Radio Resource Management for D2D-based V2X Communication

By

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Except where acknowledged in the customary manner, the material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree in any university.

Xiaoshuai Li

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List of Publications

The publications of the author during her PhD study are listed as follows.

1. **X. Li**, L. Ma, R. Shankaran, Y. Xu, and M. A. Orgun. *Joint power control and resource allocation mode selection for safety-related v2x communication.* IEEE Transactions on Vehicular Technology 68(8), 7970 (2019).

2. **X. Li**, R. Shankaran, M. A. Orgun, G. Fang, and Y. Xu. *Resource allocation for underlay d2d communication with proportional fairness.* IEEE Transactions on Vehicular Technology 67(7), 6244 (2018).

3. **X. Li**, L. Ma, Y. Xu and R. Shankaran. *Resource allocation for d2d-based v2x communication with imperfect csi.* IEEE Internet of Things (2019). (Under Review)

4. **X. Li**, L. Ma, Y. Xu, R. Shankaran, and M. Orgun. *Joint distributed and centralized resource scheduling for d2d-based v2x communication.* In *2018 IEEE Global Communications Conference (GLOBECOM)*, pp.1-6 (IEEE, 2018).

5. **X. Li**, R. Shankaran, M. Orgun, L. Ma, and Y. Xu. *Joint autonomous resource selection and scheduled resource allocation for d2d-based v2x communication.* In *2018 IEEE 87th Vehicular Technology Conference (VTC Spring),* pp. 1-5 (IEEE, 2018).

6. **X. Li**, L. Ma, R. Shankaran, M. Orgun, and G. Fang. *Joint mode selection and proportional fair scheduling for d2d communication.* In *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC),* pp. 1-6 (IEEE, 2017).

7. **X. Li**, L. Ma, Y. Xu, and R. Shankaran. *Joint power control and proportional fair scheduling for d2d communication underlaying cellular networks.* In *2016 IEEE 13th International Conference on Signal Processing (ICSP),* pp. 1307-1312 (IEEE, 2016).

Abstract

This thesis proposes effective and efficient resource management approaches to mitigate the interference issue for Device-to-Device (D2D) based Vehicle-to-Everything (V2X) communication while satisfying different application requirements of safety-related and non-safety-related V2X services.

Firstly, we investigate the resource management problem of safety-related V2X communication. Considering different network load conditions, we propose a novel approach of joint power control and resource allocation mode selection to mitigate the co-channel interference of V2X networks. In order to meet the specific Quality of Service (QoS) related demands of safety-related V2X communication, we maximize the overall information value of V2X communication by considering both ProSe Per-Packet Priority (PPPP) and communication link quality of V2X messages while meeting the requirements of minimum signal-to-interference-plus-noise ratio (SINR) and maximum transmit power limitation for both pedestrian user equipments (PUEs) and vehicular user equipments (VUEs).

Secondly, we propose a novel joint power control and resource scheduling scheme to enhance both the network throughput and the users' fairness of underlay non-safety-related V2X communication network. Unlike other previous works in this area, our scheme aims at maximizing the sum of all users' proportional fairness functions while simultaneously taking into account factors such as fairness, SINR requirements and severe interference. The proposed algorithm takes into consideration time slots of long duration and is implemented in two stages: stage 1 realizes the initialization of the average data rates of all users by the proposed joint power control and resource allocation method; and stage 2 develops the proposed joint power control and proportional fair scheduling scheme from the second time slot to time slot T to improve both the system throughput and fairness over a period of time.

Prior works mainly focus on one-to-one matching between VUEs and cellular user equipments (CUEs). In contrast, here we propose a new scheme in which each VUE is allowed to occupy resources of multiple CUEs while each CUE's resource can be reused by one VUE at most. This scheme can not only guarantee the QoS of CUEs but also can improve the system throughput of the V2X network dramatically. Considering the high mobility of vehicles, in each Transmission Time Interval (TTI), the imperfect channel state information (CSI) is taken into account to track the fast variations of the channel state caused by the Doppler effect. To reduce the signalling overhead of the network, we propose a low-complexity Lower Bound-based One-to-Many matching (LB-O2M) algorithm to maximize the sum ergodic capacity of all VUEs under the restrictions of maximum transmit power of VUEs and the QoS requirements of both CUEs and VUEs.

Extensive simulation results have demonstrated that the proposed resource management approaches can significantly and effectively improve the overall system performance of D2D-based V2X communication in terms of road safety, system fairness and network throughput.

Contents

List of Abbreviations

The following list is neither exhaustive nor exclusive, but may be helpful.

Table 1: Abbreviations

Abbreviation	**Explanation**
V2X	Vehicle-to-Everything
D2D	Device-to-Device
CUEs	Cellular User Equipments
VUEs	Vehicular User Equipments
PUEs	Pedestrian User Equipments
QoS	Quality of Service
PPPP	ProSe Per-Packet Priority
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
RBs	Resource Blocks
TTI	Transmission Time Interval
RBs	Resource Blocks
CSI	Channel State Information
LB-O2M	Lower Bound-based One-to-Many matching
ITS	Intelligent Transportation System
LTE	Long-Term Evolution
3GPP	3rd Generation Partnership Project
V2V	Vehicle-to-Vehicle
V2P	Vehicle-to-Pedestrian
V2N	Vehicle-to-Network
V2I	Vehicle-to-Infrastructure
eNB	evolved NodeBs
RSU	RoadSide Unit
RBs	Resource Blocks
ProSe	Proximity Services
VRBPA	Vacant Resource Blocks and Power Allocation
ORBPA	Occupied Resource Blocks and Power Allocation algorithm
GS algorithm	Gale-Shapley algorithm
O2M	One-to-Many

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Table 1 – *Continued from previous page*

Abbreviation	**Explanation**
ETSI	European Telecommunications Standards Institute
CEN	European Committee for Standardization
ARIB	Association of Radio Industries and Businesses
DSRC	Dedicated Short-Range Communications
WLAN	Wireless Local Area Network
VANETs	Vehicular Ad hoc Networks
CSMA	Carrier-Sense Multiple Access
C-V2X	Cellular V2X
RAN	Radio Access Network
NR networks	New Radio networks
VUTs	VUE Transmitters
VURs	VUE Receivers
MINLP	Mixed-Integer Nonlinear Program
BB	Branch-and-Bound
SA	Simulated Annealing
mmW	Millimetre wave
EE	Energy efficiency
SWIPT	Simultaneous Wireless Information and Power Transfer
NFV	Network Functions Virtualization
SDN	Software-Defined Networking

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1
Introduction

1.1 D2D-based V2X Communication

With the rapid development of wireless communication, sensing and computing technologies, the transportation system is evolving toward an intelligent transportation system (ITS) which is more efficient, smarter and safer than ever before. An important facilitator for this evolution is the paradigm of V2X communication, which enables diverse types of connected vehicular communication [1, 2]. Long Term Evolution-based V2X (LTE-V) proposed by the 3rd Generation Partnership Project (3GPP) [3] is the most promising technology to support V2X communication [4]. Based on 3GPP [5], as shown in Fig. 1.1, there are four different types of V2X communication services including Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrian (V2P), Vehicle-to-Network (V2N) and Vehicle-to-Infrastructure (V2I). Two radio interfaces are considered for LTE-V. LTE-Uu based V2X interference is designated for V2I/N communication [6]. PC5 based V2X communication interface (or D2D-based V2X) supports V2V/P/I [7].

- V2V communication enables vehicles to exchange information with one another, such as collision avoidance safety information and location.
- V2P communication supports the information exchange between vehicles and pedestrians/bicyclists, such as pedestrain warning and infotainment information.
- V2N communication enables vehicles to exchange real-time traffic, routing and cloud services information with evolved NodeBs (eNB) or core network.
- V2I communication supports vehicles to exchange information with RoadSide Unit(RSU), such as road safety information and traffic signal information.

Fig. 1.2 illustrates the procedure of how V2X communication supports the ITS. By using the state of the art technologies such as GPS, sensors and cameras, the knowledge

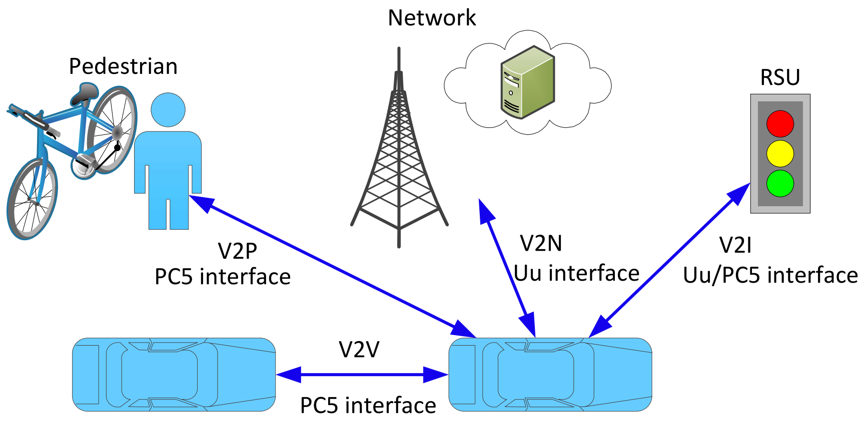


FIGURE 1.1: Illustration of V2X communication

from the local environment can be gathered and processed by entities which may influence vehicular movements. The information so gathered will then be shared between vehicles and these entities and transmitted to the application server (eNB or core network). By subsequent data analysis and processing, the server can make sound decisions on optimal route planning, optimal traffic flow strategies, etc. Therefore, V2X communication has the capability of improving the driving situation awareness, reducing accidents rates, easing the traffic congestion and decreasing environmental impacts etc. V2X communication is useful and essential not just for the current transportation system but also for the automated driving systems in the near future [8, 9].

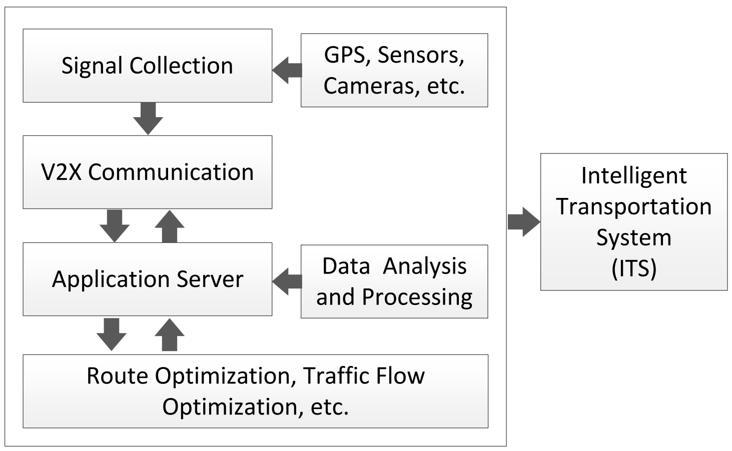


FIGURE 1.2: Illustration of how V2X communication supports ITS

V2X messages can be generally classified into two main sub-categories: safety-related information and non-safety-related information [10, 11]. Safety-related information plays a critical role in improving road safety and in the prevention of road fatalities through the use of warning messages such as stop warning, collision warning and avoidance at intersections. Non-safety-related information is considered to be supplemental information which can be utilized to efficiently manage the traffic. This, in conjunction with certain features offered by advanced V2X communication technology such as driver assistance control, automated parking assistance, and in-car entertainment can be of immense benefit to drivers [12]. The QoS requirement of V2X services depends upon the type of applications and services that a V2X system is deployed for. For the safety-related application, such as road safety, the stringent low latency and high reliability are required. In contrast, considering non-safety-related applications, such as traffic efficiency, and infotainment services, there are no strict requirements on reliability and latency. However, high data rates and low latency produce high link quality which is an essential requirement to support such applications [4].

With respect to various V2X application requirements, the emerging 5G technologies are able to accelerate the realization of advanced V2X communication such that the transportation experience and quality of life can be enhanced. One key and noticeable paradigm is D2D technology which has been proposed as an enabler for V2X communication [13]. D2D communication as a proximity-based service (ProSe) enables direct communication between two devices without the intervention of the eNB [14]. D2D communication can greatly improve the spectral and energy efficiency of a conventional network. Furthermore, it also provides low latency and high data rates. Accordingly, D2D communication is an ideal technology for V2X communication platforms [15, 16]. We use the existing LTE terminology of sidelink to define D2D communication in order to distinguish it from the traditional cellular uplink (UE-to-eNB) and downlink (eNB-to-UE).

1.2 Progress of Standardization Activities on V2X Communication

There are two prominent standards on V2X communication that are in use today. The first one is IEEE 802.11p published in 2010 to support wireless local area network (WLAN)-based vehicular ad hoc networks (VANETs). By using DSRC technology, VANETs provides direct communication for V2I and V2V services [17]. The second one is 3GPP release 14 published in 2016 to support LTE-based V2X services. LTE-based V2X extends the communication capability of IEEE 802.11p (V2V, V2I) by including two additional types of V2X services: V2P and V2N [1, 3]. Different from VANETs, the direct communication for V2X communication is realized by D2D communication in 3GPP, which is called D2D-based V2X communication in this thesis.

1.2.1 V2X Communication Support with IEEE 802.11p

In the past decade, IEEE 802.11p standard is well studied for V2X communication. It is considered as the first specific standard to support direct communication for high-speed V2V and V2I communication. This standard is the basis for the on-going DSRC standardized by USDOT in the United States [18] and ITS-G5 standardized by ETSI in Europe [19]. The technology DSRC-based VANETs communication supported by IEEE 802.11p has the capability of providing low end-to-end latency and flexible node organization without the involvement of eNB [20].

However, the collision avoidance medium-access scheme of IEEE 802.11p is based on carrier-sense multiple access (CSMA) which does not meet the stringent reliability requirements for safety-related V2X applications. Furthermore, RSUs are not widely deployed in the current network architecture, which results in the low scalability of the vehicular network. Furthermore, if we enlarge the deployment of IEEE 802.11p, tremendous investments on network infrastructure are required [21].

1.2.2 V2X Communication Support with 3GPP

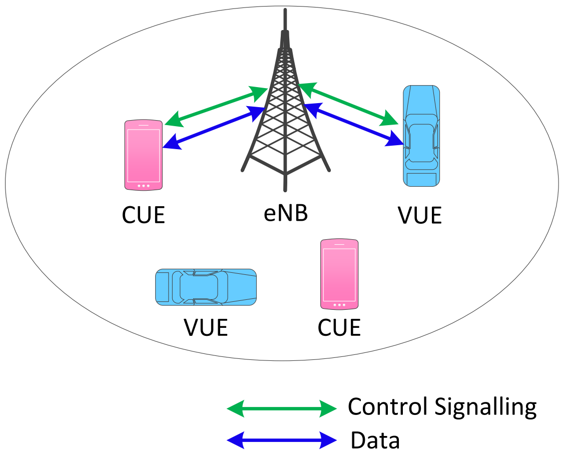
Considering the drawbacks of IEEE 802.11p, another alternative specification is LTE-based V2X Services proposed by 3GPP. The distinct attribute of LTE-based V2X from DSRC is the presence of mobile cellular network as the V2X access technology. Therefore, LTE-based V2X is also referred to as LTE-V2X, LTE-V or cellular V2X (C-V2X) [22]. In 2016, the concept of LTE-based V2X was first proposed in 3GPP Release 14 which illustrates different categories of V2X application, the V2X operation scenarios and the specific V2X service requirements on latency, reliability, message size, etc. [3, 5]. In Feb. 2018, 3GPP published Release 15 as an enhancement of 3GPP support for 5G V2X communication, including the 5G V2X use cases and 5G radio access network (RAN) requirements [23]. The on-going Release 16 published in Nov. 2018 further elaborates the procedure for deploying V2X in 5G New Radio (NR) networks [24]. Both Release 15 and 16 pay more attention to the use case of automated driving [23–25]. Similar to VANETs, D2D-based V2X communication supported by 3GPP can execute direct communication for V2V/P/I without transferring the data via eNB. But the difference is that D2D-based V2X communication is under the jurisdiction of eNB [26–28].

Different from IEEE 802.11p, the collision-avoidance mechanism of LTE-based V2X depends on the resource allocation modes VUEs work in. For Mode 3, since this mode works in a centralized control system, the corresponding collision-avoidance mechanism can be implemented by proper resource management methods under the control of eNB, such as power control, channel allocation and mode selection. By contrast, Mode 4 works in a distributed control system which enables users to transmit data independently without being dependent on the core network or eNB. Therefore, the collision-avoidance mechanism of mode 4 is also based on CSMA which is based on principles of carrier sensing to avoid collisions [29].

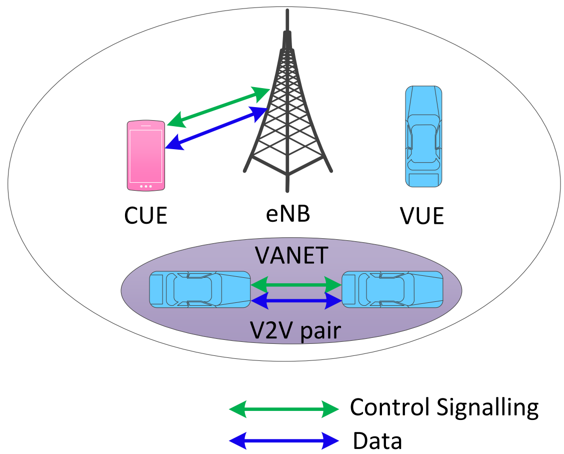
1.2.3 Comparison Between Different V2X Network Architectures

Based on the discussion of the last subsection, the network architectures support for V2X communication platform can be categorized into three different groups. The first one is the traditional cellular-based V2X network which enables some simple information and entertainment services for drivers and passengers. As shown in Fig. 1.3(a), in this network architecture, both control signalling and data go through the eNB, which results in long latency and low reliability for V2X communication. Therefore, traditional cellular communication is not well suited for strictly required V2X services, like safety-related information.

