data to the video user in the first time slot. Relay users overhear this transmission in the first time slot as well. In the second time slot, one relay user forwards the data to the video user using different techniques depending on different cooperative modes, as shown in Fig. 3-2(b). There are two popular cooperative modes, Amplify-and-Forward (AF) and Decode-and-Forward (DF) [102][103]. In AF relaying, the relay terminal transmits a scaled version of received signal without decoding the message. In DF relaying, the relay terminal decodes its received signal and then re-encodes it for transmission to the destination, thus requiring higher processing requirements as the signals have to be processed at the relays before being forwarded. DF provides substantial performance gain by improving communication reliability, which is essential for communication systems. The fundamental destructive effect encountered in AF-based wireless networks is the re-transmission of the amplified version of the noise terms while the most important problem in DF-based cooperative systems is the error propagation due to the decoding errors at relay terminals which cause reduction in the effective SNR at the destination. In general, both modes achieve diversity gain and outperform the equivalent single-input single-output, which only uses the direct link.

Denote the RSU as s (sender), a video user as p (destination) and a relay user as r (relay). Regarding different transmission modes, the link capacities between the RSU and the video user in different modes are calculated as follows.

- **Direct Transmission**

  In direct transmission mode, no relay is employed. Both time slots in each resource segment are used for directly transmitting video data for the video user. The link capacity $C(s,p)$, which is already defined in Section 2.2.3, is calculated as follows.

  $$C(s,p) = Z\log_2(1 + SNR_{s,p}),$$

  where Z is the bandwidth of the channel. $SNR_{s,p}$ is the signal to noise ratio defined in Section 2.2.3. In order to distinguish the capacity between the direct transmission and cooperative transmission, we use $C_{DT}(s,p)$ to denote the link capacity of direct transmission.

- **AF Transmission**

  In AF mode, the relay user r overhears the signal from the RSU s in the first time slot. In the second slot r amplifies the received signal and transmits it to p. The total achievable capacity $C_{AF}(s,r,p)$ [102] is

  $$C_{AF}(s,r,p) = \frac{Z}{2}\log_2(1 + SNR_{s,p} + \frac{SNR_{s,r} \cdot SNR_{r,p}}{SNR_{s,r} + SNR_{r,p} + 1}). \tag{3.1}$$

- **DF Transmission**

  When employing the DF mode, relay user r will decode and estimate the signal received from the RSU in the first time slot. Then r encodes and retransmits the estimated data to the video user in the second time slot. The total achievable capacity for DF mode, denoted as $C_{DF}(s,r,p)$, is

  $$C_{DF}(s,r,p) = \frac{Z}{2}\min\{\log_2(1 + SNR_{s,r}), \log_2(1 + SNR_{s,p} + SNR_{r,p})\}. \tag{3.2}$$

The proposed MUI algorithm can be equally applied in AF and DF modes, as long as we can get the network information to calculate $SNR_{s,p}$, $SNR_{s,r}$ and $SNR_{r,p}$ from the RSU. In vehicular networks environment, we find that both AF and DF are feasible for the cooperative communication. Research about both AF and DF, or adaptive AF/DF selection have been done by fellow researchers [104][105].

When the RSU tries to assign a relay user for one video user to improve its throughput, it is not necessary to assess all the available relay users on the road. Actually each video user has a certain feasible relay range, denoted as $[\theta, \eta]$. Only the relay users in this range can improve the throughput of this video user. In $[\theta, \eta]$, there is

$$\begin{cases} C_{DT}(s,p) \leq C_{AF}(s,r,p), & \text{in AF mode;} \\ C_{DT}(s,p) \leq C_{DF}(s,r,p), & \text{in DF mode.} \end{cases} \tag{3.3}$$

According to the definitions of $C_{DT}(s,p)$, $C_{AF}(s,r,p)$ and $C_{DF}(s,r,p)$, we have

$$\begin{cases} (1+SNR_{s,p})^2 \leq 1+SNR_{s,p}+\frac{SNR_{s,r}\cdot SNR_{r,p}}{SNR_{s,r}+SNR_{r,p}+1}, & \text{in AF mode;} \\ (1+SNR_{s,p})^2 \leq \min\{1+SNR_{s,r}, 1+SNR_{s,p}+SNR_{r,p}\}, & \text{in DF mode.} \end{cases} \tag{3.4}$$

Based on the definition of SNR in Eq. (2.1), there is

$$\begin{cases} (1+\frac{P}{|X_s-X_p|^{\gamma}\cdot N_0})^2 \leq 1+\frac{P}{|X_s-X_p|^{\gamma}\cdot N_0}+\frac{\frac{P}{|X_s-X_r|^{\gamma}\cdot N_0}\cdot\frac{P}{|X_r-X_p|^{\gamma}\cdot N_0}}{\frac{P}{|X_s-X_r|^{\gamma}\cdot N_0}+\frac{P}{|X_r-X_p|^{\gamma}\cdot N_0}+1}, & \text{in AF mode;} \\ (1+\frac{P}{|X_s-X_p|^{\gamma}\cdot N_0})^2 \leq \min\{1+\frac{P}{|X_s-X_r|^{\gamma}\cdot N_0}, 1+\frac{P}{|X_s-X_p|^{\gamma}\cdot N_0}+\frac{P}{|X_r-X_p|^{\gamma}\cdot N_0}\}, & \text{in DF mode.} \end{cases} \tag{3.5}$$

When the locations of the RSU X_s and the video user X_p are known, we can calculate θ and η as follows. Since $C_{AF}(s,r,p)$ and $C_{DF}(s,r,p)$ are continuous functions regarding the X_r value, the feasible relay range boundaries θ and η are two of the valid solutions/roots of X_r in the equations $C_{DT}(s,p) = C_{AF}(s,r,p)$ in AF mode and $C_{DT}(s,p) = C_{DF}(s,r,p)$ in DF mode. By solving these equations, we find θ and η among all the solutions/roots. Remark that the values of θ and η should be between X_s and X_p. It is also possible that the equations do not have solutions between the location of the user and the location of the RSU. This will happen when the user is very close to the RSU, and DT will provide higher throughput than CT no matter where the relay user is located.

However, the closed-form expressions of θ and η cannot be presented, since such values are the roots of high degree equations, as shown in Eq. (3.5). For an example, when we follow the parameter setting in TABLE. 2.2, θ and η are the roots of sextic equations. Remark that the value of the pass loss exponent γ in Eq. (2.1) is usually between 2.4 to 4.

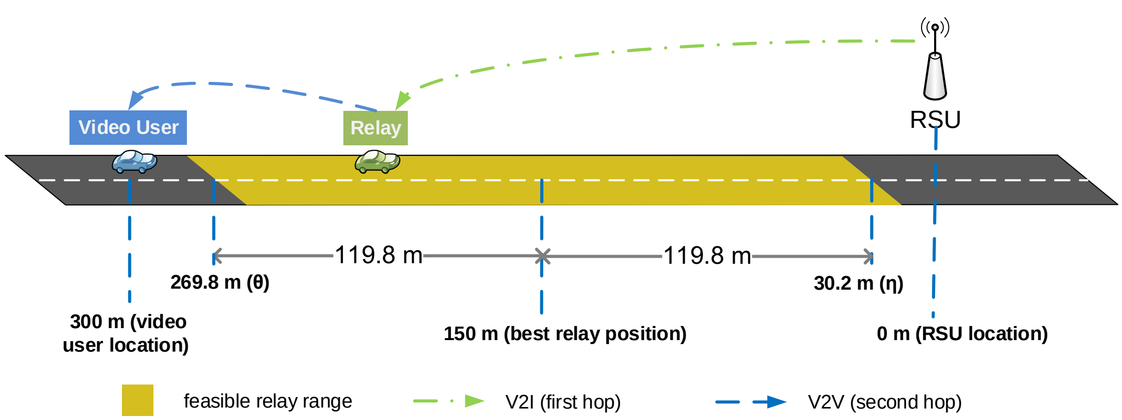

Figure 3-3: The feasible relay range when the distance between the RSU and the relay user is 300 m in AF mode.

Figure 3-3 shows an example of the feasible relay range when the distance between the RSU and the video user is 300 m. The parameter settings are the same with

TABLE. 2.2 in AF mode. In this case, the feasible relay range is $[30.2, 269.8]$ m. The location of the relay with the best throughput is also shown in the figure. Since the transmission power of the RSU and the relay user is the same and the vertical distance from the RSU to the road is quite small, the best relay position is almost right in the middle of the RSU and the video user.

When we focus on the relay assignment issue, some limitations should be considered. In $[t_0, t_0 + T]$, each relay user can be assigned for no more than one video user at the same time, and cannot be switched to another user before $t_0 + T$. Also, we assume that one video user cannot employ more than one relay user. As a result, the relay assignment problem is a one to one match among video users and relay users.

Denote $\vec{\beta} := \{\beta_{i,r} \in \{0,1\} \mid 1 \leq i \leq I, 0 \leq r \leq R\}$ as the resource allocation vector. We assign the relay user r for the user i when $\beta_{i,r}$ equals one and vice versa. Remark that when $1 \leq r \leq R$, r is the index of one relay user. While $r = 0$ stands for using the direct transmission method instead of cooperative transmission.

3.2.3 Resource Model

In this chapter, we follow the resource model in Section 2.2.3 . The network resource is divided into resource segments.