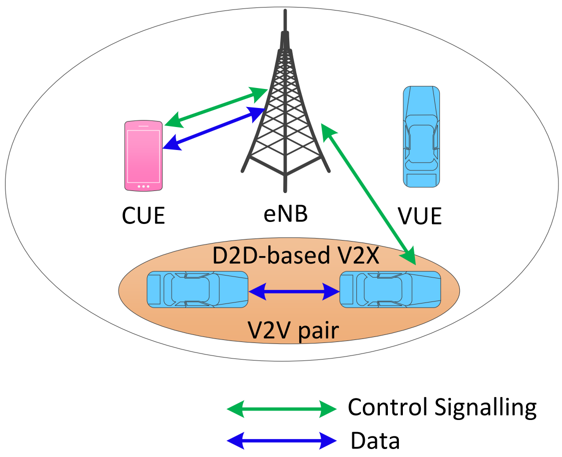
The second one is VANETs support with IEEE 802.11p, which is shown in Fig. 1.3(b). VANETs are created through the integration of mobile ad hoc networks into vehicular communication. It enables direct communication between vehicles (V2V) or between vehicles



(a) Traditional cellular-based V2X network



(b) VANET



(c) D2D-based V2X network

Figure 1.3: Comparison between different V2X network architectures

and infrastructure (V2I), where both control signalling and data do not traverse eNB. Accordingly, this architecture is completely self-configuring, self-organizing and not depending on fixed infrastructure (infrastructure-less) [30]. Therefore, VANETs provide low latency and high data rates to the vehicular network. The collision avoidance medium-access scheme of this network is CSMA which is based on principles of carrier sensing to avoid collisions [31]. In fact, without the availability of a core network, the resources become scarce making it difficult to eliminate interference in VANETS.

When compared to VANETs, D2D-based V2X communication perfectly combines the advantages of traditional cellular communication and ad hoc communication. As we can see in Fig. 1.3(c), for D2D-based V2X, the control signalling goes through the eNB while the data link is connected directly between two vehicles. This not only enables the VUEs to communicate directly with other entities but also allows them to be scheduled by the core network by which the co-channel interference can be managed very well.

The benefits of LTE-based V2X is concluded as follows:

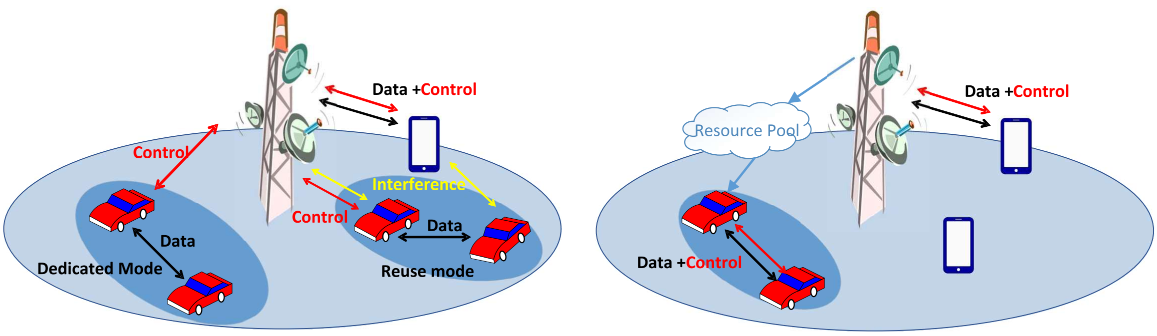
- When compared to the vehicular communication services (V2V and V2I) in IEEE 802.11p, 3GPP LTE supports two additional V2X applications: vehicle-to-pedestrian and vehicle-to-network [5]. These diverse V2X applications proposed in 3GPP provide a platform through which precise knowledge of the global environment can be easily gathered.
- Furthermore, unlike DSRC which operates in unlicensed bands, LTE-V2X supports both licensed and unlicensed bands services, which provides more flexible V2X communication environment [13].
- In addition, benefiting from the wide and global deployment of LTE architecture, LTE-V2X can achieve high data rates with the ubiquitous coverage. Furthermore, under the centralized control in the cellular network, the strict QoS requirement of V2X services can be satisfied [1, 32].
- Instead of the ad-hoc technology in VANETs, the direct communications between vehicles and other entities can be implemented by LTE D2D technology which can guarantee the stringent high reliability and low latency requirements of vehicular communication links.
- The high scalability of the network architecture and the evolutionary path to 5G are also two important characteristics of LTE-V2X.

On the basis of observations made above, we take into account LTE-V2X as the access technology for V2X in this thesis.

1.3 Resource Allocation Mechanisms for D2D-based V2X Communication

D2D Communication is studied as Proximity Services (ProSe) to support public safety communications by 3GPP Release 12 [33]. In this case, two categories of resource allocation mechanisms are standardized for LTE based D2D communication: The first one is Mode 1 designed for the centralized system and the second one is Mode 2 for the distributed system. However, unlike D2D communication, LTE-based V2X communication involves high mobility and requires high reliability and low latency and must also cater to periodic or event-triggered V2X messages [34]. Therefore, two new resource allocation mechanisms referred to as Mode 3 and Mode 4 are proposed in 3GPP Release 14 with a view to addressing these unique requirements of V2X communication [35]:

- Mode 3: As shown in Fig. 1.4(a), Mode 3 is defined as scheduled resource allocation where UEs request transmission resources from eNB which allocates licensed Resource Blocks (RBs) to UEs for their data transmission. This mode is a centralized control system and only suitable for the in-coverage V2X services.
- Mode 4: As illustrated in Fig. 1.4(b), Mode 4 is UE autonomous resource selection mode where VUEs independently select resources (without the involvement of eNB)



(a) Mode3 (b) Mode 4

Figure 1.4: Different V2X resource allocation modes

from pre-configured unlicensed resource pools. When compared to Mode 3, Mode 4 is a distributed control system which can exclude eNB to provide both in-coverage and out-of-coverage V2X services.

Besides, there are three different D2D communication modes summarized as follows:

- Cellular mode: This mode is the conventional cellular communication where the transmitter first sends the data to eNB by using the uplink resource and then eNB will send this data to the receiver with the downlink resource. Due to the long latency and low data rates, this mode is taken into account only if the other two modes are not available.

- Dedicated mode: This mode enables two UEs to build direct communication with one another by using a dedicated resource which is not currently occupied by any other UE. When compared to cellular mode, this mode can not only save the radio resources but also can improve the data rates and energy efficiency due to its attribute of proximity services.

- Reuse mode: Different from the other two modes, this mode enables two UEs to communicate directly by reusing the resource of CUEs. It further enhances spectral efficiency. On the other hand, due to the channel reuse, it also introduces co-channel issues to the cellular network [36].

By taking into consideration D2D communication modes [37], as shown in Fig. 1.4(a), we further categorize Mode 3 into two sub-modes: the dedicated mode where VUEs communicate directly by using dedicated spectrum resources without any co-channel interference, and the reuse mode where VUEs can directly communicate by reusing the resources occupied by CUEs. In particular, as shown in the figure, when VUEs work in the reuse mode by reusing the uplink resources, the VUE transmitter introduces the interference signal to eNB while its corresponding reuse CUE sends the interference signal to VUE receiver.

1.4 Research Motivation

The significant increase in the data traffic load coupled with the paucity of available cellular resources brings great challenges to the current wireless communication network. Underlay D2D-based V2X communication is able to provide an efficient solution to this problem by reusing cellular resources, thereby enhancing the network spectral and energy efficiency. However, the introduction of D2D-based V2X communication also results in severe co-channel interference in cellular networks [38–40]. In particular, if the interference caused by VUEs is not properly managed, it would severely degrade the cellular network's performance. By managing the resources in an intelligent way, this problem of co-channel interference can be effectively addressed. However, due to the various V2X application requirements (safety-related and non-safety-related applications), the resource management of D2D-based V2X communication becomes more complicated and intractable to handle than that of traditional D2D communication. Hence, there is an urgent need to develop an efficient resource management scheme to mitigate the interference issue for D2D-based V2X communication while satisfying different V2X application requirements [41]. In this thesis, we focus on the resource management problem of D2D-based V2X communication by considering different application requirements of safety-related and non-safety-related V2X services. Below we discuss the research motivations of safety-related and non-safety-related V2X communication separately.

1.4.1 Safety-related V2X Communication

Safety-related V2X communication plays an essential role in road safety and requires stringent high reliability and low latency [42]. A vast majority of the existing literature on safety-related V2X communication have solely focused on ways to reduce the data transmission latency and improve the system throughput. PPPP of data transmission proposed by the 3GPP standard [32] is also a very important feature of safety-related V2X communication and has so far been overlooked. For data transmission, the application layer assigns an independent ProSe Per-Packet Priority to each V2X message to be transmitted at a lower layer. Furthermore, the PPPP is used by the ProSe access stratum to prioritise both, intra and inter UE data transmissions. That is to say, protocol data units associated with different priorities queue up for transmission inside the same or different UEs.

Therefore, in this thesis, we not only consider the stringent restrictions of latency and reliability but also take into account the PPPP for safety-related V2X information. The work done by Gu et al. [26] jointly consider both the data weight and communication link quality for V2X communication. The main drawback of this approach is that it only considers situations in which a VUE can gain access to a dedicated resource. In fact, the paucity of available spectrum resources is a vexing issue in cellular networks. Therefore, the spectral efficiency in the scheme of [26] is limited in its applicability within a wider context. Furthermore, most of the research works done so far only examine the resource allocation problem of V2X communication for the scheduled resource allocation mode and hence are limited in scope.

In contrast, we propose to jointly schedule resources between Mode 3 (licensed RBs) and Mode 4 (unlicensed RBs) to further enhance the overall system performance. We have developed this model in our work [27, 29]. This work extends the model to offer a practical solution to address the resource allocation problems that arise in different realistic network load conditions. Furthermore, to address the resource allocation problem for V2X communication in the reuse mode, the works in [27, 29] adopted Hungarian Algorithm to obtain the optimal reuse PUEs for VUEs. However, this algorithm can result in unstable matching between VUEs and PUEs because PUEs can swap their reused VUEs if such a swap is beneficial to both the parties [43]. This motivation has led us to propose a stable matching algorithm with a low computational complexity. This algorithm is capable of assigning RBs to PUEs and VUEs in a satisfactory way by taking into consideration the preference lists of both VUEs and PUEs.

1.4.2 Non-safety-related V2X Communication

When compared to the safety-related V2X services, non-safety-related V2X services do not have strict requirements on communication link reliability and data transmission latency. Therefore, in this thesis, we investigate the resource management problem of non-safety-related V2X communication with a view to improving the users' fairness as well as the overall throughput in the system.

Fairness-based V2X Communication

In general, we want to optimize the overall network throughput by allocating sufficient radio resources to some users whose channel conditions are better than the average. Furthermore, we expect that the radio resources can be scheduled fairly so as not to starve users whose channel conditions are poor (below the average data rate). Based on the above consideration, we propose a new joint power control and resource scheduling scheme by taking into account the property of fairness, SINR requirements and co-channel interference for underlay D2D-based V2X communication.

Our work [44, 45] developed this idea and investigated the overall system performance with the goal of enhancing the overall throughput and the fairness of the network by using proportional fair scheduling. However, the schemes proposed in these papers did not significantly improve the overall system performance because the users' average data rates for the previous transmission time intervals were assumed to be constant and therefore the proportional fair scheduling is only adopted in the current transmission time interval. In particular, it has been observed that proportional fair scheduling can dramatically enhance the overall system performance as well as fairness when it takes into consideration longer duration of data transmission. Therefore, in this thesis, we extend our analysis to long-duration data transmission of users and study how proportional fair scheduling affects the overall system performance at any given transmission time interval T.

Unlike schemes proposed in previous works in this area, our model is the first to consider both the system fairness and the system throughput in unison for underlay D2D-based V2X communication while satisfying the SINR requirements on all links that are used by both V2X communication and cellular communication. It improves previous works [36, 46–48], by allocating radio resources with the proportional fair scheduler to boost the overall system fairness. Furthermore, our scheme also improves upon schemes such as those described in [39, 49, 50] by appropriately controlling the transmit power of both VUE transmitter and its reuse cellular transmitter to reduce the co-channel interference.

Throughput-based V2X Communication

How to significantly improve the overall throughput of D2D-based V2X network while guaranteeing the QoS requirements of both CUEs and VUEs is a key challenge and a vexing research problem. One effective way to improve the overall throughput of V2X communication is to enable each VUE to occupy multiple spectrum resources simultaneously for communication. However, as the primary user in the cellular network, CUEs must be effectively shielded from the co-channel interference. If the resource of each CUE is allowed to be shared with multiple VUEs as mentioned in [51–55], the welfare of CUEs will be definitely degraded. Therefore, in this thesis, we propose a novel V2X communication scheme wherein where each VUE can reuse spectrum resources of multiple CUEs but the resource of each CUE can be shared with one VUE at most and the maximum number of reuse CUEs for each VUE is limited by the maximum transmit power of the VUE. In the proposed scheme, not just the QoS of CUEs can be guaranteed, but also the data rates of V2X communication can be improved dramatically. The proposed scheme is useful for a lot of different practical use cases, such as night driving scenarios, tunnel driving, overpass driving and freeway driving.

Furthermore, unlike conventional D2D communication, the effect of the Doppler shift caused by high mobility of vehicles poses a challenge to V2X communication. However, most of the existing works done so far are based on either the perfect CSI assumption [27, 53, 56] or the statistical CSI without considering the Doppler effect [16, 41, 51, 54, 55], and hence are not directly applicable in the context of V2X networks. To make the scenario of V2X communication more accurate and practical, it is necessary to take into consideration the Doppler effect for the channel modelling of D2D-based V2X communication. This motivated us to investigate the resource allocation problem of D2D-based V2X communication on the imperfect CSI to track the fast variations of channel state caused by Doppler effect. Even though Le et al. [16] have investigated ways to improve the system throughput by joint spectrum and power allocation under the delayed CSI feedback and Doppler effect, the focus was solely on the communication scenario wherein the spectrum resource of each CUE can be reused by one VUE at most and each VUE can only be allowed to share one CUEs resource. Accordingly, the improvement in the system performance of V2X networks is limited [16].

1.5 Contributions of the Thesis

Based on the research motivations discussed in section 1.4, we highlight the major contributions of this thesis in the following subsections.

1.5.1 Resource Allocation for Safety-Related V2X Communication

In this thesis, we propose a scheme of joint power control and resource allocation mode selection with a view to satisfying QoS related demands of safety-related V2X communication in terms of both PPPP and communication link quality. In the context of safety-related V2X communication, our major contributions are threefold:

(1) We propose a system model to specifically support the safety-related V2X communication. In this model, VUEs can choose to work either in the Mode 3 (centralized system) or in the Mode 4 (distributed system). We further divide Mode 3 into two different communication modes: dedicated mode and reuse mode. To guarantee the QoS of safety-related V2X communication, we aim at maximizing the sum of information values of all VUEs by considering both PPPP value and communication link quality of V2X messages. Furthermore, the minimum SINR requirements of UEs which include not just the PUEs but also the VUEs can be guaranteed.

(2) We propose a novel approach of joint power control and resource allocation mode selection with low computational complexity to solve the resource allocation problem of the mixed centralized/distributed V2X communication system under different network load conditions. Specifically, we propose different power control approaches for each of the proposed resource allocation modes such that, in each case, the information value of a single VUE is maximized and the co-channel interference between the VUE and its reuse PUE is drastically reduced. By using the results so obtained, we further simplify the original optimization problem into a problem of resource allocation mode selection.

(3) Keeping in mind realistic network load conditions, we propose two algorithms to solve this resource allocation mode selection problem: Vacant Resource Blocks and Power Allocation (VRBPA) algorithm for lightly loaded network conditions, and Occupied Resource Blocks and Power Allocation algorithm (ORBPA) for heavily loaded network conditions. These two algorithms are designed to optimize the sum of information values of VUEs by joint resource scheduling of three different resource allocation modes. In particular, a distributed resource allocation algorithm which is included in VRBPA algorithm is designed for Mode 4. In contrast, a centralized resource allocation algorithm is designed for Mode 3, which is realized by VRBPA algorithm in conjunction with ORBPA algorithm. Furthermore, ORBPA algorithm can perform stable matching for any number of pairs of VUEs and PUEs.

1.5.2 Resource Allocation for Underlay D2D-based V2X Communication with Fairness

In order to address the resource allocation problem of non-safety-related V2X communication with the fairness requirement, our major contributions are summarized below.

(1) We model a system of underlay D2D-based V2X communication wherein multiple VUEs and CUEs co-exist. We obtain the general expressions for SINR, instant data rate and proportional fairness function of active CUEs and VUEs which successfully obtain the radio resource for communication.

(2) We propose a new scheme of joint power control and proportional fair scheduling to improve system fairness and throughput simultaneously. In the proposed scheme, our

goal is to optimize the sum of all users' proportional fairness functions while considering the following factors: fairness, SINR requirements and co-channel interference.

(3) Our optimization problem is solved in two different stages: Stage 1: We propose a method of joint power control and resource allocation to optimize the system throughput for the first transmission time interval; Stage 2: We propose a novel scheme of joint power control and proportional fair scheduling to maximize the sum of all users' proportional fairness functions, and apply it for the subsequent transmission time intervals, starting from the second transmission time interval to the current transmission time interval T.

1.5.3 Resource Allocation for D2D-based V2X Communication with Imperfect CSI

Unlike the approaches discussed in sub-sections 1.5.1 and 1.5.2 where the perfect CSI is available, in this subsection, we consider the resource allocation problem for non-safety-related V2X communication with imperfect CSI to make the system more practical. Furthermore, we consider a one-to-many matching communication scheme to further improve the throughput of V2X network. The details of our contributions are summarised as follows:

(1) We propose a novel communication scheme wherein each VUE can get access to multiple CUEs' resources while each CUE's resource can be reused by one VUE at most. Furthermore, the resources allocated to VUEs can be either vacant or be occupied by CUEs. In the proposed scheme, not just the QoS of CUEs can be guaranteed, but also the data rates of V2X communication can be improved dramatically. To the best of our knowledge, this work is the first one to consider such a communication scheme for V2X communication.

(2) We base the resource allocation of V2X communication on the perfect information of large-scale fading and imperfect information of small-scale fading in each TTI to track the fast channel variations as well as to address the challenges posed by the Doppler effect caused by high mobility. Furthermore, we aim at maximizing the sum ergodic capacity of all VUEs under minimum SINR requirements of CUEs and the restriction of maximum transmit power of VUEs while the reliability of vehicular links is guaranteed by maintaining the outage probability of received SINR below a small threshold.