We assume the time duration of each resource segment is fixed and there are M resource segments in the duration of one GOP. The integer constant M is defined as the G/R coefficient, which is short for the GOP playback time/Resource segment time coefficient. Thus the number of resource segments is $K = MJ$.

Denote $\vec{\alpha} := \{\alpha_{i,k} \in \{0,1\} \mid 1 \leq i \leq I, 1 \leq k \leq K\}$ as the resource allocation vector. We assign the resource segment k for the user i when $\alpha_{i,k}$ equals one and vice versa.

Figure 3-4 shows a valid SVC layer selection and resource allocation result for a simple cooperative scenario, which is extended from Fig. 2-4 in Section 2.2.3. The first 5 resource segments out of 8 resource segments in total are assigned for user A.

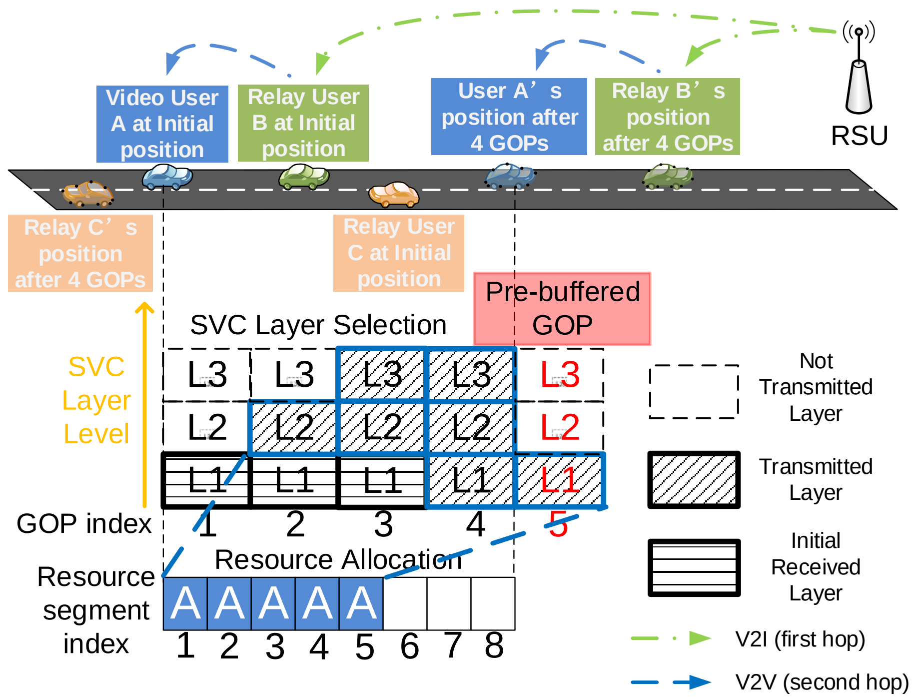

Figure 3-4: Cooperative SVC layer selection, resource allocation and relay selection for user A in 5 GOPs ($J = 4$ and $B = 1$), 3 SVC layer levels, 8 resource segments, 2 available relay users and $M = 2$ scenario.

Cooperative communication is employed to improve the throughput. Two available relay users, thus relay user B and C are deployed on the road. A has three choices in this scenario: DT, CT with B and CT with C. In CT mode, the RSU transmits the video data to the relay user using V2I communication as the first hop. Then the relay user forwards the video data to A using V2V communication as the second hop. We notice that even C would provide a better throughput for A, it is not a good choice to select C as the relay user, since the direction of C is different with A, and will run far away from the RSU later. As a result, A will select B as the relay user.

The G/R coefficient is 2. There are 8 resource segments, in which the first 5 resource segments are assigned for A. The layer selection results are $\{1, 2, 3, 3, 1\}$ for these GOPs.

Assume that the SNR values between the users and the RSU at each time are already known. The data volume contained in each resource segment can be obtained from the Shannon capacity formula [81]. Define the data volume of the resource segment k for user i that assisted by relay user r as $d^{seg}_{i@r,k}$. Remark that the DT is also included in this expression when we let $r = 0$.

3.2.4 Utility Model

We follow the utility definition introduced in Section 2.2.4. Our objective is to maximize the system utility, i.e., $\sum_{i=1}^{I}\sum_{j=1}^{J+B}(u_{i,l_{i,j}} - u_{i,l^{init}_{i,j}})$. Since $l^{init}_{i,j}$ is a fixed value, we can eliminate $u_{i,l^{init}_{i,j}}$ in the expression. In the objective function, the GOP number of each user is the same and each GOP of each user is calculated only once in the objective function. Moreover, the function to calculate the utility value, like PSNR value, of each GOP is usually a log-like function, i.e., as the SVC layer level increases, the increment of the utility value is becoming smaller.

3.3 Formulation

We define $d^{rec}_{i,j}$ as the received data before the playback of GOP j, i.e.,

$$d^{rec}_{i,j} := \sum_{k=1}^{MV_j}\sum_{r=0}^{R}\alpha_{i,k}\beta_{i,r}d^{seg}_{i@r,k}, \quad 1 \le i \le I, 1 \le j \le J+B, \tag{3.6}$$

where V_j is defined as

$$V_j := \begin{cases} j, & 1 \le j \le J; \\ J, & J < j \le J+B. \end{cases} \tag{3.7}$$

The meaning of V_j is that, since $\{J+1, ..., J+B\}$ are pre-buffered GOPs and there is no more resource segment to assign by the RSU after GOP J, the received data before the playback of the pre-buffered GOPs is equal to the received data before the playback of GOP J. We define $\vec{d}_i^{rec} := \{d_{i,j}^{rec} \mid 1 \leq j \leq J+B\}$ as the received data vector for user i.

Regarding the definition of $\beta_{i,r}$, $\sum_{r=0}^{R} \beta_{i,r} d_{i@r,k}^{seg}$ is the achievable data volume when the resource segment k is assigned for user i based on the relay assignment $\vec{\beta}$.

The problem formulation is shown as follows,

$$\max_{\{\vec{\alpha},\vec{\beta},\vec{l}\}} \sum_{i=1}^{I} \sum_{j=1}^{J+B} u_{i,l_{i,j}}, \tag{3.8}$$

subject to

$$\sum_{j=1}^{\tau} (d_{i,l_{i,j}} - d_{i,l_{i,j}^{init}}) \leq d_{i,\tau}^{rec}, \quad 1 \leq i \leq I,$$

$$1 \leq \tau \leq J+B, \tag{3.8C1}$$

$$l_{i,j}^{init} \leq l_{i,j} \leq L_i, \quad 1 \leq i \leq I, \ 1 \leq j \leq J+B, \tag{3.8C2}$$

$$\alpha_{i,k} \in \{0,1\}, \quad 1 \leq i \leq I, \ 1 \leq k \leq K, \tag{3.8C3}$$

$$\sum_{i=1}^{I} \alpha_{i,k} \leq 1, \quad 1 \leq k \leq K, \tag{3.8C4}$$

$$\beta_{i,r} \in \{0,1\}, \quad 1 \leq i \leq I, \ 0 \leq r \leq R, \tag{3.8C5}$$

$$\sum_{i=1}^{I} \beta_{i,r} \leq 1, \quad 1 \leq r \leq R, \tag{3.8C6}$$

$$\sum_{i=r}^{R} \beta_{i,r} \leq 1, \quad 1 \leq i \leq I. \tag{3.8C7}$$

Constraint (3.8C1) shows the network resource constraint for the SVC video playback. Before the playback of GOP j, the user should have already received enough data to playback the GOPs $\{1, ..., j\}$ with the selected SVC layer level $l_{i,j}$. $\alpha_{i,k}$ and $\beta_{i,r}$ are 0-1 integers, shown in constraint (3.8C3)(3.8C5). Constraint (3.8C4) shows the constraint that each resource segment cannot be assigned for more than one user. Constraint (3.8C6) shows that for each relay user, it cannot be assigned for more than one video user in $[t_0, t_0+T]$. Remark that $r = 0$ is not included in Constraint (3.8C6), since $r = 0$ stands for the video user will use DT instead of CT, which means it is possible that multiple video users select $r = 0$ in $[t_0, t_0 + T]$. Since the relay users and the video users are one to one match, constraint (3.8C7) shows that each video user cannot employ more than one relay user.

The problem shown by Eq. (3.8) is NP-hard, since the joint resource allocation and SVC layer selection problem proposed in Eq. (2.5) is NP-hard, which we already explained in Section 2.3. Problem (3.8) can be considered as a special case when we let all users use DT in Eq. (3.8). In order to get a solution that has comparable utility value with the optimal solution, and can be computed in polynomial time, we introduce the proposed MUI algorithm.

3.4 Algorithm

We propose a Maximum Utility Increment (MUI) algorithm to do the resource allocation, relay selection and SVC layer selection. In MUI we explicitly take the utility into consideration, since the object of this chapter is to maximize the system utility value.

The basic idea of MUI is that, we assign the resource segments in RSU one by one for the video users. For each resource segment, we will allocate this segment for the user with the maximum segment utility increment gain.

3.4.1 Segment Utility Increment

We define the segment utility increment of direct video users as

$$\Delta u_{i,r,k} := \frac{d^{seg}_{i@r,k}}{d_{i,l} - d_{i,l-1}} \cdot (u_{i,l} - u_{i,l-1}), \tag{3.9}$$

where $d^{seg}_{i@r,k}$ is the data volume contained in resource segment k for user i assisted by relay user r, defined in Section 3.2.2 . Remark that DT and CT are equally considered in $\Delta u_{i,r,k}$, correspondingly there is $r = 0$ or $1 \leq r \leq R$. Denote $l - 1$ as the current SVC layer level. MUI will upgrade the SVC layer level using the received resource segment from the next GOP to the last GOP one by one. We will discuss the MUI in details as follows.

3.4.2 Relay Assignment (RA) Phase

Regarding the definition of segment utility increment $\Delta u_{i,r,k}$ given in Eq. (3.9), before we compare each video user's segment utility increment value, we should know which relay user is assigned to assist it in CT mode, or it will directly receive date from the RSU without relay user in DT mode. In this section, we introduce the relay assignment mechanism in the proposed MUI algorithm.

Denote the set of video users as $\mathcal{I}$ and the set of relay users as $\mathcal{R}$. As we discussed in the previous part, the video users in $\mathcal{I}$ and the relay users in $\mathcal{R}$ are one-to-one match. However, with the definitions of $\mathcal{I}$ and $\mathcal{R}$, it is not enough to represent the relay assignment problem, since the DT mode is not considered yet. We extend the relay set $\mathcal{R}$ to a reconstructed set $\bar{\mathcal{R}}$. Define

$$
\begin{aligned}
&\mathcal{I} := \{i \ \mid \ 1 \leq i \leq I\},\\
&\bar{\mathcal{R}} := \{r \ \mid \ 1 \leq r \leq R\} \cup \mathcal{I},\\
&\mathcal{E} := \{(i, r) \ \mid \ i \in \mathcal{I}, r \in \mathcal{R}\} \cup \{(i, i) \ \mid \ i \in \mathcal{I}\}.
\end{aligned}
$$

With such definitions, we build a bipartite graph $(\mathcal{I}, \bar{\mathcal{R}}, \mathcal{E})$. The relay assignment problem can be transformed to find a subset of $\mathcal{E}$. Denote such subset as $\mathcal{E}^{\star}$, which fulfills the one-to-one match constraint as well. Remark that when there is an edge $(i, r), i \in \mathcal{I}, r \in \mathcal{R}$ in $\mathcal{E}^{\star}$, this edge stands for assigning the relay user r for user i. While when there is an edge $(i, i), i \in \mathcal{I}$, it means user i selects DT mode without any relay user.

In order to solve the relay assignment problem expressed as graph $(\mathcal{I}, \bar{\mathcal{R}}, \mathcal{E})$, we define a weight function $w(e)$, over each edge $e \in \mathcal{E}$. The definition of $w(e)$ is given as below.

$$w(e) := \begin{cases} d^{seg}_{i@r,k}, & e \in \{(i,r) \mid i \in \mathcal{I}, r \in \mathcal{R}\}; \\ d^{seg}_{i@0,k}, & e \in \{(i,i) \mid i \in \mathcal{I}\}. \end{cases} \tag{3.10}$$

So the weight over each edge is defined as the data volume regarding the resource segment k. It is rational that a proper relay assignment is given by the case when the total weight values regarding $\mathcal{E}^\star$ are maximized. As a result, the relay assignment problem is transformed to the Maximum Weighted Bipartite Matching (MWBM) problem [106][107].

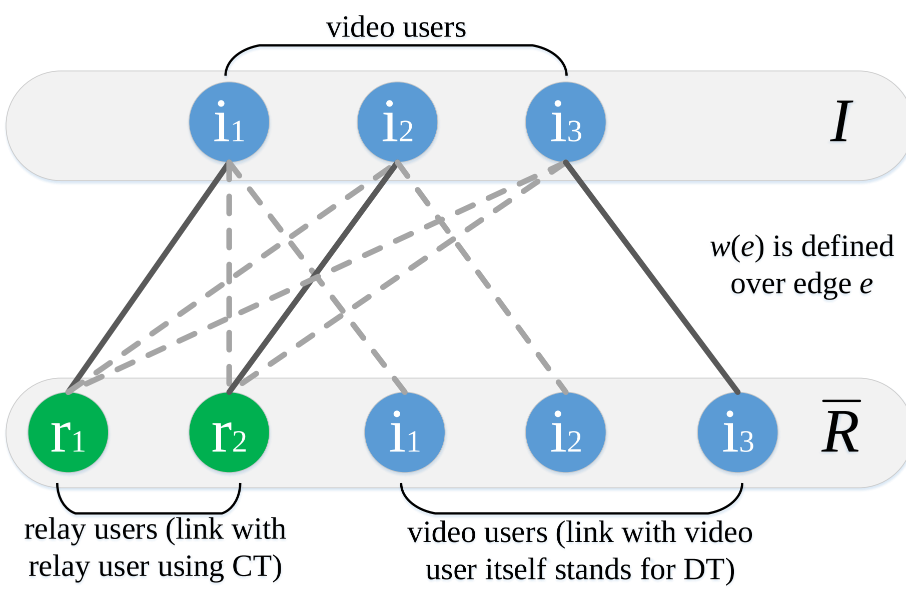

Figure 3-5: MWBM problem for 3 video users and 2 relay users.

In Fig. 3-5, we show a simple example of the proposed MWBM problem with 3 video users and 2 relay users. The dash lines between the elements in $\mathcal{I}$ and elements in $\bar{\mathcal{R}}$ are all possible relay assignments. Remark that the link with video user itself stands for using direct transmission instead of cooperative transmission. The weight function is defined on each edge. The solid lines show a feasible relay assignment solution with the one to one match constraint. To solve the MWBM problem, we introduce the theorem as below.

Theorem 3.4.1 *MUI guarantees to find the optimal relay assignment result in the MWBM problem* $(\mathcal{I}, \bar{\mathcal{R}}, \mathcal{E}, w)$ *with computational complexity* $O(I^2R)$*.*

Regarding this MWBM problem, the well known Hungarian algorithm [108][109] and Bellman-Ford [110][111] algorithm give the optimal result in $O(I^2R)$. The correctness of Theorem 3.4.1 is obvious. The Hungarian algorithm, also known as Kuhn-Munkres algorithm or Munkres assignment algorithm, is a combinatorial optimization algorithm that solves the assignment problem in polynomial time. The assignment problem is presented as follows. Assume that we have N workers and N jobs that should be done. For each pair (worker, job) we know salary that should be paid to worker for him to perform the job. Our goal is to complete all jobs minimizing total inputs, while assigning each worker to exactly one job and vice versa. The assignment problem is a special case of the transportation problem, which in turn is a special case of the min-cost flow problem, so it can be solved using algorithms that solve the more general cases. Also, our problem is a special case of binary integer linear programming problem (which is NP-hard). The Hungarian algorithm is based on the fact that if a number is added to or subtracted from all of the entries of any one row or column of a cost (salary) matrix, then on optimal assignment for the resulting cost matrix is also an optimal assignment for the original cost matrix.

Like Dijkstra's Algorithm [112], Bellman-Ford is based on the principle of relaxation, in which an approximation to the correct distance is gradually replaced by more accurate values until eventually reaching the optimum solution. In both algorithms, the approximate distance to each vertex is always an overestimate of the true distance, and is replaced by the minimum of its old value with the length of a newly found path. However, Dijkstra's algorithm uses a priority queue to greedily select the closest vertex that has not yet been processed, and performs this relaxation process on all of its outgoing edges; by contrast, the Bellman-Ford algorithm simply relaxes all the edges, and does this $| V | -1$ times, where $| V |$ is the number of vertices in the graph. In each of these repetitions, the number of vertices with correctly calculated distances grows, from which it follows that eventually all vertices will have their correct distances. This method allows the Bellman-Ford algorithm to be applied to a wider class of inputs than Dijkstra. Bellman-Ford runs in $O(| V || E |)$ time, where $| V |$ and $| E |$ are the number of vertices and edges respectively. Cooperated with the Bellman-Ford algorithm, the computation time of the Hungarian algorithm is further improved.

We notice that even the optimal relay assignment regarding resource segment k is not hard to get, as for different resource segments, the optimal relay assignment regarding each k can be different as well. However, the relay assignment cannot be changed that fast to meet the requirement of each resource segment in $[t_0, t_0 + T]$. Since for each T, we can change the relay assignment for only once, we take the resource segment $\bar{k}$ which is located right in the middle point of $[t_0, t_0 + T]$ as the one to evaluate. We have

$$\bar{k} = \frac{1}{2}MJ, \tag{3.11}$$

where M is the G/R coefficient as defined in Section 3.5.2, and J is the number of GOPs in $[t_0, t_0 + T]$.

3.4.3 Resource Allocation and SVC Layer Selection (RS) Phase

Suppose that user i has already known how much data, thus $d_{i,j}^{rec}$, it will get before the playback of GOP j. One choice is that it can buffer GOP j as the highest SVC layer level as it can, up to the data volume limit of $d_{i,j}^{rec}$. However, another choice is that to buffer more SVC layers for the GOPs after J as well, and try to keep all the GOPs $\{j, j+1, ..., J+B\}$ with the same SVC layer level and upgrade the SVC layer levels one by one gradually from j to $J+B$.