(3) We propose a Lower Bound-based One-to-Many matching (LB-O2M) algorithm with low computational complexity to solve the resource allocation problem of the proposed scheme. By using the Lower Bound-based power control method, an acceptable optimal power allocation of all possible combinations of VUEs and CUEs can be guaranteed. Based on these power allocation results, we then use the proposed one-to-many matching method to find the optimal reuse CUEs for each VUEs such that the sum ergodic capacity of all VUEs can be maximized.

1.6 Thesis Organization

In this thesis, based on safety-related and non-safety-related V2X application requirements, we explore different resource management approaches to mitigate and eliminate the interference issues for D2D-based V2X communication while guaranteeing the QoS levels of both vehicular and cellular links. The rest of the thesis is organized as follows.

Chapter 2 presents a comprehensive literature review on V2X communication and provides solid foundations for the following chapters. This chapter first illustrates the V2X use cases and the corresponding V2X service requirements. Then the interference issues and key interference mitigation techniques of D2D-based V2X communication are analyzed. Thereafter, the state-of-the-art resource management methods in this area are discussed.

Chapter 3 studies the resource management problem of safety-related V2X communication. This chapter first models a system where V2X communication can occur on either Mode 3 or 4. Then it highlights the data transmission requirements of safety-related V2X messages and defines a utility function named information value to measure the priority of V2X messages, by which both ProSe Per-Packet Priority value of a V2X message as well as the communication link quality are taken into account. The goal of this chapter is to enhance the QoS of VUEs in terms of PPPP and communication link quality of safety-related V2X data transmission while satisfying the minimum SINR requirements of all types of UEs. The resource allocation problem is solved by the proposed joint power control and resource allocation mode selection algorithm. This work is based on our papers submitted to IEEE Transactions on Vehicular Technology 2019 [57], published at IEEE GLOBECOM 2018 [29], and IEEE VTC Spring 2018 [27].

Chapter 4 explores the resource management problem of non-safety-related V2X communication with a view to improving the system throughput and system fairness simultaneously by using the proportional fair scheduling. In this chapter, we first model a system of underlay V2X communication network for lengthy time slots and then describe proportional fair scheduling. The proposed novel joint power control and resource scheduling scheme is developed in two phases: the joint power control and resource allocation for the first time slot; followed by the joint power control and proportional fair scheduling for general time slots starting from second transmission time interval to the current transmission time interval. This chapter is based on our work published at IEEE Transactions on Vehicular Technology [58], IEEE PIMRC [45], and IEEE ICSP [44].

Unlike the schemes proposed in chapters 3 and 4, chapter 5 investigates how to further enhance the system performance of D2D-based V2X network under imperfect CSI. In this chapter, in order to guarantee the QoS of CUEs and improve the overall throughput of V2X communication, a novel V2X communication scheme is proposed in which each VUE can reuse spectrum resources of multiple CUEs but the resource of each CUE can be shared with one VUE at most. Furthermore, in this chapter, the power control problem is solved by the proposed Lower Bound-based power control method which is able to achieve an closed-form optimal power allocation result of each VUE with low computational complexity. Then the channel allocation problem is solved by the proposed one-to-many two-sided matching channel allocation algorithm. This work is done based on the paper under preparation for submission to IEEE Transactions on Communications [59].

Finally, Chapter 6 summarizes the main contributions of this thesis and outlines directions for future work of V2X communication.

2

Literature Review

2.1 An Overview of V2X Communication

Most major cities around the globe experience acute traffic congestion due to the ever-increasing demand for vehicular usage. This has an adverse effect on urban road network often requiring emergency management of traffic accidents. Furthermore, motor vehicles are found to be one of the primary causes of air pollution worldwide. Therefore, an ITS has come into being to make the transportation system safer, greener, more efficient and more enjoyable [60]. However, it is expected that ITS not only can provide support to the rapidly increasing number of vehicular applications but also can cater to the demand for high data rates of vehicular infotainment services. Due to its support for the high reliability and low latency, D2D technology can be perfectly applied into V2X communication, which enables vehicles to directly and efficiently exchange vehicular information with other vehicles (V2V), pedestrians (V2P), infrastructure (V2I) and network (V2N) in proximity. D2D-based V2X technology is one key driver to push forward the development of the ITS [61].

V2X communication is an essential tool to support automated driving [62]. Currently, most of the automated driving is carried out by using a perception subsystem and a control subsystem. This perception subsystem is composed of onboard sensors which can gather knowledge locally to build an environment map for automated driving. Based on this map, the control system determines the driving direction to perform the longitudinal and lateral motion [63]. However, by using the current perception subsystem, the performance of automated driving cannot be improved significantly. For example, the detection range of the current perception subsystem becomes restricted to its vicinity without the cooperation between vehicles and other entities. As a result, the vehicles are unable to obtain global environment knowledge from the remote area. This problem can be addressed by V2X communication which enables vehicles and other vehicles, pedestrians, RSU, infrastructures, and network to communicate with one another. The cooperative communication will definitely enlarge the sensing range of vehicles and provide a more cost-effective, accurate and safer environment for automated driving [64].

The worldwide efforts from auto companies, academic institutions, and government agencies have been made to promote the development of V2X communication. The U.S. Department of Transportation (USDOT) [18], the European Telecommunications Standards Institute (ETSI), the European Committee for Standardization (CEN) [19], and the Association of Radio Industries and Businesses (ARIB) [65] have considered dedicated short-range communications (DSRC) technology and reserved the dedicated radio spectrum bands to support V2X communication. In contrast, another technology called LTE-V2X is recommended by the Chinese government as the underlying platform for implementing V2X communication [66]. And the spectrum in the 5.9GHz band has been set aside for LTE-V2X networks. Furthermore, in November 2018, Qualcomm Technologies joined major Chinese automakers cooperating with Datang Telecom Group and three software companies to demonstrate LTE-V2X networks [67].

2.2 V2X Use Cases and Service Requirements

3GPP LTE Release 14, 15 and 16 [13, 23, 24] have studied the V2X communication and its enhancement (eV2X) in different application scenarios. These Releases include a wide range of connected vehicles and the 5G use cases and their corresponding services requirements [3, 5, 25]. According to different application purposes and requirements, the use cases of V2X [3] and eV2X [25] can be generally grouped into four major categories.

(1) *Road Safety:* Road safety is the most important application for V2X communication. This service is expected to protect human beings and their property from the injury and damage caused due to vehicle collisions. Release 14 illustrates a multiplicity of safety-related V2X applications, such as pre-crash sensing warning which enables vehicles to obtain the imminent and unavoidable collision information after a crash is detected; the forward collision warning which is aimed at avoiding or mitigating rear-end vehicle collisions in the forward path of travel; the control loss warning by which the surrounding drivers will be informed and take measures to avoid the vehicle collisions; pedestrian collision warning which warns the vulnerable road users, e.g. pedestrian or cyclist, to avoid the dangerous collision from the moving vehicles. In this thesis, all these road safety use cases are collectively referred to as safety-related applications and are characterized by the stringent requirements with respect to the transmission latency, reliability, message size, range and vehicle speed. Among all road safety use cases, the QoS requirement of pre-crash sensing warning information is the most stringent. ETSI defines that the maximum transmission latency and the broadcast frequency for pre-crash sensing warning are 50ms and 10Hz, respectively, while the maximum round-trip delay defined by both the U.S. Department of Transportation [68] and 3GPP is 20ms [5]. However, with respect to other types of road safety uses cases, the maximum allowable latency is 100ms. Further details can be found in Table 2.1.

(2) *Infotainment:* Infotainment is a combination of information and entertainment [22] and composed of informative or entertaining services which are not driving-related. This use case includes services like video sharing on the website, online gaming, proximity-aware social networking by social media apps, and advertisements. The goal of Infotainment is to

provide an enjoyable trip for drivers and passengers. The latency requirement for this use case is not strict ($500 - 1000$ms). But in order to meet the soaring data rates demanded by user applications, the throughput requirement is expected to be around or above 80Mbps which is as high as the conventional cellular users [69, 70].

(3) *Traffic Efficiency:* The use cases on traffic efficiency pertain to V2X application in order to optimize global road traffic or individual vehicle driving efficiency [71]. For example, the cooperative adaptive cruise control mechanism enables vehicles to exchange information with other group vehicles such that congested roads can be avoided and fuel efficiency can be enhanced. V2N traffic flow optimisation enables V2I/N communication. In this case, the centralized control server can create an optimal routing map for different vehicles and mitigate the traffic jam according to the traffic situation. Remote diagnosis and just in time repair notification application help Car Repair Center to make the local/remote diagnosis for the broken vehicles by the periodic repair notification information carried by passing-by vehicles and then give some maintenance suggestions to the driver. The QoS requirements of the traffic efficiency are not as stringent as those of the traffic safety applications but are nevertheless a bit more strict in comparison to infotainment applications.

(4) *Automated driving:* Automated driving is driverless which is totally different from the aforementioned use cases and has been regarded as the key application in 5G V2X use cases in Release 15 [23]. To realize automated driving requires the full road network coverage which can be realized by V2I, V2N, V2V and V2P communication. The V2X services for automated driving are denoted as enhancement V2X (eV2X) which has more stringent requirements than LTE-V. This eV2X should have the capability of supporting vehicle platooning by which both the distances between vehicles and the number of drivers can be reduced, the overall fuel consumption can be degraded and the traffic efficiency can be improved. According to the vehicle density, two sets of requirements are considered for vehicle platooning in 3GPP. Set 1 is for normal density platooning where the minimum distance between two vehicles is 2m, the absolute vehicle speed 100km/h, the message transmission frequency up to 40Hz, the end-to-end latency 25ms and the message size about $300 - 400$ bytes. Set 2 is for high density platooning where the minimum distance between two vehicles is 1m, the absolute vehicle speed 100km/h, the message transmission frequency up to 100Hz, the minimum end-to-end latency 10ms and the message size about $50 - 1200$ bytes. More eV2X use cases and service requirements for automated driving can be found in [25]. Table 2.1 highlights V2X communication use cases above along with their service requirements [5, 22, 72].

Table 2.1: V2X Communication Use Cases and Service Requirements

V2X use cases	Latency	Reliability	Message Size
Road safety	$20 - 100$ ms	Around 100%	1200 bytes
Infotainment	$500 - 1000$ ms	Not a concern	50-300 bytes
Traffic efficiency	$100 - 5000$ ms	Not yet explicited	50-300 bytes
Autonomous driving	$1 - 25$ ms	Around 100%	50-1200 bytes

2.3 Interference Mitigation for D2D-based V2X Communication

The paucity of available spectrum resources limits the number of VUEs which get access to network resources and thereby the performance optimization for the D2D-based V2X network is restricted. As an effective solution, underlay D2D-based V2X communication is introduced into the cellular network where VUEs can share the same RBs with traditional cellular users [73, 74]. In this case, not only can the spectral and energy efficiency of the system be improved, but also the access rate of VUEs in the cellular network can be increased. Meanwhile, the introduced co-channel interference by D2D-based V2X communication should be kept in mind such that the QoS of surrounding existing communication services is not affected or detraded [75].

2.3.1 Interference Category for D2D-based V2X Communication

Underlay D2D-based V2X communication has the capability of enhancing the network spectral and energy efficiency by reusing cellular resource. However, as a result, the interference introduced into the cellular network should also be taken into account. Since D2D-based V2X network and traditional cellular network are different and independent from one another, we classify the interference issue of D2D-based V2X communication into two categories:

- Inter-cell interference: This interference refers to the interference between V2X network and traditional cellular network when VUEs reuse the same RBs of CUEs. In this case, the interference of V2X-to-cellular and cellular-to-V2X should be managed properly.

- Intra-cell interference: Intra-cell interference refers to the interference among VUEs if multiple VUEs share the same RB.

Considering that CUEs are the primary user in the cellular network, the QoS of ongoing cellular communication services should not be affected or degraded by the introduction of V2X communication [76]. Therefore, to protect CUEs, our approach takes into consideration the communication scenario where the resource of each CUE is only reused by one V2X pair at most to protect CUEs from interference. That is to say, in this thesis, we focus on the study of inter-cell interference issue of D2D-based V2X communication.

In the underlay V2X network, D2D-based V2X communication can be established by either sharing uplink resource or sharing the downlink resource of traditional cellular users. Fig. 2.1 presents these two different reuse situations. As shown in the figure, when VUE pairs share the uplink resources with CUEs, VUE transmitters (VUTs) send the interference signal to eNB while VUE receivers (VURs) are interfered by the reuse CUEs. However, in the case of sharing downlink resources, CUEs will get the interference signal from VUEs while eNB sends the interference signal to VURs.

There exists a wide body of literature on the uplink resources reuse situation. Xue et al. [77] study how to improve the system energy efficiency with uplink resource sharing by using a multi-round combinatorial double auction algorithm. Lu et al. [78] investigate the resource allocation problem for the scenario where cellular users are multiplexed on the

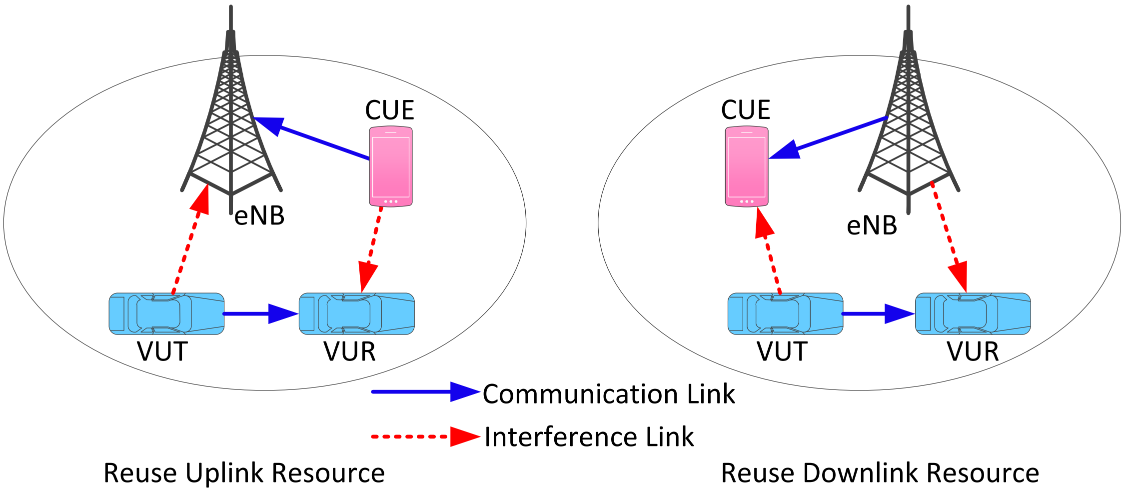


Figure 2.1: Illustration of underlay V2X communication by reusing either uplink or downlink resources

same uplink resource with the underlaid D2D pair and both cellular users and D2D users harvest energy from the hybrid access point. The authors of [79–81] propose to share the uplink non-orthogonal multiple access (NOMA) resource for D2D communication where the NOMA users work on the same resource.

Sharing Downlink cellular resource for D2D communication has also attracted much interest in recent past. Yang et al. [82] investigate the resource allocation problem for the D2D communication which is allowed to reuse both the uplink and the downlink resources. VO et al. [83] propose a joint caching and downlink resource sharing optimization framework to maximize the system delivery capacity. Ma et al. [84] investigate the downlink multichannel D2D resource sharing problem where each downlink channel can be shared by multiple cellular users and D2D users. Pan et al. [85] address the joint power control and channel assignment problem for D2D Communications taking place in a NOMA-Based Cellular Network. They believe that, in the future network, it is becoming less asymmetric in the traffic between uplink and downlink and thereby downlink resource sharing should also be studied.

When compared to the downlink resource reuse, researchers prefer the uplink resource as the reuse candidate for D2D communication. The advantages of reusing uplink resources are summarized as follows [86, 87]:

- Generally, the network tends to have heavier traffic in the downlink than the uplink. Accordingly, there are more resources that are available in uplink that can be reused for underlay D2D communication.

- In the uplink resource reuse case, eNB will receive the interference signal from D2D users while for the downlink resource reuse, traditional cellular users are victims. Obviously, the co-channel interference issue can be better handled by eNB than the user terminal because eNB can perform complex signal processing and computing.

- For the downlink resource reuse, in the broadcast communication case, eNB will send the interference signal to all underlay D2D users which reuse cellular resources present in their respective coverage areas.

- The transmit power of cellular users is much easier to control than that of eNB to mitigate co-channel interference.

Based on above consideration, in this thesis we adopt the uplink resource reuse case for underlay V2X communication.

2.3.2 Key Techniques for Interference Mitigation

Interference mitigation has been intensively explored by researchers worldwide over the past few years. Good interference mitigation approaches can improve system performance while guaranteeing the QoS of both vehicular users and cellular users. In this thesis, three key techniques, namely, power control, channel allocation, and resource allocation mode selection are taken into consideration to tackle this resource management problem.

Power Control

One direct way to mitigate and eliminate co-channel interference is through power control. By properly regulating the transmit power of VUEs, cellular communication can avoid the interference problem while meeting the minimum SINR requirement of VUEs, and vice versa [88, 89]. Power control works not just for interference mitigation but also for the enhancement of the system performance. With the high transmit power, D2D-based V2X communication can bring high reuse gains to the conventional cellular network, but it also causes high co-channel interference to traditional cellular networks. Therefore, how to manage the transmit power of VUEs effectively is an important challenge for V2X communication.

There exist several methods that we can use to solve the power control problem, such as game-theoretic methods, meta-heuristic methods and convex optimization methods. Lin et al. [89] and Zhang et al. [90] study the power control problem under a game-theoretical framework. They regard all users sharing the same channel as players in a non-cooperative power-control game and then employ an iterative algorithm to achieve the Nash equilibrium for this power control game. Wang et al. [91] investigate the power control problem by heuristic brute-force method. To further reduce the complexity, they further use the heuristic simulated annealing approach to achieve an acceptable optimal power allocation.

Even though the game-theoretic method and meta-heuristic method can be used to solve the power control problem, they are not able to obtain the globally optimal solution. Furthermore, in general, these methods are time intensive on computation and converge slowly because the number of their iteration is very large. An alternative method is the convex optimization theory which is able to reach the optimal solution for the power control problem with the low complexity. The work done in [92–94] study how to mitigate the co-channel interference and maximize the system performance by the appropriate power control and slove the optimal power control problem by using the theory of convex optimization. Similar to these works, in this thesis, we also adopt the convex optimization theory to solve the power control problem.