Since the utility has the property that $u_{i,l}$ is non-decreasing and concave over the discrete $\{1, 2, ..., L_i\}$ values for user i. The second way to do the SVC layer selection is a better choice. Because by doing the SVC layer selection like this, we may use the limited network resource to gain more segment utility increment. In MUI, we will buffer the SVC layers for all the GOPs from j to $J + B$, and upgrade the SVC layer level one by one gradually from $\min\{L_{i,\hat{j}}^{init} \mid j \leq \hat{j} \leq J + B\}$ to the highest layer level. In Eq. (3.9), we let the current SVC layer level $l - 1 = \min\{L_{i,\hat{j}}^{init} \mid j \leq \hat{j} \leq J + B\}$ and video user $i = \arg\min\{L_{i,\hat{j}}^{init} \mid j \leq \hat{j} \leq J + B\}$.

As a summary of the proposed MUI algorithm, at time t_0, we solve the relay assignment problem at first. With the relay assignment result, then we calculate and find the maximum segment utility increment among all video users, and assign the corresponding resource segment for this user. When all the resource segments are assigned, the algorithm is finished. The computational complexity of MUI is $O(I^2R + IJ^2)$.

3.4.4 MUI with Base Layer Guarantee

In this section, we discuss the Maximize Utility Increment with Base layer guarantee algorithm (MUIB). Besides the system utility value of all GOPs of all video users, the playback freeze is also concerned in MUIB, as we already discussed in Section 2.4.4.

In MUIB, the base layer guarantee scheme is similar with RALS with BG. At first we solve the relay assignment problem with the same scheme we introduced in Section 3.4.2. In the second step, we primarily assign the resource segments for video users who have not received the base SVC layer for the next GOP playback with the same action we took in RALS with BG. However, MUIB deals with the base layer guarantee as the first step. After the base layer guarantee process, we assign the remain resource segments for other video users and do the SVC layer selection as same as MUI.

However, the base layer guarantee is much easier to fulfill in the cooperative vehicular network scenario. The relay users could improve the throughput of the users far from the RSU, which is the most challenge problem in one-hop scenario. As a result, the system utility decrement of MUIB will not be too much compared with the system utility given by MUI, since we no longer need to assign much resource segments to support the base layer guarantee.

3.5 Simulation Results

3.5.1 Simulation Setup

In the simulation, we use JSVM [93] as the SVC encoder. We encoded two video sequences, thus *Kendo* and *Pantomime* [94] in our simulation. The parameters related to the video sequences can be found in TABLE 2.1. We use the PSNR value as the utility value. The PSNR value is calculated between the video received and decoded at the user side and the ground truth (original video) at the server side. The PSNR calculation method is explained in the 2.5.4.

A 2000-meter-long highway with multiple lanes in each direction is deployed in the simulation. The RSU is at the middle point of the road, refer to Fig. 3-1. The distance from the RSU to the road is 10 m. We follow the parameter settings of the highway vehicular network scenario shown in TABLE 2.2, and modified some parameters and added some new parameters in TABLE 3.1. In the simulation, vehicles are randomly distributed upon the road following the uniform distribution. The velocities of the vehicles are ranging from 80 kmph to 120 kmph. Assume that there are enough lanes to allow all vehicles to run with different velocities without crash.

In order to show the performance of the proposed MUI algorithm over a period of time instead of a short STW time T, we execute MUI for multiple times T after T and evaluate the sum GOP utility values of all GOPs of all video users. Let $\bar{T}$ be the time cost when one vehicle runs through the 2000 m road with the highest speed limit 120 kmph. We have $\bar{T} = 60$ s. Refer to the definition of J, the total number

Table 3.1: Additional Parameter Setting for the Highway Scenario

#video users on the road I	{10,20,30,40}
#relay users on the road R	{10,20,30,40}
STW time T (s)	{1,3,5,7}
Duration of each round $\bar{T}$ (s)	60
GOP number in $\bar{T}$	120

of GOPs for each user while will be played in $\bar{T}$ is 120. Moreover, each vehicle has pre-buffered 10 GOPs before we run the simulations. Each buffered GOP has the base SVC layer level. Notice that these initially buffered GOPs are employed to support a smooth playback at the beginning stages of the simulation, and relevant statics are not counted in the simulation results.

We conduct the simulation for as long as $5\bar{T}$, thus 5 rounds. Suppose we begin the simulation at time 0, we collect the data regarding time interval $[4\bar{T}, 5\bar{T}]$. When one vehicle A runs out of the range, we assume that a new vehicle B runs into the range on the other side of the road. B wants to watch the same video as A and has already pre-buffered at most 10 GOPs with the same SVC layer levels as in A's buffer before A runs out. By this way, we generate the traffic on the road with a fixed vehicle number. Note that we conduct the simulation for 5 rounds in order to evaluate the performance of MUI with a more convincing pre-buffered GOP levels, since the SVC layer levels in each user's buffer at the beginning of the fifth round is given by the results of the fourth round.

In the simulation, we initialize the data volume $d^{seg}_{i@r,k}$ of the resource segment k for user i assisted by relay user r in CT mode or using directly transmission method in DT mode based on the Shannon capacity equation with a given distance from i to the RSU. Remark that the location of each vehicle at the time when k is assigned can be calculated when we know the initial location and the velocity of this vehicle.

3.5.2 Comparison Schemes

To better evaluate the performance of the proposed scheme, we compare the result of MUI with other five schemes.

MUI with relay

The proposed MUI scheme in the cooperative scenario. Relay users are used to assist video users.

MUI w/o relay

The same MUI algorithm in the one-hop communication scenario. Each video user only uses DT mode. By comparing this scheme with MUI with relay could show the improvement by enabling the cooperative communication.

RALS with relay

We extend the RALS algorithm as proposed in Chapter 2. For resource allocation and SVC layer selection, we follow the same strategy as proposed in RALS. Before the resource allocation process, we use the same relay assignment method to assign relay users for the video users.

RALS w/o relay

The same RALS scheme as proposed in Chapter 2.

MDR with relay

In the MDR scheme, the relay assignment is conducted in the same way with the proposed MUI algorithm. However, the resource segment is assigned for the video user which has the highest data rate, instead of the segment utility increment. For each GOP, MDR uses all resource segments that received before the playback of this GOP to assign the SVC layer level as high as possible.

MDR w/o relay

The same MDR scheme by disabling the cooperative communication.

3.5.3 Analysis

The simulation results are shown in Figs. 3-6 to 3-18. The average values calculated from 10 runs and the maximum and minimum values are shown in the figures. The performances of MUI in different scenarios are presented.

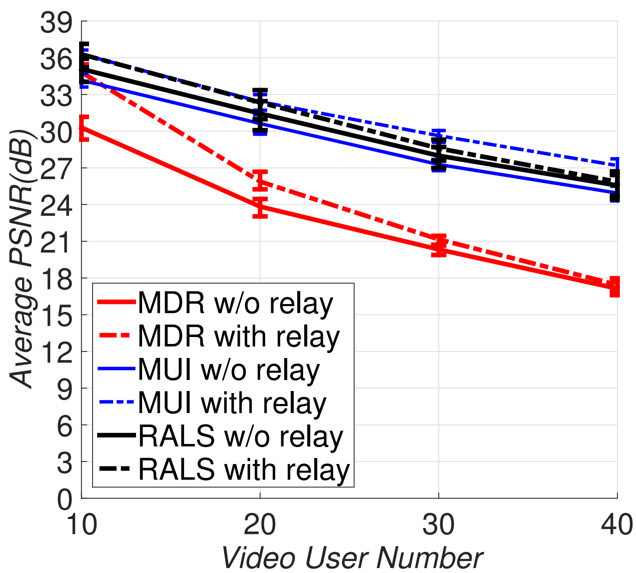

Figure 3-6: Average PSNR values varying the number of video users with 20 relay users and STW is 3 second.

Figure 3-6 shows the performance comparison of all 6 schemes, while the relay user number was fixed as 20, the STW time was fixed as 3 s and varying the number of video users from 10 to 40. Even though the performance of RALS is the best in one-hop scenario, MUI with relay has quite good performance compared with RALS with relay, especially for 30 and 40 video users scenario. When more video users were deployed in the same area, the network resource were shared by more users. That was the reason the average PSNR values were decreasing for all schemes. For all 3 schemes, thus RALS, MUI and MDR, enabling the cooperative communication could improve the average PSNR values obviously. For MUI, cooperative communication improved the average PSNRs for at least 1.5 dB. We found that when more video users were deployed on the road, the average PSNR increment by enabling cooperative communication was becoming smaller in RALS and MUI. This was because in both RALS and MDR schemes, the users who were most close to the RSU could get the resource segments. However the relay users were more likely to improve the data rate for users that were far from the RSU, due to the property of Eqs. (2.2)(3.1)(3.2). When the number of video users were not much, after the users near the RSU had already buffered enough GOPs, the users that were far from the RSU still had chance to get resource segments. While when the number of video users were big, the users far from the RSU were unable to get any resource segments even the data rate was improved by cooperative communication. As a result, the difference between one-hop scenario and cooperative scenario was quite small when many video users were deployed.