Channel Allocation

Channel allocation is another essential method for improving the system performance of the V2X communication network by proper spectrum resource allocation. In scenarios wherein multiple UEs communicate, the presence of an efficient channel allocation scheme greatly mitigates co-channel interference. According to the CSI of different links, channel allocation can implement the procedure of properly arranging spectrum resources to different UEs such that the resources of VUEs allocated are not occupied by the interfering CUEs and the overall system performance can achieve the optimal status. Therefore, how to allocate different spectrm resources to different VUEs to mitigate the interference and improve system performance is also a big challenge for V2X communication that needs to be addressed.

There have been some initial efforts in developing efficient and effective channel allocation solutions for underlay cellular networks. Auction-Based resource allocation problem in wireless communication networks has been extensively studied by game theorists for decades [95, 96]. Tao et al. [97] use auction method to solve the channel allocation problem of VANETs where V2V pairs act as goods, cellular channels represent bidders and BS is served as the auctioneer. Mahfoudhi et al. [98] employ an iterative combinatorial auction method to solve the channel allocation problem for D2D underly cellular networks. Another effective tool to mitigate the co-channel interference issues for underlay cellular network is graph theory which has been exploited for channel allocation design for years [51, 99]. The works in [52, 100] leverage hypergraph-based channel allocation method to mitigate co-channel interference when multiple users share the same resource. The Hungarian algorithm has been applied in [36, 56] to find the maximum matching between cellular and D2D users.

In recent past, the matching theory has also been widely applied to solve diverse wireless channel allocation problems. Considering that VUEs and CUEs are two-sided disjoint sets, the channel allocation problem can be perfectly cast to the matching problem. By using matching theory [101], not only can the overall system performance be improved, but also the system stability can be guaranteed. Based on different co-channel interference scenarios, the matching relationship between VUEs and CUEs can be generally classified into three different groups:

(1) One-to-one matching: Under this scheme, the resource of each CUE is only reused by one VUE and each VUE is allowed to get access to one CUE's resource at most. In this case, ach VUE is interfered by only one CUE and each CUE receive the interference signal from one VUE at most. This matching scheme has been widely studied [102];

(2) One-to-many matching: In this paper, we consider this scheme as the scenario where each VUE can get access to multiple CUEs' resources while each CUE allows only one VUE to share its resource. The interference scenario of this scheme is the same as the one-to-one matching scheme [103];

(3) (3) Many-to-many matching: Under this scheme, the resource of each CUE can be shared with multiple VUEs while each VUE can reuse multiple CUEs' resources. In this case, each user including both VUEs and CUEs gets interference signals from multiple other users, which results in the severe co-channel interference to both cellular and vehicular links [104].

Resource Allocation Mode Selection

In the provision of D2D-based V2X communication, another key challenge is how to assign VUEs to work in different resource allocation modes to mitigate the interference problem in the network [27, 29, 57, 105]. As discussed in Chapter 1.3, there are two resource allocation mechanisms (Mode 3 and Mode 4) for V2X communication and three different communication modes for D2D communication. Combining with different D2D communication modes, we can further categorize Mode 3 into two sub-modes: the dedicated mode and the reuse mode. The circumstance of interference is different when VUEs work in different resource allocation modes. The co-channel interference occurs only if VUEs works in the reuse mode. For the dedicated mode and Mode 4, all resources are orthogonal to one another thereby nullifying the possibility of any co-channel interference to arise between VUEs. However, due to the paucity of spectral resources, only a fraction of the total number of VUEs in the system are able to get access to vacant resources and the rest of VUEs have to share resources with traditional cellular users. That is to say, in the V2X network, some of VUEs are assigned to the dedicated mode or Mode 4 while the other VUEs are allocated to the reuse mode. If different VUEs can be properly assigned to different communication modes based on their channel states, it is possible to improve the system performance significantly. Furthermore, Modes 3 and 4 can independently operate in different kinds of resource pools, licensed resources for Mode 3 and unlicensed resources for Mode 4. Therefore, how to optimize the resource allocation between different V2X communication modes is a critical challenge for V2X networks, which is being currently being investigated by the 3GPP (refer to 3GPP Release 15) [23].

There exist plenty of works focusing on the mode selection algorithm design. Huang et al. [106] propose a centralized decision-making framework for D2D-Enabled Two-Tier Cellular, where the mode selection problem between three D2D communication modes (cellular mode, dedicated mode and reuse mode), resource allocation problem and power control problem for reuse mode are jointly considered to mitigate the interference issues. Azam et al. [107] investigate how to use the outer approximation approach to tackle the joint admission control, mode selection, and power allocation problem for an underlay D2D network which aims at maximizing the overall system throughput and the number of admissible D2D users. Albonda et al. [108] propose a mode selection algorithm to avoid overload in the sidelink resources of V2X networks. Our previous works [27, 29] also investigate how to mitigate the co-channel interference and improve the system performance of V2X network by employing appropriate mode selection methods.

2.4 Resource Management for D2D-based V2X communication

Underlay D2D-based V2X communication can introduce high reuse gains into the conventional cellular network. But it causes co-channel interference to the cellular links. Proper resource management approaches for D2D-based V2X communication not only can mitigate the interference and improve the spectral/energy efficiency of the system but also can offload the cellular network and improve the system performance of V2X communication.

Since the improvement in the system performance is limited by using the key techniques separately, most of the works focus on exploiting these key techniques jointly to further enhance the system performance. In recent years, the resource management of D2D-based V2X communication has been intensively investigated.

The data transmission requirements for safety-related V2X information is more stringent when compared to that of conventional cellular communication. Sun et al. [56] analyze the latency and reliability requirements of safety-related vehicular links and propose a separate RB and power allocation algorithm for the communication scenario of one-to-one matching between VUEs and CUEs. They further study the joint power control and resource allocation problem for the scenario where mutiple VUEs can share same resource [53]. A non-orthogonal multiple access scheme for V2X communication with a view to enhancing the packet reception probability and reducing the access latency is proposed by Di et al. [55]. Fakhar et al. [109] propose a hybrid scheme with a goal of optimizing the sum of the latency reduction of V2X data transmission so that the packet delivery ratio and the throughput of vehicular networks can be enhanced. However, aforementioned previous works solely focus on ways to reduce the data transmission latency and improve the system throughput. ProSe Per-Packet Priority of data transmission proposed is also a very important feature of safety-related V2X communication and has so far been overlooked.

Knowledge of accurate and timely CSI is an indispensable factor for performing efficient power control, channel allocation and resource allocation mode selection. Generally, the traditional D2D users can be regarded as static in each TTI because of their low mobility. Hence, it is reasonable to assume that eNB has the capability of acquiring the perfect CSI of D2D users. Unfortunately, compared to conventional D2D users, VUEs faces more complicated and diverse communication scenarios involving high mobility patterns. For the low-speed D2D-based V2X communication, such as in traffic congestion or in carpark, the vehicles either move very slowly or do not move at all. In this case, we can regard the status of VUEs as being static in each TTI. Therefore, in the low-speed case, we can consider the CSI of the vehicular link as perfect as the traditional D2D link. Feng et al. [36] study how to optimize the overall throughput using an approach of joint power control and resource allocation for a system model which involves multiple D2D users and CUEs. A joint mode selection and resource allocation method is investigated to manage acute interference problem described in [46]. Ban et al. [47] study the overlay D2D communication to avoid the co-channel interference with a centralized scheduling method and distributed scheduling method, respectively. Zhang et al. [48] propose an interference graph construction protocol which involves the use of two phases, namely, the announcement and collision-resolution in an iterative manner.

However, in the high-speed case, CSI of VUEs is greatly influenced by the Doppler Shift. In this case, a perfect CSI is impossible to achieve. Hence, to make the system more practical, the imperfect knowledge of CSI should be taken into account at eNB. On the other hand, if the instantaneous CSI feedback is required in the system, the rapid channel information change of vehicular links may introduce an intolerable overhead at eNB [53, 56]. The trade-off between the accuracy of CSI and its resulting overhead should also be taken into account in the V2X network. Therefore, how to model the vehicular communication channel for different communication scenarios is a crucial challenge for V2X communication.

There exist several contributions in the literature on restricting the co-channel interference for high-speed D2D-based V2X communication. Liang et al. [16] study the spectrum and power allocation problem of vehicular links with statistical CSI, which aims at maximizing the sum capacity of all V2I links. By taking into account the effect of high mobility of VUEs on the channel state, they also study how to optimize the sum ergodic capacity of all V2I links with the statistical CSI information [110]. Yang et al. [41] propose a transfer actor-critic learning method to implement the intelligent resource management for D2D-enabled V2X communication such that the overall throughput of V2I links is maximized. Unlike the aforementioned works, that, in general, considered only the scheduled resource allocation mode. Our work takes into account both scheduled resource allocation mode and autonomous resource selection mode and addresses the problem of how to optimize resource allocation between these two modes [27, 29].

The works mentioned in [16, 27, 41, 56, 110] focus on the resource allocation problem of the one-to-one matching communication scenario where one cellular resource is only reused by one VUE while each VUE is allowed to access one cellular resource at most. Although this matching method can guarantee the QoS of both cellular and vehicular links, the enhancement of the overall system performance of V2X communication is not dramatic. As a result, in recent past, some proposals have emerged that exclusively focus on a V2X communication scenario wherein one cellular link can be allocated to multiple VUEs. Yi et al. [54] investigate how to solve the optimal power control problem for the scenario involving multiple VUEs reusing one cellular link. Chen et al. [52] introduce NOMA to the D2D-enabled V2X networks and only study the channel allocation problem. Liang et al. [51] investigate the communication case where each V2I link can be reused by multiple V2V links and apply different algorithms to make a trade-off between system performance and complexity. Di et al. [55] study the resource allocation problem for a NOMA-based mixed centralized/distributed scheme where the dynamic power control and the time-frequency resources allocation are jointly considered for the scenario of many-to-many matching between users and spectrum resources.

Fairness is an important factor in resource allocation and incidentally, it has also been taken into account in 5G networks. However, most of existing works focus on optimizing the throughput of the overall network while completely ignoring the fairness aspect. Unlike the previous works, we propose a fair resource allocation method in scenarios wherein multiple VUEs coexist with multiple CUEs. Generally, Max-min [111], Round Robin [112] and Proportional Fairness [113] algorithms are applied to improve the system fairness. Max-min and Round Robin algorithms can improve the system fairness considerably, but they also cause a decrease in the system throughput. In principle, there is a conflict between the maximum throughput and fairness. If we optimize the overall network throughput, the system fairness will be reduced, while on the other hand if we try to maximize the system fairness, the throughput will be degraded. The Proportional Fairness algorithm can offer a better system performance when compared to other scheduling algorithms because it can effectively deal with this conflict between throughput and fairness. Hence, we take into consideration this algorithm to improve the system fairness in this thesis.

Several proposals in the literature have explained how proportional fair scheduling works to enhance the overall performance of the system. Calabuig et al. [49] study proportional fair scheduling for heterogeneous wireless systems based on the linear programming method. Kim et al. [50] develop an approach for users' selection with proportional fair scheduling in LTE Uplink using the SC-FDMA scheme. But all these schemes do not consider the vexing co-channel interference issue. Based on these schemes, Gu et al. [39] investigate the problem of proportional fair scheduling for underlay D2D communication by taking into consideration the problem of co-channel interference caused by the D2D users. But the proposed scheme cannot guarantee the minimum SINR requirements of users since it is based on the assumption of a predefined power setting. The schemes described above either only address proportional fair scheduling for a traditional cellular network without considering the interference problem, or do not propose any measures to mitigate the interference for underlay D2D communication. These proposals are unable to further improve system performance because they lack a technique of joint power control in conjunction with proportional fair scheduling. Hence, there still exist a series of problems and challenges when the proportional fair scheduling is adopted in underlay low-speed D2D-based V2X communication networks.

2.5 Summary

In this chapter, we first presented a comprehensive literature review on V2X communication from the perspective of their use cases and the corresponding service requirements. We then analyzed the interference issues of D2D-based V2X communication and addressed the key techniques for interference mitigation. Finally, we highlighted the state-of-the-art of resource management in the area of D2D-based V2X communication. The analysis presented in this chapter provides a solid foundation for conducting further study on V2X communication in the following chapters.

3

Resource Allocation for Safety-Related V2X Communication

3.1 Preface

Safety-related V2X communication plays an essential role in road safety such as avoiding vehicular collisions and requires stringent high reliability and low latency. In this chapter, we propose a novel scheme of joint power control and resource allocation mode selection that works under different network load conditions to address the problem of resource allocation for underlay safety-related V2X communication. In particular, in scenarios where the network is lightly loaded we propose Vacant Resource Blocks and Power Allocation algorithm while for scenarios wherein the network is heavily loaded we propose Occupied Resource Blocks and Power Allocation algorithm. In order to meet the specific QoS related demands of safety-related V2X communication, we aim to maximize overall information value of V2X communication by considering both ProSe Per-Packet Priority and communication link quality of V2X messages while meeting the requirements of minimum SINR and maximum transmit power limitation for both PUEs and VUEs. Furthermore, the proposed algorithm can achieve a stable matching between VUEs and their reuse PUEs partners. Extensive simulation results show that both the information value of VUEs as well as the spectral efficiency of PUEs can be improved efficiently by the proposed approach.

The rest of the chapter is structured as: Section 3.2 presents the system model, channel model, the data transmission requirements and highlights the definition and significance of the information value in the context of V2X communication; Section 3.3 defines and formulates the problem of resource allocation; The proposed resource allocation algorithm described in Section 3.4 consists of two parts: power control algorithm and resource allocation mode selection algorithm; The system performance of the proposed algorithm is evaluated and analyzed in Section 3.5. Eventually, Section 3.6 briefly summarizes the key contributions of our work and provides some concluding remarks.

3.2 System Model for Safety-Related V2X Communication

3.2.1 System Model of V2X Communication in Different Resource Allocation Modes

Based on the road configuration for V2X communication in an urban setting proposed in [13], we model our system as a single road grid with its centre being eNB as shown in Fig. 3.1. The total size of the road grid is 433m × 250m. The lane width is 3.5m and the sidewalk width is 3m. There are M traditional PUEs, N VUE pairs, L vacant licensed RBs, and U vacant unlicensed RBs. We define $\mathcal{C} = \{\mathrm{PUE}_1, \mathrm{PUE}_2, \ldots, \mathrm{PUE}_M\}$ as the set of PUEs, $\mathcal{V} = \{\mathrm{VUE}_1, \mathrm{VUE}_2, \ldots, \mathrm{VUE}_N\}$ the set of VUE pairs, $\mathcal{F_L} = \{F_1, F_2, \ldots, F_L\}$ the set of vacant licensed RBs, and $\hat{\mathcal{F}}_{\mathcal{U}} = \{\hat{F}_1, \hat{F}_2, \ldots, \hat{F}_U\}$ the set of vacant unlicensed RBs. We assume that PUEs are distributed uniformly along the sidewalk, where the inter-pedestrian distance is equal to the ratio of the total length of sidewalk to the total number of PUEs. VUE transmitters are dropped at different points on roads using a spatial poisson process and they are also the centres of different circles in which the corresponding VUE receivers are distributed uniformly. Furthermore, VUE receivers are also dropped along the vehicle lanes where, in one lane, the average inter-vehicle distance is determined by calculating 2.5 sec × v km/h (absolute vehicle speed). We further assume that, for each VUE pair, the running directions of VUE transmitter and VUE receiver are same and the vehicle speed is same in all lanes.

Based on 3GPP standardization [32], PPPP is used by the ProSe access stratum to prioritize both, intra and inter-user data transmissions. In particular, for data transmission, the application layer assigns an independent ProSe Per-Packet Priority to each V2X message to be transmitted at a lower layer. Then protocol data units associated with different priorities queue up for transmission inside the same or different users. As we can see, PPPP is a numerical value which has been assigned by the application layer before data transmission. Based on the above discussion, we find that PPPP is related to the priority of the safety-related V2X message and has no relationship with the size of V2X message. Therefore, we assume that each VUE sends one V2X message with an independent PPPP value. We define $\Theta = \{\theta_1, \theta_2, \ldots, \theta_N\}$ as the PPPP set.

In this model, V2X communication is realized by D2D technology. VUEs can work in either Mode 3 or 4. When operating in Mode 3, VUEs can further choose to use either of the two available sub-modes: dedicated or reuse mode. We assume that, in each TTI, one VUE pair can operate in one specific resource allocation mode. Furthermore, considering that the size of the safety-related V2X message is not big (generally less than 1200 bytes), therefore, the use of one RB would suffice for safety-related V2X message transmission. Here, RB is the smallest time-frequency resource unit used for data transmission and is composed of a group of 12 sub-carriers contiguous in frequency over one time slot (corresponding to 180 kHz in the frequency domain and one slot 0.5ms in the time domain). To mitigate the co-channel

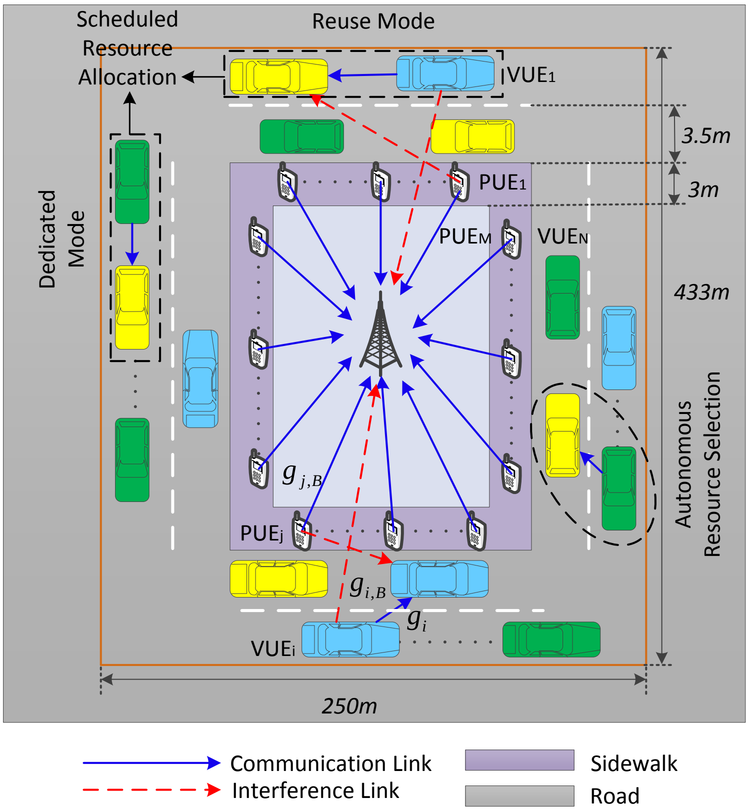


Figure 3.1: The system model of safety-related V2X communication

interference and guarantee the QoS requirements of both vehicular and cellular links, the proposed system is modelled as a special case of the practical V2X communication networks, wherein, in each TTI, each VUE pair is allowed to reuse the resource of one PUE at most while each PUE's resource can be shared by only one VUE. Each PUE is assumed to occupy one RB and all RBs are orthogonal to one another so that there is no co-channel interference between PUEs. Besides, only the uplink resources can be shared between VUEs and PUEs. In this case, VUE transmitters will cause interference at eNB while VUE receivers suffer from the interference caused by PUEs.

3.2.2 Channel Model of Safety-related V2X Communication

The perfect CSI of both cellular and vehicular links can be obtained at eNB through the use of control signal feedback mechanism. Due to the effects of multi-path propagation and shadowing, all cellular links are assumed to be characterized by both small-scale fading and large-scale fading. However, vehicular links experience rapid fluctuations in small-scale fading because of the Doppler shift caused by the high mobility. In such situations, if we keep continually updating the CSI at eNB, then eNB will likely experience a high signalling overhead. Therefore, only the large-scale fading effect is taken into account in our proposed system [53]. Furthermore, the long-term resource scheduling can guarantee the channel resources are still available for those VUEs which move out of the coverage area temporarily. We define $g_{j,B}$ as the instant channel gain between PUE j and eNB, which is given as:

$$g_{j,B} = G\beta_{j,B}\zeta_{j,B}L_{j,B}^{-\alpha}, \tag{3.1}$$

where G is defined as constant gain introduced by antenna and amplifier, $\beta_{j,B}$ the multi-path fading gain with an exponential distribution, $\zeta_{j,B}$ the shadowing fading gain with a log-normal distribution, α the pathloss exponent, and $L_{j,B}$ the distance from PUE j to eNB. In addition, we define g_i as the instant channel gain between VUE transmitter i and VUE receiver i. The channel gain due to the co-channel interference from PUE j (VUE transmitter i) to VUE receiver i (eNB) is defined as $g_{i,j}$ ($g_{i,B}$).

When the data transmission of VUE i is not interfered by any other UE, its Signal-to-Noise Ratio (SNR) ξ_i^V and instant data rate r_i^V are shown as follows:

$$\xi_i^V = \frac{p_i^V g_i}{\sigma^2}, \tag{3.2}$$

$$r_i^V = \log_2(1+\xi_i), \tag{3.3}$$

where p_i^V denotes the transmit power of VUE i. σ^2 denotes the power of additive white Gaussian noise. When VUE i shares the same RB with a PUE j, its SINR $\xi_{i,j}^{(3)}$ and data rata $r_{i,j}^{(3)}$ can be expressed as follows:

$$\xi_{i,j}^{(3)} = \frac{p_{i,j}^{(3)} g_i}{p_{i,j}^C g_{i,j} + \sigma^2}, \tag{3.4}$$

$$r_{i,j}^{(3)} = \log_2(1+\xi_{i,j}^{(3)}), \tag{3.5}$$

where $p_{i,j}^{(3)}$ represents the transmit power of VUE i working in reuse mode. $p_{i,j}^C$ represents the transmit power of PUE j.

Similarly, when PUE j does not share the RB with any other VUEs, its SNR ξ_j^C and instant data rate r_j^C are shown as follows:

$$\xi_j^C = \frac{p_j^C g_{j,B}}{\sigma^2}, \tag{3.6}$$

$$r_j^C = \log_2(1+\xi_j^C), \tag{3.7}$$

where p_j^C denotes the transmit power of PUE j without interference signal. However, if the RB of PUE j is reused by VUE i, the SINR $\xi_{i,j}^C$ and data rata $r_{i,j}^C$ of PUE j can be expressed as follows:

$$\xi_{i,j}^C = \frac{p_{i,j}^C g_{j,B}}{p_{i,j}^{(3)} g_{i,B} + \sigma^2}, \tag{3.8}$$

$$r_{i,j}^C = \log_2(1+\xi_{i,j}^C), \tag{3.9}$$

3.2.3 Data Transmission Requirements and the Definition of Information Value for V2X Communication

Sun et al. have analyzed the stringent low-latency and high-reliability requirements of safety-related V2X communication. These requirements are together expressed as a constraint of minimum SINR requirement for V2X communication [56]. We too consider the use of SINR as a metric to meet the requirements needed to ensure the successful transmission of safety-related V2X messages within a maximum tolerable elapsed time. We require the SINR ξ_i^V to be above a certain threshold $\xi_{\min}^V$ as shown below:

$$\xi_i^V \geq \xi_{\min}^V, \tag{3.10}$$

As outlined by the 3GPP specification, PPPP ordering is used to sequence V2X packets transmission for inter-UE scenarios. Generally, the PPPP value of the safety-related V2X message is higher than that of the non-safety-related one. On the other hand, a high communication link quality is also very critical to ensure the successful and reliable transmission of safety-related V2X packets. Therefore, we use a utility function called information value to define the priority of V2X messages for data transmission in inter-VUE communication scenario. This information value takes into account both PPPP value of a V2X message as well as the communication link quality to meet and satisfy stringent QoS requirements of safety-related V2X message. The information value Inf_i is given as:

$$Inf_i = \theta_i \cdot r_i, \tag{3.11}$$

where θ_i and r_i indicate values of the PPPP and the instant data rate of UE i, respectively.

3.3 Problem Formulation for Safety-related V2X Communication

Since safety-related V2X communication is necessary to realize safety-critical services, our aim is to maximize the overall information value of V2X communication to enhance the QoS of VUEs in terms of PPPP and communication link quality of V2X data transmission while satisfying the minimum SINR requirements of all types of UEs. To simplify the system model, we assume that, in one TTI, each VUE pair can only choose one resource allocation mode. Therefore, in our proposed scheme, the resource allocation problem for safety-related V2X communication in one TTI can be mathematically formulated by using the following equation (3.12) under certain system constraints:

$$\begin{aligned}(\mathbf{x}^*, \mathbf{p}^*) = \underset{\mathbf{x},\mathbf{p}}{\operatorname{argmax}} \Bigg\{ &\sum_{i=1}^{N} x_i^{(1)} \theta_i^{(1)} \log_2 \left(1 + \frac{p_i^{(1)} g_i}{\sigma^2}\right) \\ &+ \sum_{i=1}^{N} x_i^{(2)} \theta_i^{(2)} \log_2 \left(1 + \frac{p_i^{(2)} g_i}{\sigma^2}\right) \\ &+ \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j}^{(3)} \theta_i^{(3)} \log_2 \left(1 + \frac{p_{i,j}^{(3)} g_i}{p_{i,j}^{C} g_{i,j} + \sigma^2}\right) \Bigg\},\end{aligned} \tag{3.12}$$

subject to

$$x_i^{(1)}, x_i^{(2)}, x_{i,j}^{(3)} \in \{0,1\}, \forall i, j, \tag{3.12a}$$

$$\sum_{i=1}^{N} x_i^{(1)} \leq U, \forall i, \tag{3.12b}$$

$$\sum_{i=1}^{N} x_i^{(2)} \leq L, \forall i, \tag{3.12c}$$

$$x_i^{(1)} + x_i^{(2)} + \sum_{j=1}^{M} x_{i,j}^{(3)} \leq 1, \forall i, \tag{3.12d}$$

$$\sum_{i=1}^{N} x_{i,j}^{(3)} \leq 1, \forall j, \tag{3.12e}$$

$$\sum_{i=1}^{N} x_{i,j}^{(3)} \xi_{i,j}^{C} + \left(1 - \sum_{i=1}^{N} x_{i,j}^{(3)}\right) \xi_j^C \geq \xi_{\min}^{C}, \forall j, \tag{3.12f}$$

$$x_i^{(1)} \xi_i^{(1)} + x_i^{(2)} \xi_i^{(2)} + \sum_{j=1}^{M} x_{i,j}^{(3)} \xi_{i,j}^{(3)} \geq \xi_{\min}^{V}, \forall i, \tag{3.12g}$$

$$\sum_{i=1}^{N} x_{i,j}^{(3)} p_{i,j}^{C} + \left(1 - \sum_{i=1}^{N} x_{i,j}^{(3)}\right) p_j^C \leq P_{\max}^{C}, \forall j, \tag{3.12h}$$

$$x_i^{(1)} p_i^{(1)} + x_i^{(2)} p_i^{(2)} + \sum_{j=1}^{M} x_{i,j}^{(3)} p_{i,j}^{(3)} \leq P_{\max}^{V}, \forall i, \tag{3.12i}$$

In the proposed scheme, VUE can work in one of three distinct resource allocation modes namely Mode 4, dedicated mode and reuse mode. We define $\mathbf{x} = \{\mathbf{x}^{(1)}, \mathbf{x}^{(2)}, \mathbf{x}^{(3)}\}$ as a mode selection matrix in which $\mathbf{x}^{(1)}$, $\mathbf{x}^{(2)}$ and $\mathbf{x}^{(3)}$ are the indication matrices for the situations of VUEs working in Mode 4, dedicated mode and reuse mode, respectively. The size of both $\mathbf{x}^{(1)}$ and $\mathbf{x}^{(2)}$ is N-the total number of VUEs. The element of $\mathbf{x}$ is a binary variable and is set to 1 if the corresponding resource allocation mode is chosen for V2X communication; Otherwise, it is set to 0. Let us take for instance Mode 4. When VUE i works in this mode, $x_i^{(1)} = 1$; otherwise, $x_i^{(1)} = 0$. In addition, U indicates the number of available vacant unlicensed RBs while L represents the number of available vacant licensed RBs. The minimum SINR requirements of PUEs and VUEs are denoted by $\xi_{\min}^{C}$ and $\xi_{\min}^{V}$, respectively while their maximum transmit power requirements are denoted by $P_{\max}^{C}$ and $P_{\max}^{V}$, respectively. In the optimization problem of equation (3.12), the transmit power matrix is $\mathbf{p} = \{\mathbf{p}^{(1)}, \mathbf{p}^{(2)}, \mathbf{p}^{(3)}, \mathbf{p}^{\mathbf{C}}\}$ in which, when VUEs work in Mode 4, their transmit power vector is indicated by $\mathbf{p}^{(1)}$, dedicated mode indicated by $\mathbf{p}^{(2)}$, and reuse mode indicated by $\mathbf{p}^{(3)}$, respectively. Similarly, the transmit power matrix of PUEs is given as $\mathbf{p}^{\mathbf{C}}$, in which when the RB of PUE j is shared by VUE i, the element $p^C = p_{i,j}^C$; otherwise, $p^C = p_j^C$.

We assume that the number of VUEs working in Mode 4 and dedicated mode is restricted to less than the total number of vacant unlicensed and licensed RBs by constraints (3.12b) and (3.12c), respectively. We further assume that, at any given TTI, a VUE pair can work at most in one of the resource allocation modes and one RB can be shared by only one VUE pair with one PUE as indicated by the constraints (3.12d) and (3.12e), respectively. The SINR requirements of PUEs and VUEs can be enforced through the use of constraints (3.12f) and (3.12g), respectively. The maximum transmit power of PUEs and VUEs are restricted by constraints (3.12h) and (3.12i), respectively.

The original problem in (3.12) is a non-convex and Mixed-Integer Nonlinear Program (MINLP) problem as discussed in Appendix A.1. Generally, the non-convex MINLP is considered to be NP-hard, thereby making it difficult to obtain an optimal solution in the polynomial time [114]. Theoretically, the convex MINLP problem is much easier to handle when compared to non-convex MINLP problem. Therefore, we will first convert the optimization problem in (3.12) into an equivalent convex MINLP problem (3.13) under the same constraints. The equivalent problem (3.13) given below has the same optimal solution as the problem in (3.12).

$$\begin{aligned}(\mathbf{x}^*, \mathbf{p}^*) = \underset{\mathbf{x},\mathbf{p}}{\operatorname{argmax}} \Bigg\{ &\sum_{i=1}^{N} x_i^{(1)} \theta_i^{(1)} \log_2 \left(1 + \frac{p_i^{(1)} g_i}{\sigma^2}\right) \\ &+ \sum_{i=1}^{N} x_i^{(2)} \theta_i^{(2)} \log_2 \left(1 + \frac{p_i^{(2)} g_i}{\sigma^2}\right) \\ &+ \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j}^{(3)} \theta_i^{(3)} \log_2 \left(1 + \frac{H}{I}\right) \Bigg\},\end{aligned} \tag{3.13}$$

where

$$H = p_{i,j}^{(3)} g_i g_{j,B}, \tag{3.13a}$$

$$I = \xi_{\min}^{C} p_{i,j}^{(3)} g_{i,B} g_{i,j} + \xi_{\min}^{C} \sigma^2 g_{i,j} + \sigma^2 g_{j,B}. \tag{3.13b}$$

Proof: Since the logarithm function shown in equation (3.12) monotonically decreases with respect to $p_{i,j}^{C}$, the maximum information value of equation (3.12) can be obtained when $p_{i,j}^{C}$ reaches its minimum value $p_{i,j}^{C^*}$. According to the constraint (3.12f), when VUE i works in the resue mode, the minimum value $p_{i,j}^{C^*}$ can be obtained when the left-hand side of the constraint function in (3.12f) is equal to the minimum SINR requirement $\xi_{\min}^{C}$, as shown:

$$p_{i,j}^{C^*} = \frac{\xi_{\min}^{C} p_{i,j}^{(3)} g_{i,B} + \xi_{\min}^{C} \sigma^2}{g_{j,B}}, \tag{3.14}$$

By substituting $p_{i,j}^{C^*}$ into equation (3.12), the original optimization problem can be altered to the formulation (3.13) with the same constraints that govern equation (3.12), which concludes the proof.

As proved in Appendix A.2, the optimization problem in (3.13) is a convex MINLP problem for which Branch-and-Bound (BB) algorithm is considered to be an effective method to find its optimal solution [115]. In the worst case scenario, the computational complexity of BB algorithm is quite high and is comparable to that of an exhaustive search. In our case, BB method may enumerate $\binom{m}{n}$ possible combinations, where $m = \max(M, N)$ and $n = \min(M, N)$. For each combination, there is $n!$ matching arrangements between VUEs and PUEs. Therefore, the worst-case complexity of the BB algorithm for our proposed scheme is $\frac{m!}{(m-n)!}$.

3.4 Joint Power Control and Resource Allocation Mode Selection

As discussed in the last section, even though we have altered the non-convex MINLP problem in equation (3.12) to the convex MINLP problem (3.13) which can be solved by BB algorithm, the computational complexity of the BB algorithm is very high as it tends to grow exponentially with a corresponding increase in the number of UEs. Therefore, in this section, we propose an approach of joint power control and resource allocation mode selection to find a sub-optimal solution to the optimization problem (3.12). In order to reduce the computational complexity, the proposed algorithm is developed by two subproblems. We first solve the optimal power control problem under different resource allocation modes. Using the results so obtained, we further simplify the problem (3.12) into the problem of resource allocation mode selection and solve this through the use of two algorithms that are novel: The VRBPA algorithm in conjunction with ORBPA algorithm under different network load conditions.