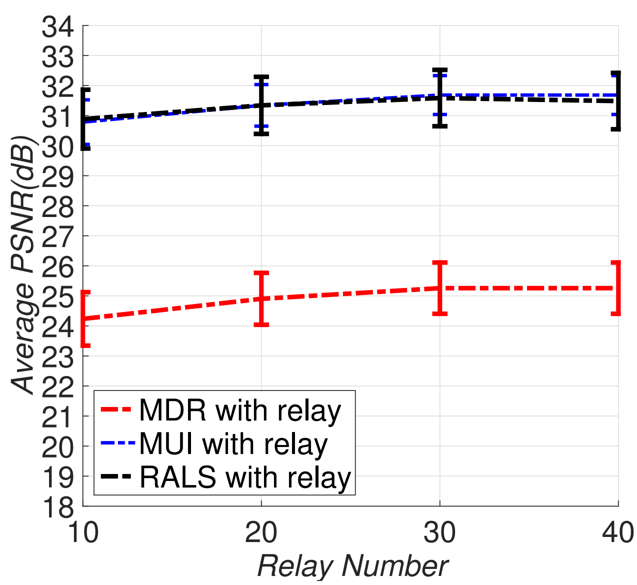

Figure 3-7: Average PSNR values varying the number of relay users with 20 video users and STW is 3 second.

When we fixed the number of video users as 20 and the STW time as 3 s, the performance of all 6 schemes over a varying number of relay users are shown in Fig. 3-7. It is easy to find out that adding more relays could improve the average PSNR values. However the slope of the curves was decreasing. This was because when there were less relay users, the density of relay users were small. At this point, adding one new relay user in the area would lead to a great improvement. This newly added relay user would has a high possibility to be assigned for one video user. However when many relay users were already deployed in the same area, the average PSNR gain would be limited by adding a new relay user.

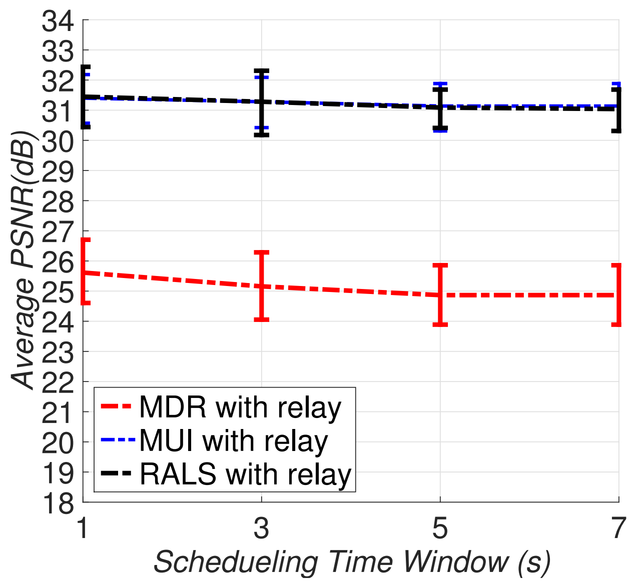

Figure 3-8: Average PSNR values varying the STW time with 20 video users and 20 relay users.

Figure 3-8 shows the simulation result when we vary the STW time, with a fixed video user number as 20 and a fixed relay user number as 20 as well. The average PSNR values were slightly decreased when the STW time was increased. Based on the definition of STW, STW is decided by how often we can reassign the relay users for different video users. Generally a more frequent adjustment of the relay assignment would provide a more accurate reconfiguration regarding the changing situations. That was the reason why the curves were decreasing. However such decrement was not big as shown in the figure.

Figures 3-9 to 3-20 show the layer distributions and average PSNRs over 180 GOPs for 10 and 40 users scenarios. The relay user number was fixed as 20 and STW was

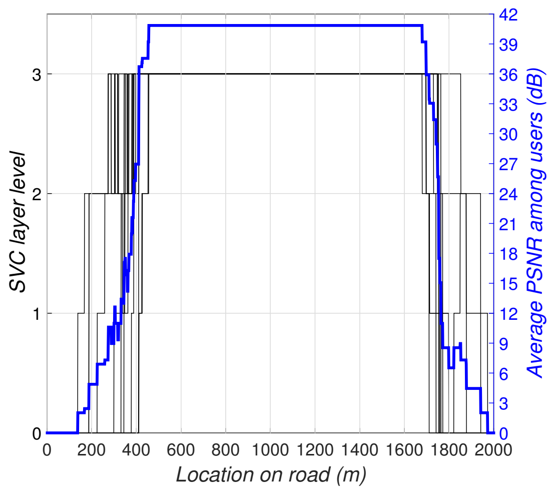

Figure 3-9: MDR w/o relay for 10 users scenario.

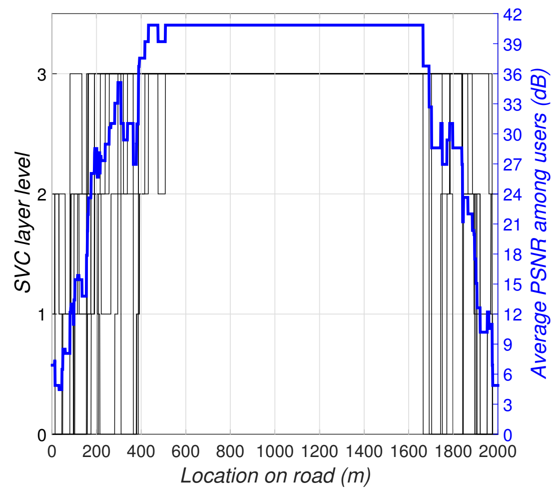

Figure 3-10: MDR with relay for 10 users scenario.

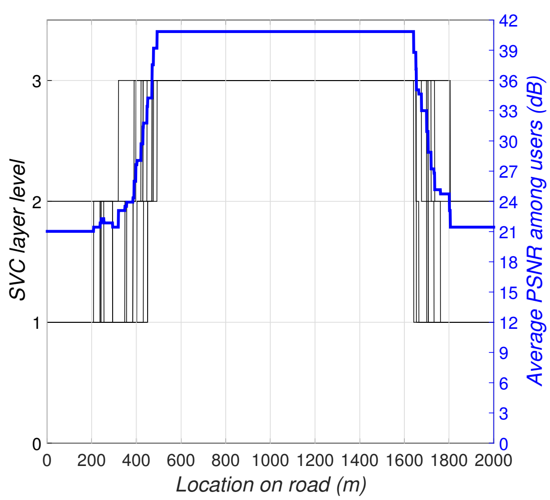

Figure 3-11: MUI w/o relay for 10 users scenario.

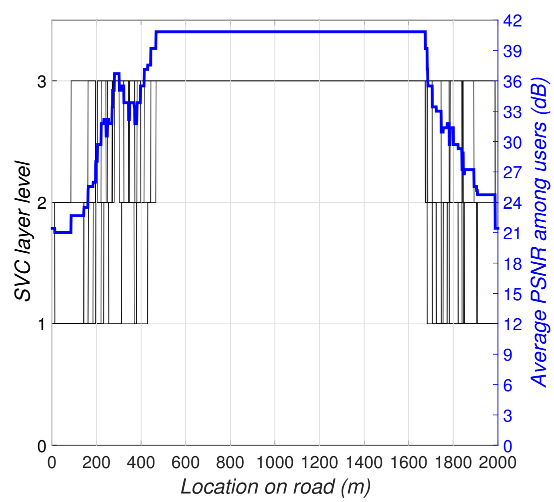

Figure 3-12: MUI with relay for 10 users scenario.

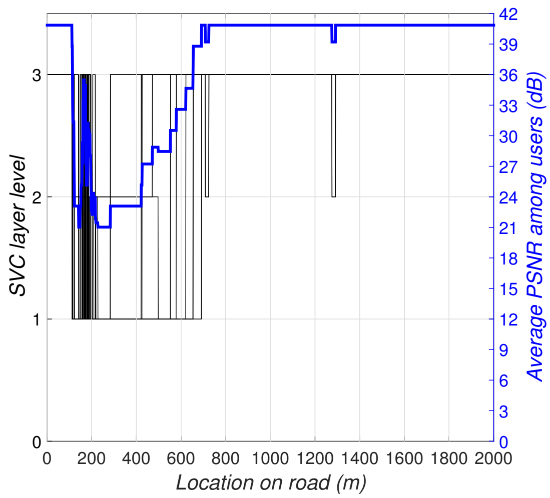

Figure 3-13: RALS w/o relay for 10 users scenario.

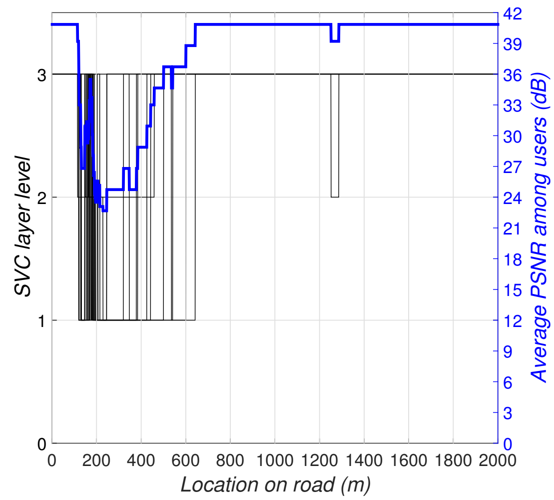

Figure 3-14: RALS with relay for 10 users scenario.