3.4.1 Power Control for Different V2X Communication Modes

In this section, for each mode of operation of a VUE, we will suggest a way to maximise its information value by using an optimal power approach. In addition, we also investigate ways to meet the requirements of minimum SINR and maximum transmit power limitation for both PUEs and VUEs by proper use of power control. When a VUE pair i operates either in Mode 4 or in dedicated mode, VUE i occupies a dedicated RB to communicate without being subject to co-channel interference. We get the maximum information value of VUE i at its maximum transmit power shown as:

$$P_{\max}^{V} = p_i^{V^*} = \underset{p_i^V}{\operatorname{argmax}} \left\{ \theta_i \log_2 \left(1 + \frac{p_i^V g_i}{\sigma^2} \right) \right\}, \tag{3.15}$$

where p_i^V is the transmit power of VUE i. When VUE pair i works in the reuse mode, to mitigate the interference problem, we propose a joint optimal power control approach with a view of maximizing the information value of VUE i while meeting the requirements of minimum SINR and maximum transmit power limitation for both PUEs and VUEs. Refer to equation (3.16) given below:

$$\left(p_{i,j}^{C^*}, p_{i,j}^{(3)^*} \right) = \underset{p_{i,j}^C, p_{i,j}^{(3)}}{\operatorname{argmax}} \left\{ \theta_i^{(3)} \log_2 \left(1 + \frac{p_{i,j}^{(3)} g_i}{p_{i,j}^C g_{i,j} + \sigma^2} \right) \right\}. \tag{3.16}$$

subject to

$$\xi_{i,j}^{C} = \frac{p_{i,j}^{C} g_{j,B}}{p_{i,j}^{(3)} g_{i,B} + \sigma^2} \geq \xi_{\min}^{C}, \forall j, \tag{3.16a}$$

$$\xi_{i,j}^{(3)} = \frac{p_{i,j}^{(3)} g_{i}}{p_{i,j}^{C} g_{i,j} + \sigma^2} \geq \xi_{\min}^{V}, \forall i, \tag{3.16b}$$

$$p_{i,j}^{C} \leq P_{\max}^{C}, \forall j, \tag{3.16c}$$

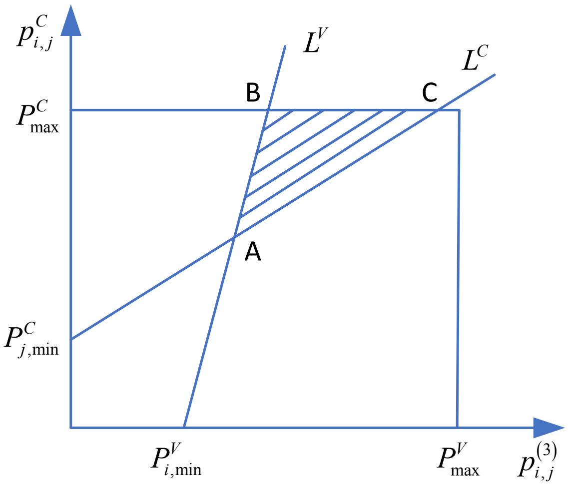
$$p_{i,j}^{(3)} \leq P_{\max}^{V}, \forall i, \tag{3.16d}$$

The feasible region of the basic solution to problem (3.16) should be the intersection set of all constraints from (3.16a) to (3.16d). We can draw three possible scenarios for this feasible region as shown in the shaded part in Fig. 3.2(a), 3.2(b) and 3.2(c), respectively. In Fig. 3.2, L^V and L^C are the lines which represent the function of the left-hand side is equal to the value of the right-hand side of constraints (3.16a) and (3.16b) , respectively. The square is composed of constraints (3.16c) and (3.16d) with equality. The shaded part is also called admissible region for VUE pairs where VUE pair i is permitted to reuse the same RB of PUE j. This implies that optimal power allocation vector $\left(p_{i,j}^{C^*}, p_{i,j}^{(3)^*}\right)$ should reside in the admissible region. When VUE i does not resue the RB of PUE j, $p_{j,\min}^{C}$ and $p_{i,\min}^{V}$ are the minimum transmit power of PUE j and VUE i, respectively. We can calculate $p_{j,\min}^{C} = \xi_{i,j}^{C}\sigma^2/g_{j,B}$ from constraint (3.16a) if $p_{i,j}^{(3)} = 0$. Similarly, we can obtain that $p_{i,\min}^{V} = \xi_{i,j}^{(3)}\sigma^2/g_i$ from constraint (3.16b) when $p_{i,j}^{C} = 0$. We then denote A as the intersection point of L^V and L^C. According to constraints (3.16a) and (3.16b), we can calculate the coordinates of A $(p_{i,j,A}^{(3)},\ p_{i,j,A}^{C})$. Obviously, the admissible region is conditional upon the intersection point A being within the square area. Therefore, the admissible conditions to enable VUE i to gain access to the spectrum resource of PUE j can be expressed as:

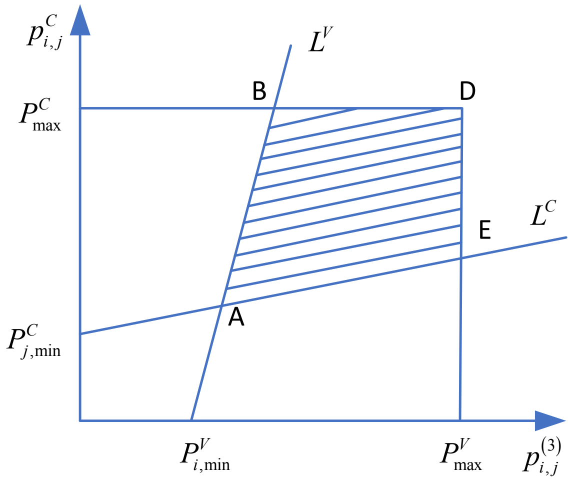
$$\begin{cases} 0 < p_{i,j,A}^{(3)} = \frac{\left(g_{i,j}\xi_{\min}^{C}\xi_{\min}^{V} + g_{j,B}\xi_{\min}^{V}\right)\sigma^2}{g_i g_{j,B} - g_{i,j} g_{i,B}\xi_{\min}^{C}\xi_{\min}^{V}} \leq P_{\max}^{V}, \\ 0 < p_{i,j,A}^{C} = \frac{\left(g_{i,B}\xi_{\min}^{C}\xi_{\min}^{V} + g_{i}\xi_{\min}^{C}\right)\sigma^2}{g_i g_{j,B} - g_{i,j} g_{i,B}\xi_{\min}^{C}\xi_{\min}^{V}} \leq P_{\max}^{C}, \end{cases} \tag{3.17}$$

Proposition 1. *The optimal power allocation vector* $\left(p_{i,j}^{C^*}, p_{i,j}^{(3)^*}\right)$ *of the problem (3.16) can be obtained in the corner points set* Ω *of the admissible region in which all constraints (3.16a)-(3.16d) are satisfied. As shown in Fig. 3.2, the corner points set* Ω *includes points B, C, D, E and F.*

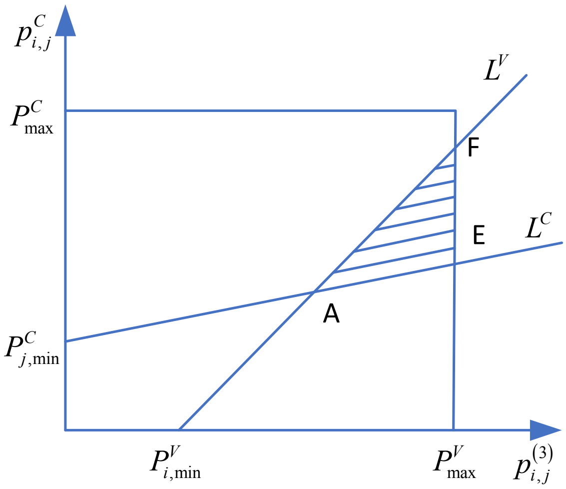
$$\left(p_{i,j}^{C^*}, p_{i,j}^{(3)^*}\right) = \underset{\left(p_{i,j}^{C}, p_{i,j}^{(3)}\right)\in\Omega}{\operatorname{argmax}} \left\{ \theta_i^{(3)} \log_2\left(1 + \frac{p_{i,j}^{(3)} g_i}{p_{i,j}^{C} g_{i,j} + \sigma^2}\right)\right\}, \tag{3.18}$$



(a) Scenario I



(b) Scenario II



(c) Scenario III

FIGURE 3.2: The different admissible regions scenarios.

where

$$\Omega = \begin{cases} \{(P^C_{max}, P_1), (P^C_{max}, P_2)\}, \\ if \frac{P^C_{max} g_{j,B}}{P^V_{max} g_{i,B} + \sigma^2} < \xi^C_{min}, \ and \ \frac{P^V_{max} g_i}{P^C_{max} g_{i,j} + \sigma^2} \geq \xi^V_{min}, \\ \\ \{(P_3, P^V_{max}), (P_4, P^V_{max})\}, \\ if \frac{P^C_{max} g_{j,B}}{P^V_{max} g_{i,B} + \sigma^2} \geq \xi^C_{min}, \ and \ \frac{P^V_{max} g_i}{P^C_{max} g_{i,j} + \sigma^2} < \xi^V_{min}, \\ \\ \{(P^C_{max}, P_1), (P^C_{max}, P^V_{max}), (P_4, P^V_{max})\}, \\ if \frac{P^C_{max} g_{j,B}}{P^V_{max} g_{i,B} + \sigma^2} \geq \xi^C_{min}, \ and \ \frac{P^V_{max} g_i}{P^C_{max} g_{i,j} + \sigma^2} \geq \xi^V_{min}, \end{cases} \tag{3.19}$$

$$P_1 = \frac{(P^C_{max} g_{i,j} + \sigma^2)\xi^V_{min}}{g_i}), \tag{3.19a}$$

$$P_2 = \frac{P^C_{max} g_{j,B} - \xi^C_{min}\sigma^2}{\xi^C_{min} g_{i,B}}, \tag{3.19b}$$

$$P_3 = \frac{P^V_{max} g_i - \xi^V_{min}\sigma^2}{\xi^V_{min} g_{i,j}}, \tag{3.19c}$$

$$P_4 = \frac{(P^V_{max} g_{i,B} + \sigma^2)\xi^C_{min}}{g_{j,B}}, \tag{3.19d}$$

Proof: Since the logarithm function is a monotonically increasing function and θ_i is a constant, we can simplify problem (3.16) into an equivalent problem (3.20) governed by the same constraints, shown as follows,

$$f(p^C_{i,j}, p^{(3)}_{i,j}) = \max\left\{\frac{p^{(3)}_{i,j} g_i}{p^C_{i,j} g_{i,j} + \sigma^2}\right\}, \tag{3.20}$$

The second derivative of function (3.20) with respect to $p^C_{i,j}$ is:

$$\frac{\partial^2 f}{\partial p^{C^2}_{i,j}} = \frac{2p^{(3)}_{i,j} g_i g^2_{i,j}}{(p^C_{i,j} g_{i,j} + \sigma^2)^3} > 0, \tag{3.21}$$

The second derivative of function (3.20) with respect to $p^{(3)}_{i,j}$ is:

$$\frac{\partial^2 f}{\partial p^{(3)^2}_{i,j}} = 0, \tag{3.22}$$

Therefore, equation (3.20) is convex with $\left(p^C_{i,j}, p^{(3)}_{i,j}\right)$. Furthermore, the optimal solution to equation (3.20) should satisfy all constraints from (3.16a) to (3.16d) which are linear in nature. This is to say, the feasible region for problem (3.20) is the intersection of all these constraints, which turns to be a convex set. Therefore, (3.20) is a convex problem whose optimal power allocation vector $\left(p^{C^*}_{i,j}, p^{(3)^*}_{i,j}\right)$ occurs at a corner of the feasible region. The proof is complete.

3.4.2 Resource Allocation Mode Selection

In this section, we substitute the results of optimal power allocation $P^V_{\max}$ and $\left(p^{C^*}_{i,j}, p^{(3)^*}_{i,j}\right)$ into equation (3.12). By doing this, the original optimization problem can be altered into the resource allocation mode selection problem as follows:

$$\begin{aligned}\mathbf{x}^* = \underset{\mathbf{x}}{\operatorname{argmax}} \Bigg\{ & \sum_{i=1}^{N} x_i^{(1)} \theta_i^{(1)} \log_2 \left(1 + \frac{P_{\max}^V g_i}{\sigma^2}\right) \\ & + \sum_{i=1}^{N} x_i^{(2)} \theta_i^{(2)} \log_2 \left(1 + \frac{P_{\max}^V g_i}{\sigma^2}\right) \\ & + \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j}^{(3)} \theta_i^{(3)} \log_2 \left(1 + \frac{p_{i,j}^{(3)^*} g_i}{p_{i,j}^{C^*} g_{i,j} + \sigma^2}\right) \Bigg\},\end{aligned} \tag{3.23}$$

subject to

$$x_i^{(1)}, x_i^{(2)}, x_{i,j}^{(3)} \in \{0, 1\}, \forall i, j, \tag{3.23a}$$

$$\sum_{i=1}^{N} x_i^{(1)} \leq U, \forall i, \tag{3.23b}$$

$$\sum_{i=1}^{N} x_i^{(2)} \leq L, \forall i, \tag{3.23c}$$

$$x_i^{(1)} + x_i^{(2)} + \sum_{j=1}^{M} x_{i,j}^{(3)} \leq 1, \forall i, \tag{3.23d}$$

$$\sum_{i=1}^{N} x_{i,j}^{(3)} \leq 1, \forall j, \tag{3.23e}$$

$\mathbf{x}^*$ is the only binary variable in equation (3.23). Hence, equation (3.23) is a 0-1 integer programming problem. Using Branch-and-Bound (BB) algorithm an optimal solution to this problem (3.23) can be obtained. However, due to the high complexity of BB algorithm, it cannot be considered as a viable option [116]. Alternatively, we propose an approach of joint resource scheduling of different communication modes: Mode 4, dedicated mode, and reuse mode by using VRBPA algorithm in conjunction with ORBPA algorithm under different network load conditions. In comparison to the BB algorithm, this approach solves the problem of resource allocation mode selection with lower complexity as shown in equation (3.23).

In this paper, based on different network load conditions, two main network load categories are considered: light load and heavy load. As shown in Table 3.1, when the sum of the number of vacant unlicensed and licensed RBs is not less than the number of VUEs, i.e. $L + U \geq N$, this network is detected as the light load by eNB, where VUEs can choose either Mode 4 or dedicated mode for communication. Otherwise, if $L + U < N$, the network is considered as the heavy load by eNB, where VUEs can work in different communication modes including Mode 4, dedicated and reuse mode.

In this paper, we prefer to arrange the vacant unlicensed and licensed RBs to the VUEs with higher information value firstly even though the size of the corresponding V2X message is small. There are two main reasons for this. First of all, if the information value is very high, it means this message is very urgent and important, such as collision avoidance safety

Table 3.1: Different Network Load Conditions

$L + U \geq N$	Light load	Mode 4+dedicated mode
$L + U < N$	Heavy load	Mode 4+dedicated mode +reuse mode

information. In this case, this kind of messages must be transmitted with low latency and high reliability for the sake of the protection of people. Therefore, the vacant RBs should be first assigned to VUEs with high information value. Another main reason is that RB is the smallest time-frequency resource unit used for data transmission. Therefore, we cannot further divide RB into a smaller unit, even though the message is short. The vacant RBs allocation is realized by the proposed VRBPA algorithm when the network is lightly loaded. We then arrange the VUEs with lower information value to reuse the resources of PUEs if the network is heavily loaded, which is implemented by the proposed ORBPA Algorithm. In the proposed scheme, we assume that eNB is responsible for switching the algorithm for different network load conditions. This is achieved by eNB detecting the availability of vacant RBs via users' signalling feedback mechanism.

The proposed algorithm is executed by joint resource allocation between the distributed system (without the involvement of eNB) and the centralized system (under the control of eNB). In particular, for Mode 4 (distributed system), VUEs autonomously carry out the distributed resource allocation algorithm to obtain the resource allocation result. In contrast, for Mode 3 including dedicated and reuse mode (centralized system), eNB has the capability of obtaining the global CSI information, running the proposed centralized resource allocation algorithm and broadcasting the optimal resource allocation results to users at the beginning of each TTI.

3.4.3 Vacant Resource Blocks and Power Allocation Algorithm

In a lightly loaded network where the number of available RBs is greater than or equal to the number of available VUE pairs, we propose the VRBPA algorithm to solve the resource allocation mode selection problem for Mode 4 and dedicated mode jointly in two steps as explained below.

In step 1, to avoid the high signalling overhead at eNB, at the beginning of each TTI, VUE with the highest information value preferentially choose to work in Mode 4. Since Mode 4 is a distributed system, a distributed resource allocation algorithm is designed for this mode. In particular, Mode 4 enables VUEs to transmit data independently by choosing the dedicated RBs from the unlicensed resource pools without being dependent on the core network or eNB connectivity. In this mode, the data transmission of V-UEs is scheduled autonomously by sensing the energy level of RBs and sending/reading the scheduling assignment signal to/from other users. If multiple VUEs sensing the same vacant RB simultaneously, the VUE with the highest information value is allowed to get access the RB. This is implemented by exchanging scheduling assignment signal between VUEs by broadcasting. Furthermore, the VUE can select the resource pool based on its location by using the pre-configured mapping between geographical zones and unlicensed resource pools. Once the vacant unlicensed RB is occupied, it must be removed from the unlicensed resource pool. If all vacant unlicensed

RBs are occupied which is detected by VUEs using sensing technology, VUEs will report this information to eNB and eNB will switch the algorithm from the distributed resource allocation algorithm to the centralized resource allocation algorithm. The VRBPA algorithm moves to step 2.

In step 2, the remaining VUEs which have not obtained any available RBs, are assigned to dedicated mode. In this case, eNB takes up the responsibility of allocating the dedicated RBs to VUEs and completes the resource allocation process in dedicated mode. Thereafter, the allocated RB gets removed from the vacant licensed RB set. The resource allocation process outlined in step 2 will be terminated when there are no vacant licensed RBs left or no VUEs requesting RBs anymore; Otherwise, the rest of VUEs will be assigned to reuse mode. Steps 1 and 2 are implemented by the proposed VRBPA Algorithm shown in Algorithm 1.

Algorithm 1 Vacant Resource Blocks and Power Allocation Algorithm

$\mathbf{V}$ represents the set of unmatched VUEs;
$\mathbf{V_r}$ represents the set of VUEs sharing same RBs with PUEs;
Calculate the information value of each VUE in the dedicated RB;
while $\mathbf{V} \neq \varnothing$ **do**
    Step 1: Autonomous Resource Selection Mode Selection
    if $\hat{\mathcal{F}}_{\mathcal{U}} \neq \varnothing$ **then**
        VUE i with the highest information value in $\mathbf{V}$ gets access to vacant unlicensed RB $\hat{F}_i$ by sensing and broadcasting technology;
        $x_i^{(1)} = 1$;
        Remove RB $\hat{F}_i$ from vacant unlicensed RBs set $\hat{\mathcal{F}}_{\mathcal{U}}$;
        Remove VUE i from $\mathbf{V}$;
        Step 2: Dedicated Mode Selection
    else if $\mathcal{F}_{\mathcal{L}} \neq \varnothing$ **then**
        VUE i with the highest information value in $\mathbf{V}$ gets access to vacant licensed RB F_i by the scheduling of eNB;
        $x_i^{(2)} = 1$;
        Remove RB F_i from vacant licensed RBs set $\mathcal{F}_{\mathcal{L}}$;
        Remove VUE i from $\mathbf{V}$;
    else if $\hat{\mathcal{F}}_{\mathcal{U}} = \varnothing \& \mathcal{F}_{\mathcal{L}} = \varnothing$ **then**
        BREAK. Stop the while loop.
    end if
end while
VRBPA algorithm is finished. Obtain $\mathbf{x^{(1)}}$ and $\mathbf{x^{(2)}}$.
if $\mathbf{V} \neq \varnothing$ **then**
    Assign the rest of VUEs to the reuse set $\mathbf{V_r}$.
end if

3.4.4 Occupied Resource Blocks and Power Allocation Algorithm

In the case of a heavily loaded network, the number of VUEs is greater than the number of available vacant RBs. To mitigate co-channel interference, the proposed approach of joint power control and resource allocation mode selection is conducted by first executing VRBPA algorithm to allocate vacant RBs to VUEs. If all vacant licensed RBs are occupied which is detected by eNB, the rest of VUEs are assigned to reuse mode. Then eNB switches the algorithm from VRBPA Algorithm to ORBPA Algorithm which is designed for the resource allocation of V2X communication in reuse mode. The details of designing ORBPA is illustrated as follows.