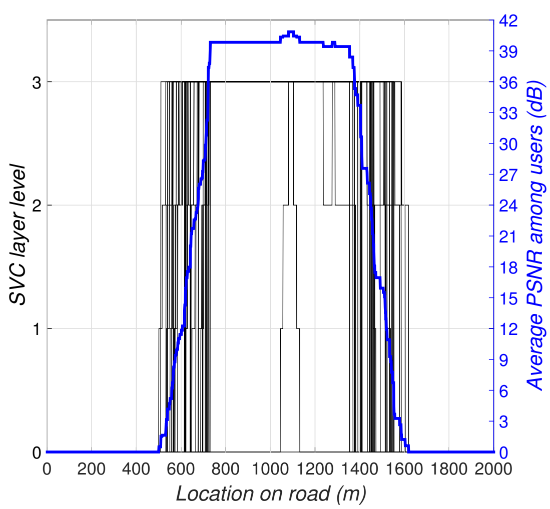

Figure 3-15: MDR w/o relay for 40 users scenario.

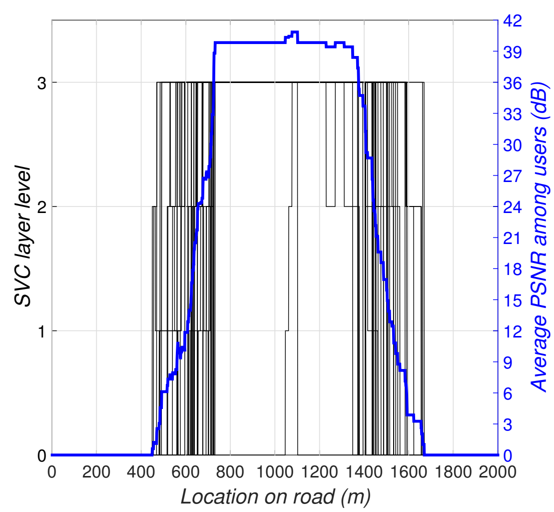

Figure 3-16: MDR with relay for 40 users scenario.

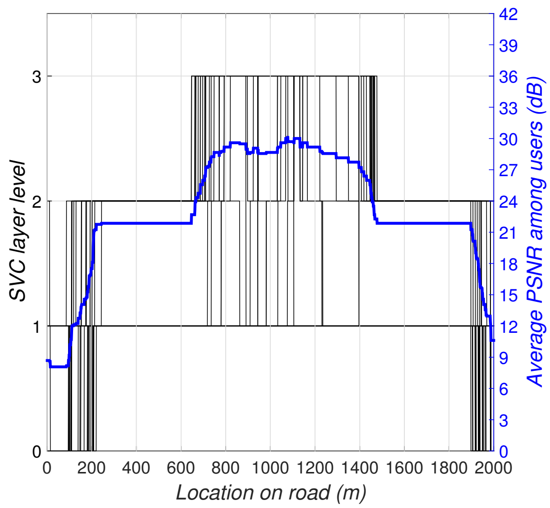

Figure 3-17: MUI w/o relay for 40 users scenario.

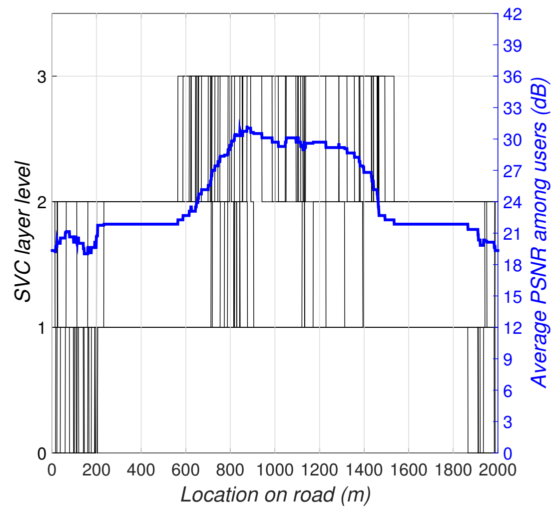

Figure 3-18: MUI with relay for 40 users scenario.

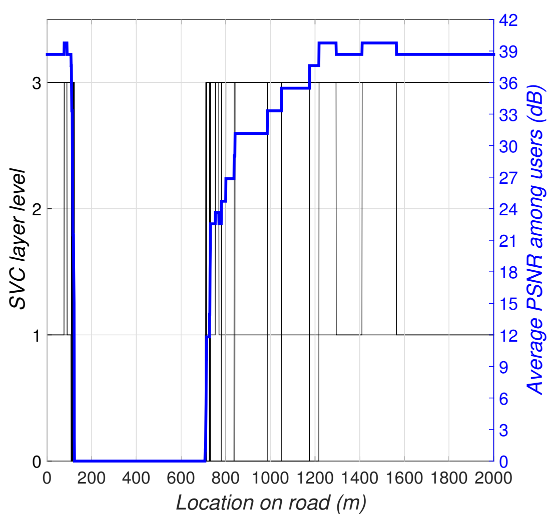

Figure 3-19: RALS w/o relay for 40 users scenario.

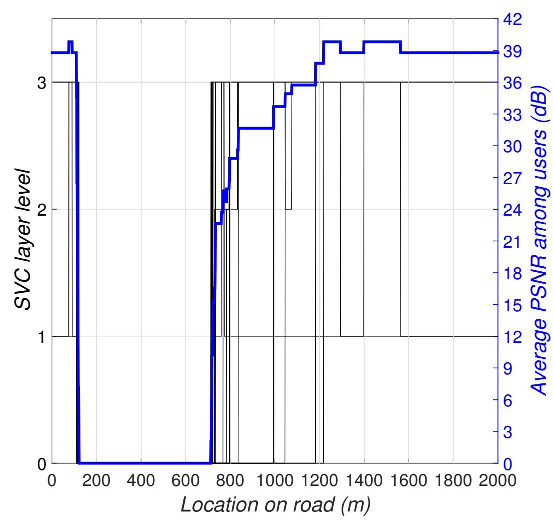

Figure 3-20: RALS with relay for 40 users scenario.

3 s. Remark that the SVC layer level 0 stands for the playback freeze.

At first, we discuss the layer distributions and average PSNRs for 10 users scenario, as shown in Figs. 3-9 to 3-14. In this case, the density of video users was relevant low. As a result, most of the video users could get a lot of resource segments. However, depending on the different resource allocation and SVC layer selection methods employed by MDR with relay, MUI with relay and RALS with relay. We found that in $[400, 1600]$ m interval, MDR with relay had more GOPs were SVC layer level 3, which is the highest level compared with MUI with relay. While in $[0, 400]$ m and $[1600, 2000]$ m intervals, the GOPs in MUI with relay had better SVC layer levels. Because in MUI with relay scheme, the resource utility increment for users with lower SVC layer levels were usually higher. As a result, such users would get a lot resource segments as well. For RALS with relay, in [0, 100] and [800, 2000] m intervals, almost all GOPs had SVC layer level 3. But the layer levels of the GOPs in [100, 800] m interval usually were not as high as that in MUI with relay. The reason is that RALS assigns the resource segments in a greedy manner. Users are hard to get resource segments when they are far from the RSU, which means the data rate is low compared with the users close to the RSU. Remark that the GOPs in [0, 100] m interval were prebuffered GOPs.

Also, we found that enabling cooperative communication could improve the average PSNR values obviously in all schemes. Compared with the one-hop scenario results, the users in $[0, 400]$ m and $[1600, 2000]$ m intervals which would never get resource segments because of low data rate, might compete and gain resource segments as well in cooperative scenario.

As shown in Figs. 3-15 to 3-20, we found more difference between MDR with relay, MUI with relay and RALS with relay schemes in 40 users scenario. In $[600, 1400]$ m interval, MDR with relay allocated a lot of resource segments for users that were close to the RSU. Such network resource let most of users had the highest SVC layer level GOPs in this interval. However for MUI with relay scheme, the SVC layer levels are more “flat”. Regarding the same resource segment, the utility increment provided by the users that are not close to the RSU may be bigger than the users near the RSU in some cases. For an example, when user X near the RSU has got all GOPs with layer level 1 and user Y which is far from the RSU has got nothing, in this case, Y will probably get the resource segment. As a result, even though the GOPs in $[600, 1400]$ m interval were not always the highest SVC layer level, the GOPs in $[0, 600]$ m and $[1400, 2000]$ m intervals always had higher SVC layer levels compared with MDR with relay. For RALS with relay, the performance is quite different. Compared with MDR with relay, even though they employ the same resource allocation scheme, the SVC layer selection scheme in RALS let more GOPs in [0, 100] and [1400, 2000] m intervals have good layer levels. Compared with MUI, we found that a lot of playback freeze would happen in [100, 700] m interval.

Similar with 10 users scenario, we found that enabling cooperative communication could improve the performance for all cases, but the increments are quite limited for MDR and RALS.

3.5.4 Base Layer Guarantee

We compared the average PSNR values of MUIB with relay and MUI with relay with different video user numbers in Fig. 3-21. The relay number was fixed as 20 and the STW time was set as 3 s. We found that for most of the cases, MUIB and MUI had the similar performance. Only for 40 video users scenario, a quite small advantage of MUI was recognized. Regarding the resource allocation and SVC layer selection mechanism we employed in MUI and the concave property of the PSNR values, MUI would naturally consider to buffer the base layer for users who had not got yet, even though we did not add the base layer guarantee process in MUI.