Matching problem formulation

By executing VRBPA algorithm we obtain $\mathbf{x^{(1)}}$ and $\mathbf{x^{(2)}}$ and by using these in equation (3.23), we can obtain a further simplified equation (3.24). Thus, the resource allocation problem boils down to finding the optimal reuse PUEs for VUEs such that the overall information values of safety-related V2X communication can be maximized, which is shown below:

$$\mathbf{x^{(3)}}^{*} = \underset{\mathbf{x^{(3)}}}{\operatorname{argmax}} \left\{ \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j}^{(3)} \theta_i^{(3)} \log_2 \left(1 + \frac{p_{i,j}^{(3)^*} g_i}{p_{i,j}^{C^*} g_{i,j} + \sigma^2} \right) \right\}, \tag{3.24}$$

subject to

$$x_{i,j}^{(3)} \in \{0,1\}, \forall i, j, \tag{3.24a}$$

$$\sum_{j=1}^{M} x_{i,j}^{(3)} \leq 1, \forall i, \tag{3.24b}$$

$$\sum_{i=1}^{N} x_{i,j}^{(3)} \leq 1, \forall j, \tag{3.24c}$$

The problem of equation (3.24) can be considered as a one-to-one matching problem because constraints (3.24b) and (3.24c) impose the restriction that one VUE can only reuse one PUE's RB and the RB of one PUE can be shared by one VUE at most.

Matching Algorithm Analysis

Since safety-related V2X information is critical, we strive to improve the QoS of V2X messages by taking into consideration both PPPP of transmitted messages as well as communication link quality. Furthermore, we do not want to degrade the throughput of PUEs whose resources are currently being used by VUEs. Taking these requirements into consideration, the matching problem between VUEs and their reuse PUEs can be perfectly cast to the stable marriage problem because it can guarantee the QoS demands of both the parties. Stable marriage problem is described as the stable matching problem between two equally sized sets of single men and single women given the preference list of the opposite sex of each person. The matching is stable only if all men and women are married off and there exist no such instances wherein a man and a woman from two different marriages still prefer each other over their current partners [117].

The well-known Gale-Shapley (GS) algorithm can solve the stable matching problem between the two sets in a satisfactory way. However, the original stable marriage problem requires two equally sized sets of men and women. This is obviously unrealistic in practical deployment scenarios of V2X communication because the exact number of PUEs and VUEs are not known a priori. Depending on the number of VUEs (either less, equal to or larger than the number of PUEs), the proposed solution modifies the GS algorithm accordingly to achieve the stable matching between the elements of VUEs set and the elements of PUEs set. In our previous work [27], we solve this matching problem using the Hungarian algorithm. The computational complexity of the Hungarian algorithm ($O(m^3)$) is higher than the computational complexity of the modified GS algorithm ($O(m^2)$). Furthermore, Hungarian Algorithm cannot achieve a stable matching between VUEs and PUEs. Hence, this chapter only uses the Hungarian Algorithm for the sake of comparison.

Matching Algorithm Design

We construct each VUEs preference list by enumerating its information value with every PUE. We denote $inf_{i,j}$ as the preference value of VUE i over PUE j. If VUE i is allowed to reuse the resource of PUE j, $inf_{i,j}$ can be obtained by using equation (3.16); otherwise, $inf_{i,j} = 0$. Likewise, we construct each PUEs preference list in which its data rate values when partnered with different VUEs are arranged in a preferential order - highest (most preferred) to the lowest (least preferred). We define the instant data rate $r^C_{i,j}$ as the preference value of PUE j over VUE i. If VUE i gets permission to share the same resource with PUE j, the preference value of PUE j over VUE i can be calculated by the following equation (3.25):

$$r^{C^*}_{i,j} = \log_2\left(1 + \frac{p^{C^*}_{i,j}\, g_{j,B}}{p^{(3)^*}_{i,j}\, g_{i,B} + \sigma^2}\right) \tag{3.25}$$

where $\left(p^{C^*}_{i,j}, p^{(3)^*}_{i,j}\right)$ is the optimal power allocation when the RB of PUE j is reused by VUE i; otherwise, $r^C_{i,j} = 0$. We define the stable matching between VUEs and PUEs as:

Definition 1. *The stable matching between VUEs set and PUEs set is defined as: For any two VUEs i and m who are allocated to PUEs j and n, respectively, there is no blocking pair VUE i and PUE n, such that VUE i prefers PUE n to PUE j ($inf_{i,n} > inf_{i,j}$), and PUE n prefers VUE i to VUE m ($r^C_{i,m} > r^C_{i,j}$).*

Due to the symmetry, GS algorithm can be made to run either using men-optimal stable matching or women-optimal stable matching, which means, if men propose to women, the matching result is optimal for men, and vice versa. In this thesis, we propose to adopt the VUE-optimal stable matching to enhance the overall information value of V2X communication. Specifically, in each resource allocation loop, a VUE first proposes to a reuse PUE partner that has the highest information value in the preference list. Thereafter, the proposed PUE will select a preferred VUE with the highest data rate from all proposals, keep this decision confidential and ignore the rest. Therefore, in the proposed scheme, not only the information value of V2X communication can be enhanced but also the QoS for the data transmission rates of PUEs can be guaranteed. The detailed procedure of the proposed ORBPA algorithm is shown in Algorithm 2.

Algorithm 2 Occupied Resource Blocks and Power Allocation Algorithm

Execute VRBPA algorithm first;
Build VUEs' Preference List and PUE's Preference List:
for all $i \in \mathbf{V_r}, j \in M$ **do**
  if VUE pair i is allowed to access the RB of PUE j **then**
    Calculate the maximum information value $inf_{i,j}$ of VUE pair i by using Eq. (3.16);
    Calculate the data rate value $r_{i,j}^C$ of PUE j by using Eq. (3.25);
  else
    $inf_{i,j} = 0$; $r_{i,j}^C = 0$;
  end if
end for
Modified GS Algorithm (VUE-Optimal)
Define $\mathbf{V_{UM}}$ as the set of unmatched VUEs;
Define $\mathbf{P_{UM}}$ as the set of unmatched PUEs;
while $\mathbf{V_{UM}} \neq \varnothing$ and $\mathbf{P_{UM}} \neq \varnothing$ **do**
  Choose any VUE i from $\mathbf{V_{UM}}$;
  Find PUE j with the maximum $inf_{i,j}$ as the best match from the set of unmatched PUEs on the preference list of VUE i;
  Make VUE i propose to PUE j;
  if PUE j is unmatched **then**
    PUE j holds VUE i on a string;
    Remove VUE i and PUE j from $\mathbf{V_{UM}}$ and $\mathbf{P_{UM}}$, respectively;
  else if PUE j is already engaged to some VUE k **then**
    Compare the data rate $r_{i,j}^C$ with $r_{i,k}^C$;
    if $r_{i,k}^C < r_{i,j}^C$ **then**
      PUE j prefers VUE i over current partner VUE k;
      PUE j keeps VUE i and rejects VUE k;
      Remove VUE i from $\mathbf{V_{UM}}$ and add VUE k to $\mathbf{V_{UM}}$;
    end if
  end if
end while
Obtain the matching matrix $\mathbf{x^{(3)}}$.

3.5 Performance Analysis for Safety-related V2X Communication

3.5.1 Scenarios and Parameters for Safety-related V2X Communication

For the simulations, WINNER+B1 Manhattan grid layout is used for VUEs pathloss model. Macrocell propagation model of the urban area is used for PUEs pathloss model. For simplicity, the PPPP value of each VUE is set to a random number in the range of $[0, 1]$.

TABLE 3.2: Simulation Parameters for Safety-related V2X Communication

Parameter	**Value**
Unlicensed bandwidth frequency	6 GHz
Bandwidth of each RB	180 kHz
Noise spectral density	-174 dBm/Hz
Pathloss model for VUEs	WINNER+B1
Pathloss model for PUEs	$128.1 + 37.6 \log(d[\text{km}])$
Multiple-path fading of PUEs	Unit mean
Shadowing standard deviation	8 dB (PUEs), 4 dB (VUEs)
SINR threshold, $\xi^C_{\min}$, $\xi^V_{\min}$	8 dB, 10 dB
Maximum power, $P^C_{\max}$	23 dBm
Maximum power, $P^V_{\max}$	18 dBm, 23 dBm
The number of vacant licensed RBs, L	3
The number of vacant unlicensed RBs, U	3
The number of PUEs, M	10-100
The speed of vehicles	$40 - 110$ km/h
V2X pair distance, r	$20 - 500$ m

We restrict the use of our method to one TTI which is set to 0.5ms [56]. Since TTI represents a short interval of time, the vehicle location does not change enough for its effect to be discernible in this interval. Furthermore, the speeds of all vehicles remain the same in all lanes. The vehicle distribution is based on the Spatial Poisson Process. The vehicle speed determines the density of VUEs in the network. Table 3.2 shows our major simulation parameters.

In this section, we compare the performance results of our algorithm with other methods. In specific, the proposed approach is compared with the methods of the optimal algorithm, the algorithm proposed in [26] and the algorithm in the model of [27]. In order to reduce the computational complexity of the optimal algorithm, BB method is adopted to obtain the optimal solution of equation (3.23) instead of equation (3.13). The algorithm proposed in [26] only takes into account the scenario where VUEs are allocated dedicated RBs. The algorithm proposed in [27] can achieve the optimal solution for the assignment problem shown in equation (3.24) by using Hungarian algorithm.

Table 3.3 compares the computational complexity of different algorithms. From the data presented in Table 3.3, we can conclude that the number of VUEs is determined by the vehicle speed v(km/h), where $P^C_{\max} = P^V_{\max} = 23\text{dBm}, M = 20, r = 100\text{m}$. As we can see, the number of VUEs gradually reduces as the vehicle speed increases. That is to say, when the vehicle speed is slow, the number of VUEs is large, and vice versa. Furthermore, in Table 3.3, we compare the computational complexity of different algorithms by calculating

Table 3.3: Computational Complexity for Different Algorithms

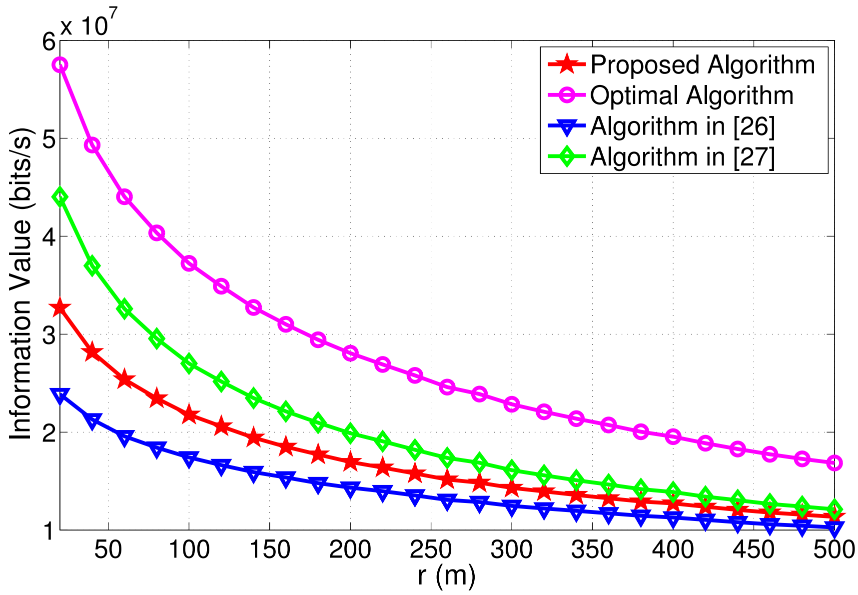
Parameter	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
v	40 km/h	50 km/h	60 km/h	70 km/h
N	49	39	32	28
O_P	1849	1089	672	484
O_H	79507	35937	17576	10648
O_O	2.3×10^{30}	1.3×10^{27}	5.6×10^{23}	5.6×10^{20}
Parameter	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**
v	80 km/h	90 km/h	100 km/h	110 km/h
N	24	21	19	17
O_P	400	400	400	400
O_H	8000	8000	8000	8000
O_O	1.2×10^{18}	2.0×10^{16}	4.8×10^{14}	6.7×10^{12}

the number of times the recursive function is called for different algorithms. We define O_P as the number of times the recursive function is executed in the proposed algorithm, O_H in the algorithm proposed in [27], and O_O in the optimal algorithm. As we can see, the proposed algorithm has the lowest computational complexity while the complexity of the optimal algorithm grows exponentially as the number of UEs increases. It is also shown that, the values of O_P and O_H remain unchanged when $v \geq$ 80km/h. This is because the complexity of the algorithm is determined either by the number of PUEs or the number of admissible VUEs, whichever being greater. If $v \geq$ 80km/h, the number of PUEs is larger than that of admissible VUEs.

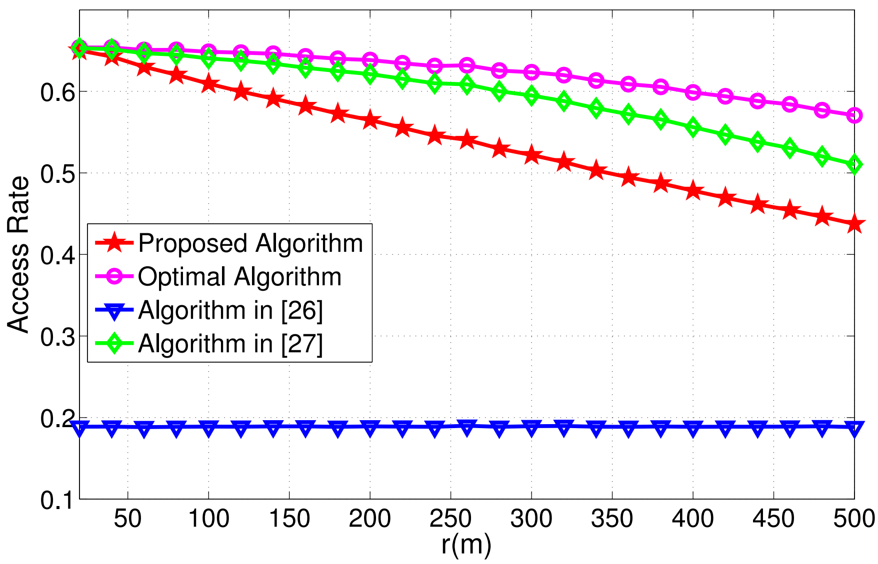
3.5.2 Simulation Results for Safety-related V2X Communication

Fig. 3.3 compares the system performance of different algorithms in terms of the information value and access rate of VUEs, where $P^C_{\max} = P^V_{\max} = 23\text{dBm}, M = 20, Speed = 60\text{km/h}$. From equation (3.11), we define the unit of the information value as "bits/s". We then measure the access rate of VUEs by using the ratio of the number of admissible VUEs to the total number of VUEs. Parameter r refers to the distance from VUE transmitter to VUE receiver. As we can see, there is a significant reduction in both the information value and access rate of VUEs when the distance r increases from 20m to 500m. This demonstrates that the increase in the pathloss caused by the corresponding increase in distance r can reduce instant data rates of VUEs sharply.

Furthermore, we can see that, in Fig. 3.3(a), the optimal algorithm achieves the best performance while the algorithm in [26] has the lowest information value. There are two main reasons for this. First, the optimal algorithm can implement the global optimization of resource allocation which allows more VUEs to get access to available RBs. Likewise, Hungarian algorithm in [27] can find the optimal reuse CUs for admissible VUEs working in



(a) The information value of VUEs against various r.



(b) The access rates of VUEs against various r.

FIGURE 3.3: Simulation results with different distance r, where $P^{C}_{\max} = P^{V}_{\max} = 23\text{dBm}, M = 20, Speed = 60\text{km/h}$.

the reuse mode. This is why these two algorithms perform better than the proposed algorithm and the algorithm proposed in [26]. However, both optimal and Hungarian algorithms cannot assign the RBs of PUEs to VUEs in a satisfactory way, which could result in an unstable matching between VUEs and their reuse PUEs. In contrast, the proposed algorithm can provide better stable matching between VUEs and PUEs by allocating RBs according to the preference lists of both VUEs and PUEs. Second, the scheme in the model of [26]

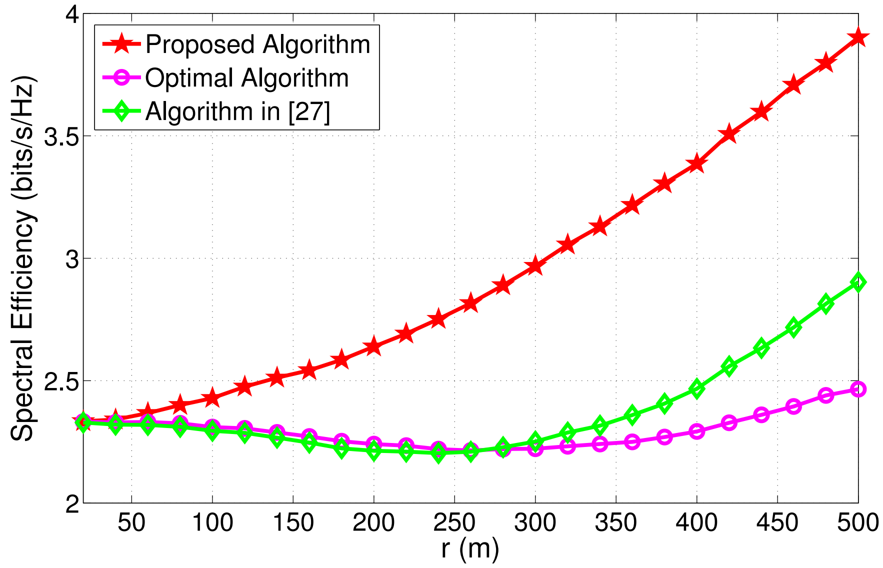


Figure 3.4: The spectral efficiency of PUEs for different r, where $P^C_{\max} = P^V_{\max} = 23\text{dBm}, M = 20, Speed = 60\text{km/h}$.

only allocates dedicated RBs to VUEs, which limits the number of VUEs accessing cellular resources. In contrast, the proposed algorithm, optimal algorithm and the algorithm in [27] make full use of all available RBs by assigning VUEs in both dedicated and reuse mode, thereby introducing high reuse gains within the cellular network. Fig. 3.3(b) demonstrates this point, where the access rate of VUEs in these three algorithms dramatically exceeds that of the system model in [26].