Figure 3-22 shows the average number of freeze GOPs of MUIB with relay and MUI with relay of each video user. Both of MUIB and MUI could provide a freeze-free playback in 10, 20 and 30 video users scenarios. In 40 users scenario, MUIB still had

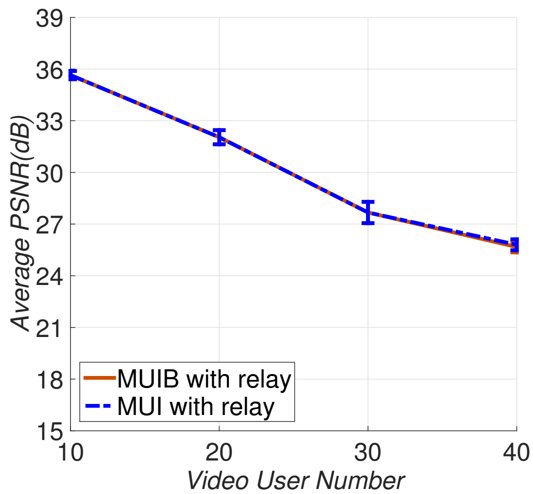

Figure 3-21: Average PSNR values varying the number of video users with 20 relay users and STW is 3 second.

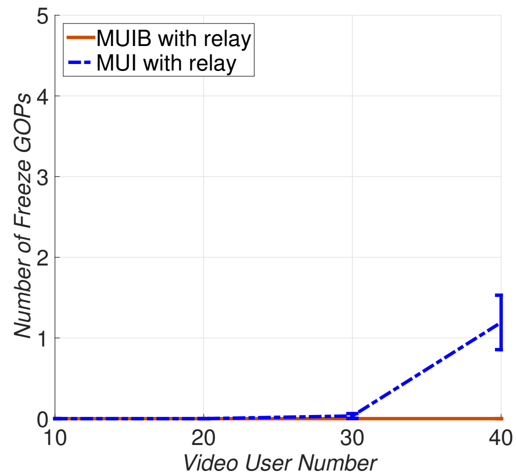

Figure 3-22: Number of freeze GOPs varying the number of video users with 20 relay users and STW is 3 second.

no freeze at all, while MUI had an average 1.2 GOPs were freeze.

The SVC layer distributions and average PSNR value curve of MUIB with relay are shown in Fig. 3-23 for 40 video users scenario. Compared with the MUI with relay in Fig. 3-18, no freeze GOP was found, but the average PSNR values in $[600, 1400]$ m interval were smaller than MUI. Regarding the base layer guarantee mechanism employed in MUIB, more resource segments were used to buffer the base SVC layer for users that were far from the RSU.

Compared with the performance of the base layer guarantee scheme in the one-hop vehicular network scenario, presented in Section 2.5.5, the base layer guarantee had much better performance in the cooperative scenario. It is obvious that the cooperative communication is quite a good mean to improve the video streaming in vehicular networks, especially for the video users that are far from the RSU.

We compare the MOS values of the proposed MUIB with relay and MUI with relay with the same method we presented in Section 2.5.6.

It is easy to find out that MUIB with relay outperforms MUI with relay when there are 40 video users. As shown in Fig. 3-21 and 3-22, the quality of the perceived

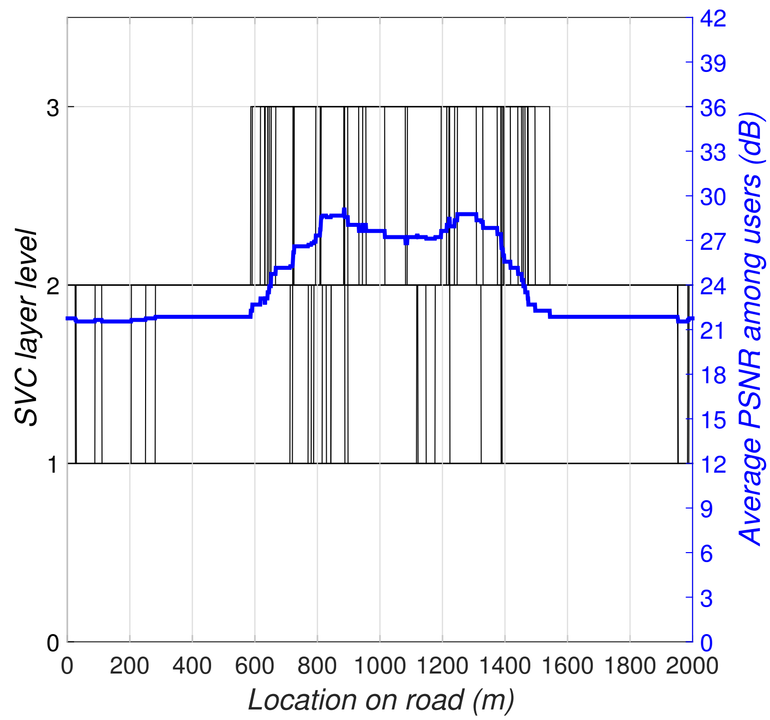

Figure 3-23: MUIB with relay for 40 users scenario.

videos are not varying much. The base layer guarantee scheme helps MUIB with relay achieve higher MOS value in this case.

3.6 Summary

In this chapter, we investigated the cooperative video streaming problem in highway vehicular networks. We considered the resource allocation, SVC layer selection and relay assignment problems jointly. The MUI algorithm is proposed to solve this problem. In MUI algorithm, we transformed the relay assignment problem to a MWBM problem and employed the Hungarian algorithm and Bellman-Ford algorithm to solve this problem. In order to solve the resource allocation and SVC layer selection problems, we explicitly took account of the segment utility increment in MUI. The performances of MUI were evaluated by extensive simulations. As shown

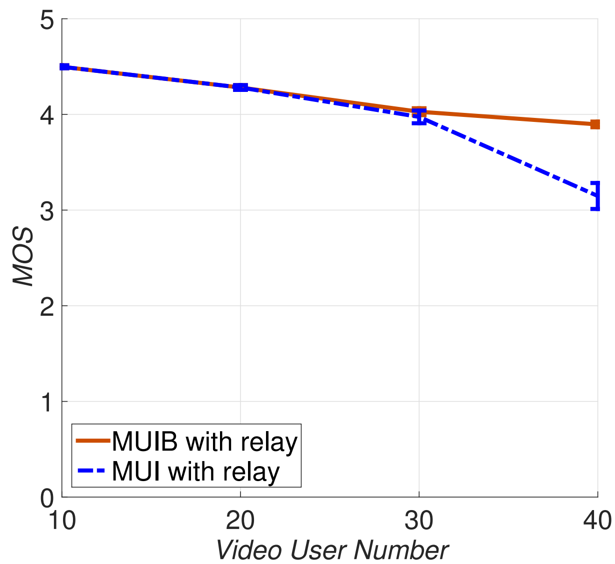

Figure 3-24: MOS comparison of MUIB with relay and MUI with relay.

in simulation results, MUI outperformed the comparison schemes in most scenarios. In the perspective of each user, the GOP distributions of all comparison schemes were also presented in the simulation result section. We extended the MUI to MUI with base layer guarantee scheme in order to reduce the freeze in the playback. Refer to the simulation results, MUI with base layer guarantee could eliminate playback freeze with quite little PSNR loss.

Chapter 4

Conclusion

4.1 Discussion

With the explosive growth of information technology, vehicular networks contribute to a more efficient driving experience by acting as a promising medium to provide a number of innovation applications, such as traffic monitoring, driving assistance, and multimedia services. We focused on the video streaming over cooperative vehicular networks issue to cope with the future applications in the next generation heterogeneous networks. In this section, we discuss the properties as well as limitations of the proposed RALS and MUI algorithms.

In both Chapter 2 and 3, we investigated the optimization problems with objective to maximize the system utility values for all video users and all GOPs. In the perspective of a centralized scheduling server or the RSU, such objective is quite convincing. As a result, some users may sacrifice its own chance to share the network resource, and let the users with higher utility values get the resource segments at first. However, each video user would like to focus on its own benefit as to receive more resource segments and buffer more GOPs with fine quality. The conflict between the system performance and selfish would be much more severe when a distributed network is employed instead of centralized network as we discussed in this thesis. In order to meet the interest of each video user, we should reconsider the design of utility value/function and our formulation as well.

Although the utility value of the proposed RALS and MUI algorithms is defined as the PSNR value of each GOP, the problem of finding a proper variable to show the quality of the received video/GOP/frame remains. In the literature, we found several variables to represent the video quality. However, the variable should meet the interest of each video user and fit the scenario as well. For an example, the video user would care more about the delay or the number of freeze than the SVC layer levels of several GOPs. That is the reason why we modified the original RALS and MUI algorithms to RALS with base layer guarantee and MUI with base layer guarantee algorithms, trying to minimize the number of freezed GOPs as well as maximize the system utility.

Regarding the fairness issue of all video users, the proposed objective function is defined as the sum of utility values over all GOPs of all video users. When the utility function is defined as the PSNR value, which is a log scaled function, the proportional fairness can be achieved approximately, as shown in Section 2.2.4.

Besides the definition of utility value/function, we should reconsider the role of relay users as well. Relaying data for other users seems has no benefit for relay users on the road. Such activity may increase the traffic load of the relay user itself and cause higher service fee required by the ISP if any. Also, the relay users may have their own services over the vehicular networks in the same frequency and channel. It is more convincing if the relay users may get some kind of reward when they perform the role of relays.

In the network structure part, although RALS and MUI are designed to fit any centralized networks, specific networks may have different properties, and some specifications should be made to fit such properties. For an example, in LTE/Device-to-Device (D2D) network, the current multiplexing model becomes no longer efficient. With an accurate calculation/estimation of the transmission interference between different users, the medium can be shared by BS and D2D communications at the same time.

Video streaming will play a more important role in the future. The next generation visual communication will be user-centric and high quality (in term of the resolution, frame rate, etc). More and more immersive communication are becoming the main trend of video streaming. For an example, the VR video has totally different structure and requirement in the video streaming. Such new video technologies bring us new challenges, and such research is required urgently.

4.2 Future Work

In the discussion section, we introduced some limitations of our work. We would like to improve our work and meet the requirements of new challenges in the following aspects, as our future work.

4.2.1 Video Streaming over LTE/D2D Networks under Vehicular Environment

Recently, the LTE/D2D network is becoming a hot zone and investigated by many researchers [113][114]. Although RALS and MUI are designed to fit any centralized networks, specific networks may have different properties, and some specifications should be made to cope with such properties. In LTE/D2D network, the current multiplexing model becomes no longer efficient. With an accurate calculation/estimation of the transmission interference between different users, the medium can be shared by direct transmission and D2D communications at the same time. How to utilize the resource allocation for video streaming over LTE/D2D networks would be a challenge issue.

4.2.2 Video Streaming in Heterogeneous Networks for Vehicular Users

Heterogeneous network [115][116] is a key technology in the next generation cellular networks. With such technology, different networks which have totally different properties are able to work together under the supervision of the Base Station (BS). Despite the cellular networks provided by the Internet Services Provider (ISP)s, users are able to access and download videos through license free networks as well, like Dedicated Short Range Communications (DSRC). New utility functions should be designed to fit the new environment. For an example, how to minimize the cost and maximize the system performance would be a very interesting issue. The tradeoff between cost and video quality should be implied in the new utility function.

In Heterogeneous Network (HetNet), the video streaming for vehicular users would be much more complicated, since the decentralized networks are also included, like DSRC, etc. How to do the resource allocation is becoming a great challenge.

4.2.3 Video Streaming over Vehicular Information-Centric Network

Recently, the Information Centric Network (ICN) [117] is introduced to vehicular networks. The new network structure brings new problems in the video streaming over vehicular networks. However, the research about video streaming over vehicular ICN is not well explored yet in the literature. As we know the vehicular networks, like DSRC, are more about lower layer design, like physical layer and MAC layer. While ICN is build on higher layer in the protocol stack. How to design a cross layer scheme to solve the video streaming over vehicular ICN would be an interesting issue.

4.2.4 Pre-caching in Vehicular Networks Video Streaming

Thanks to the current development of machine learning and more powerful computers, the network pre-caching [118] in servers and routers plays an important role in the next generation networks. Due to the high mobility environment of vehicular networks, the pre-caching in vehicular networks is a more complicated and challenging issue. We target the pre-caching in video streaming over vehicular networks as future work as well. If the mobility patterns of different vehicular users can be learned, we can pre-cach the video contents on the RSUs that are located along the route of vehicular users in advance.

4.3 Conclusion

In this thesis, we focus on the video streaming over vehicular networks problem. Video streaming services are provided by the Road Side Units (RSUs) which are located along the highway roads. While running on the road, vehicular users who want to watch realtime online videos share the network resources of the RSUs. The videos are encoded into multiple layer levels with the Scalable Video Coding (SVC) scheme. Our objective is to maximize the system utility values of all perceived videos. The system architecture, video coding model, resource model and utility model are introduced in the system model section. We decoupled this problem to two subproblems, i.e., the SVC layer selection subproblem and the resource allocation subproblem. The proposed Resource Allocation and Layer Selection (RALS) algorithm was designed to solve these subproblems separately. In RALS, we solved the SVC layer selection subproblem with dynamic programming method, and used a greedy based resource allocation scheme to deal with the resource allocation subproblem. The performance of RALS was evaluated by extensive simulations. Simulation results showed that RALS outperforms the comparison schemes in typical scenarios. Despite the system utility value, the Group Of Picture (GOP) distribution of each comparison scheme was also shown in the simulation result section. The GOP distributions illustrated the detailed performance in the perspective of each user. We also designed another scheme, thus RALS with Base layer Guarantee (BG), to reduce the playback freeze. The performance of RALS with BG was evaluated as well in the simulation section.

Besides the video users, the users who are not interested in watching videos are able to play the role of relay users, and are willing to forward data to the video users cooperatively. The video streaming problem in cooperative highway vehicular networks was investigated as our second part of work. We considered the resource allocation, SVC layer selection and relay assignment problems jointly. The Maximum Utility Increment (MUI) algorithm is proposed to solve this problem. In MUI, we transformed the relay assignment problem to a MWBM problem and used Hungarian algorithm and Bellman-Ford algorithm to solve it. To solve the resource allocation and SVC layer selection problem, we explicitly considered the segment utility increment in MUI. The performance of MUI was evaluated by exploiting extensive simulations. Simulation results showed that MUI outperforms the comparison schemes in typical scenarios. In the perspective of each user, the GOP distributions of each comparison scheme were also shown in the simulation result section. In order to reduce the freeze in the playback, we extended the MUI to MUI with base layer guarantee scheme. According to the simulation results, MUI with base layer guarantee could eliminate playback freeze with quite little PSNR loss. The base layer guarantee scheme worked much better in the cooperative vehicular network, compared with that in the cooperative scenario shown in Chapter 2.

According to the simulation results we got both from RALS and MUI, we found that the proposed scheduling algorithms have the ability to improve the video streaming over vehicular networks. We hope this piece of work could bring some new opportunities for in-vehicle infotainment services in the near future.

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Publication List

Journal

1. Ruijian An, Zhi Liu, Celimuge Wu and Yusheng Ji, *SVC-based Video Streaming over Cooperative Vehicular Networks in Highway Scenario*, **submitted to IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, Special Section on Smart Multimedia & Communication Systems, IEICE, 2017.**

2. Ruijian An, Zhi Liu, Hao Zhou and Yusheng Ji, *Resource Allocation and Layer Selection for Scalable Video Streaming over Highway Vehicular Networks*, **in IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, Special Section on Smart Multimedia & Communication Systems, Vol.E99-A, No.11, pp.1909-1917, IEICE, Nov. 2016.**

Conference & Workshop

1. Ruijian An, Zhi Liu and Yusheng Ji, *SVC-based Video Streaming over Highway Vehicular Networks with Base Layer Guarantee*, **accepted by 15th IFIP/IEEE International Symposium on Integrated Network Management (IM 2017) PAPELE workshop (6 pages), IEEE, 2017.**

2. Ruijian An, Zhi Liu and Yusheng Ji, *SVC-based Cooperative Video Streaming in Highway Vehicular Networks*, **in 31st IEEE International Conference on Advanced Information Networking and Applications (AINA-2017) HWISE workshop (6 pages), IEEE, 2017.**

3. Ruijian An, Zhi Liu and Yusheng Ji, *Video Streaming for Highway VANET*

Using Scalable Video Coding, **in 80th Vehicular Technology Conference (VTC Fall) (5 pages), IEEE, 2014.**

4. Ruijian An and Yusheng Ji, *DGA: Distributed Genetic Algorithm Based Relay Assignment in Cooperative Communication*, **in 9th International Wireless Communications and Mobile Computing Conference (IWCMC) (pp. 861-866), IEEE, 2013.**

5. Ruijian An, Yu Gu and Yusheng Ji, *Relay Assignment over Distributed Wireless Networks: A Game Theoretic Approach*, **in Globecom Workshop on Multicell Cooperation (pp. 1160-1165), IEEE, 2012.**

Others

1. Ruijian An, Zhi Liu, Hao Zhou and Yusheng Ji, *SP: A Smooth Playback Scheme for SVC Video Streaming over Vehicular Networks*, **in Proceedings of IEICE General Conference B-3-21, 2016.**

2. Ruijian An, Zhi Liu, Celimuge Wu and Yusheng Ji, *Resource Allocation and Layer Selection for Video Streaming over Highway Networks Using Scalable Video Coding*, **IEICE Tech. Rep., vol. 115, no. 408, CQ2015-104, pp. 67-72, Jan. 2016.**

3. Ruijian An, Celimuge Wu, Dong Yu, Yusheng Ji and Toshihiko Kato, *Smart Garage: Implementation of Two Hop Ad-Hoc Networks*, **in Proceedings of IEICE General Conference B-11-19, 2015.**

4. Ruijian An, Zhi Liu and Yusheng Ji, *Joint Resource Allocation and SVC Layer Selection for Video Streaming of VANETs*, **IEICE Tech. Rep., vol. 114, no. 404, CQ2014-87, pp. 7-12, Jan. 2015.**

5. Ruijian An, Zhi Liu and Yusheng Ji, *SVC Video Streaming Scheduling for Highway VANET Scenario*, **in Proceedings of IEICE General Conference BS-1-73, 2014.**

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