Fig. 3.4 clearly shows the proposed algorithm performs best among all three algorithms in terms of the spectral efficiency of PUEs. The main reason for this is that the optimal algorithm and the Hungarian algorithm in [27] aim to maximize overall information value of V2X communication while ignoring the QoS of PUEs. In contrast, the proposed algorithm takes into consideration the preference list of both VUEs and PUEs, thereby guaranteeing their QoS. We can also see that when r is small, all three algorithms show similar performance with respect to the spectral efficiency of PUEs. But, as r keeps increasing, the proposed algorithm outperforms the rest dramatically. Furthermore, the spectral efficiency of PUEs goes up as r increases. It demonstrates that the pathloss experienced by the VUEs tends to increase with the increase in r. As a result, the number of admissible VUEs falls down while the number of PUEs which experience no co-channel interference increases.

Furthermore, in Fig. 3.4, in the case of optimal and the Hungarian algorithm suggested in [27], the spectral efficiency of PUEs first goes down and then goes up with the increase in the distance r. This is because at the beginning, when r starts to increase, in order to meet the SINR requirements, VUEs have to increase their transmit power by using the optimal power control method, which causes a higher co-channel interference to PUEs. Accordingly, the spectral efficiency of PUEs decreases slightly. But, as r keeps increasing, more and more VUEs cannot meet their SINR requirements and are prevented from gaining access to the cellular resources. As a consequence, more and more PUEs are now able to communicate

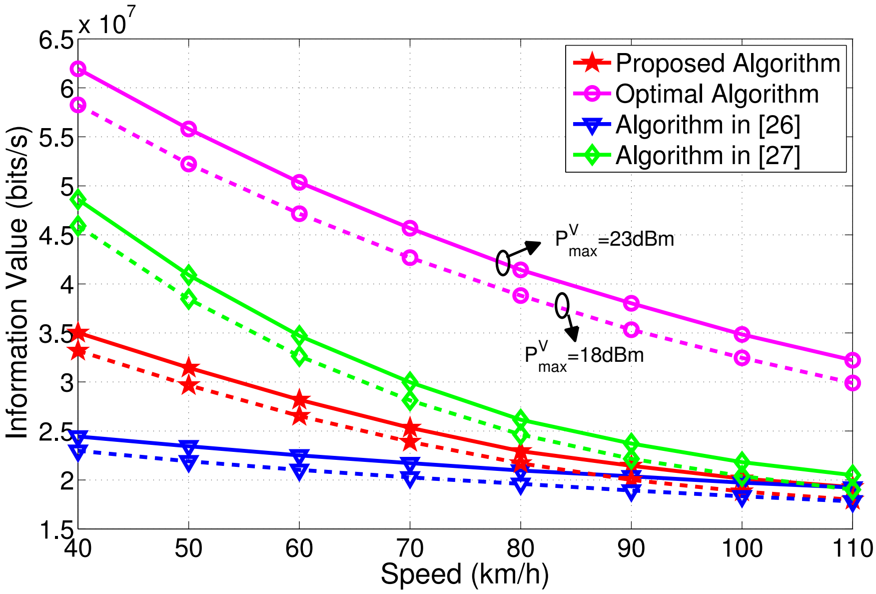
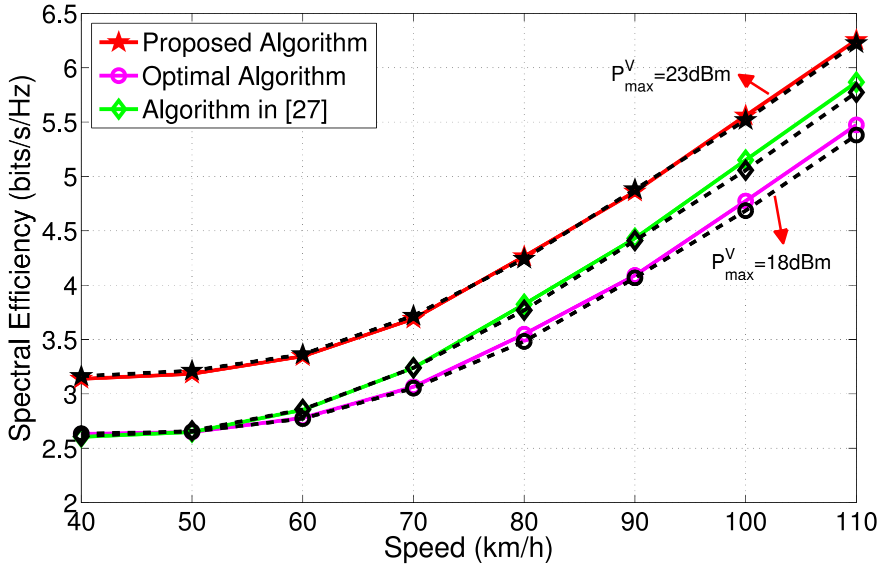


FIGURE 3.5: The information value of VUEs for different vehicle speed, where $P_{\max}^{C} = 23\text{dBm}, M = 20, r = 100\text{m}$.

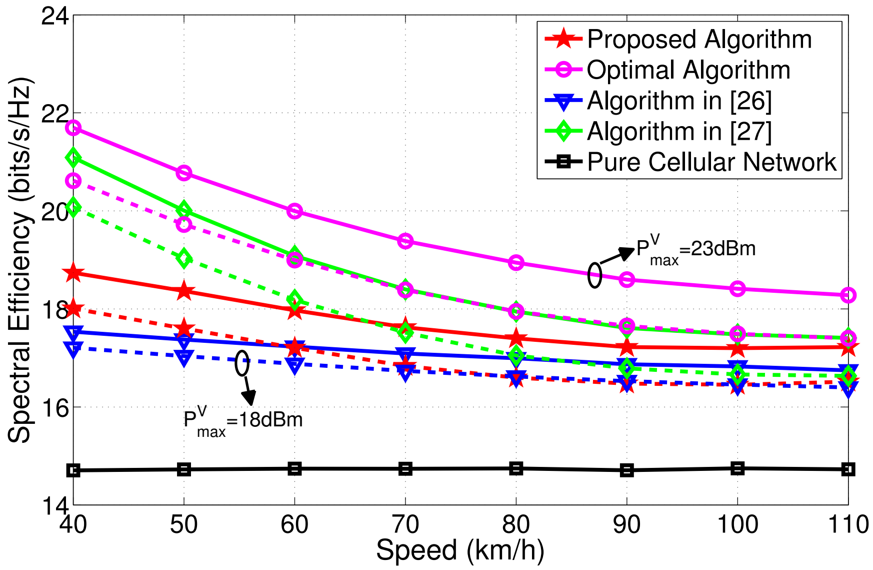
by using the dedicated RBs. Therefore, the spectral efficiency of PUEs increases when r is large enough. This also further demonstrates that the optimal algorithm and the Hungarian algorithm proposed in [27] only focus on optimizing the information value of VUEs while ignoring the QoS of PUEs.

In the proposed scheme, the vehicle speed can determine the number of VUEs in the system. Hence, in the following graphs, we will investigate the influence of the vehicle speed on the system performance. From Fig. 3.5, it is clear that the vehicle speed has a noticeable effect on the information value, where the solid line and the dashed line indicate $P_{\max}^{V} = 23\text{dBm}$ and $P_{\max}^{V} = 18\text{dBm}$, respectively. The results demonstrate that the overall information value of V2X communication is less likely to get benefitted in high-speed scenarios. Furthermore, VUEs with high transmit power perform better since this leads to high data rates. As the speed increases, the number of VUEs get reduced to be equal to or less than that of vacant RBs. Consequently, VUEs will gain access to these vacant RBs and so in this particular case, all algorithms except the optimal algorithm will tend to have similar Information values associated with VUEs.

Fig. 3.6 compares the spectral efficiency of different algorithms at different vehicle speeds. By comparing Fig. 3.6(a) and 3.6(b), we can see that, with the increase in the vehicle speed, the efficiency with which PUEs use spectral resources also increases but the overall spectral resources of the network are not efficiently utilized by the two UE types. This phenomenon is because both, the number of reuse PUEs and the reuse gain introduced by admissible VUEs decrease as the vehicle speed rises. We can see that even when VUEs transmit at different power levels it still does not bring about any discernible change in the spectral efficiency of PUEs. This is because the QoS of PUEs can be shielded from the co-channel interference by the optimal power control strategy. In contrast, a dramatic improvement in the overall throughput can be achieved by increasing the transmit power of VUEs due to the increasing



(a) The spectral efficiency of PUEs.



(b) The spectral efficiency of the overall network.

Figure 3.6: The spectral efficiency of different algorithms against various vehicle speed, where $P^C_{\max} = 23\text{dBm}, M = 20, r = 100\text{m}$.

data rates of VUEs. Furthermore, in Fig. 3.6(b), the proposed algorithm has a much higher spectral efficiency when compared to both pure cellular network and the model in [26], which proves that the proposed scheme can effectively enhance the spectral efficiency of the overall system by jointly allocating the licensed and unlicensed RBs.

Fig. 3.7 shows the access rates of VUEs for different vehicle speeds. When compared to the algorithm proposed in [26], the proposed algorithm can improve the access rates of

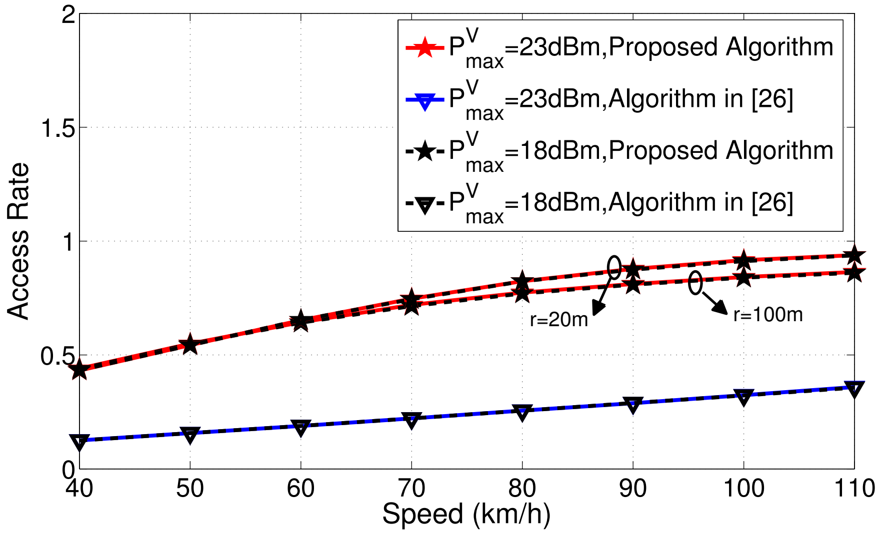
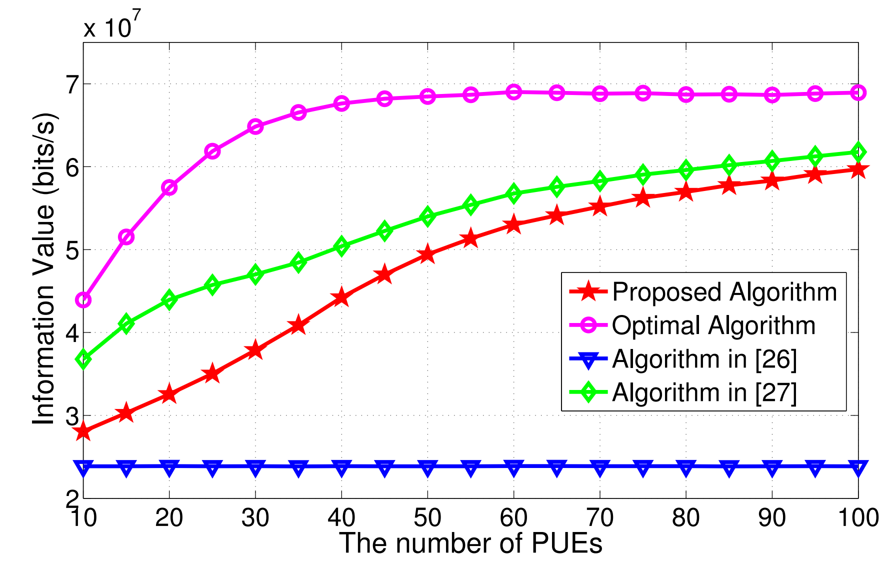


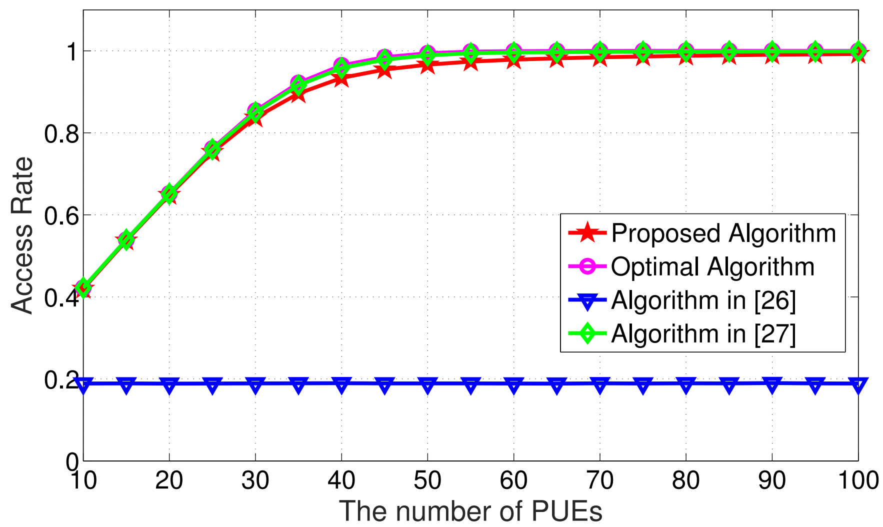
FIGURE 3.7: The access rates of VUEs for different vehicle speed, where $P^C_{\max} = 23\text{dBm}, M = 20, r = 100\text{m}$.

VUEs dramatically. In addition, as the vehicle speed increases, the access rates of VUEs are enhanced significantly because the total number of VUEs decreases with the increase in the vehicle speed. It is also shown that the access rates of VUEs with the transmit power of 23dBm are comparable to that of VUEs operating at 18dBm. This shows that at high data rates, a VUE easily meets its SINR requirement to access the cellular resource, even though its transmit power is quite low.

For different network load scenarios, Fig. 3.8(a) and 3.8(b) compare the system performance of different algorithms from the perspective of the information value and access rate of VUEs, respectively. We alter the network load scenario of the proposed scheme by increasing the number of PUEs from 20 to 100. For the simulation, we set $P^C_{\max} = P^V_{\max} = 23\text{dBm}, \mathit{Speed} = 60\text{km/h}$, and $r = 20\text{m}$. We define M as the number of PUEs. As shown in the figure, an increase in M can accordingly enhance both the information value and access rate of VUEs. Specifically, when $M < 40$, both information value and the access rate of VUEs increase sharply. This is because the number of admissible VUEs with a corresponding increase in the number of PUEs. However, when M is greater than 40, the rate at which the information value increases is slowed down. From Table 3.3, we can see that when $\mathit{Speed} = 60\text{km/h}$, the average number of VUE pairs is 32. Hence, if M keeps increasing and goes beyond 40, we observe that the number of PUEs is definitely greater than the number of VUE pairs, which implies there is a greater chance for each VUE pair to find their optimal reuse PUE partner. As a result, almost all VUEs get allocated a correponding RB, which has been demonstrated in Fig. 3.8(b) where the access rate of VUEs approaches 1 when $M > 40$. In this case, the increase in the information value of VUEs is restricted to the selection of the reuse PUEs, and this does not introduce a dramatic increase in the information value. Therefore, the information value of VUEs increases gradually when M becomes greater than 40. Furthermore, it is shown that the proposed algorithm exhibits performance similar to the algorithm proposed in [27] when M is large enough. Furthermore, the proposed algorithm



(a) The information value of VUEs.



(b) The access rate of VUEs.

FIGURE 3.8: Simulations results with different number of PUEs.

can provide a better stable matching between VUEs and PUEs when compared to the other two algorithms.

3.6 Summary

In this chapter, we have proposed a scheme of joint power control and resource allocation mode selection to support safety-related V2X services under different network load conditions. By taking into consideration different resource allocation modes: the dedicated mode, reuse mode and Mode 4, we have proposed power control strategies to specifically cater to these different modes in order to maximize the information value of a single VUE while mitigating the co-channel interference between VUE and its reuse PUE. To further improve the QoS of VUEs in terms of the ProSe Per-Packet Priority and the communication link quality, we have proposed two new algorithms, the VRBPA algorithm and the ORBPA algorithm for light network load scenario and heavy network load scenario, respectively, with a view to maximizing the sum of information values of all VUEs. This is accomplished through the use of joint resource scheduling of three resource allocation modes under different network load scenarios. The simulation results demonstrate that our proposed scheme can not only provide better performance in terms of the information value of VUEs but can also enhance the spectral efficiency of PUEs significantly when compared to other such schemes.

4

Resource Allocation for Underlay V2X Communication with Fairness

4.1 Preface

This chapter investigates the resource allocation problem for underlay non-safety-related V2X communication with a view to simultaneously improving both the system throughput and system fairness by using the proportional fair scheduling. Underlay V2X communication has the capability of offering high spectral and energy efficiency. However, the problem of co-channel interference makes the resource allocation very complex and challenging for underlay V2X communication. This chapter proposes a novel joint power control and resource scheduling scheme to enhance both the network throughput and the users' fairness of the underlay V2X communication networks. Unlike other previous work in this area, our scheme aims at maximizing the sum of all users' proportional fairness functions while simultaneously taking into account factors such as fairness, SINRrequirements and severe interference. The proposed scheme offers a practical solution because it works for lengthy Transmission Time Intervals, a realistic scenario for underlay V2X communication system. Numerical results confirm that our proposed scheme not only dramatically improves the system throughput but also boosts the system fairness while guaranteeing the QoS levels of all VUEs and CUEs. In this chapter, for simplicity, we denote one time slot as one transmission time interval in this chapter.

The rest of this chapter is organized as follows: In Section 4.2, we first model a system of underlay V2X communication network for lengthy time slots, then briefly describe proportional fair scheduling and give the mathematical models of instant data rate and proportional fairness function for each user. In Section 4.3, we formulate the resource allocation problem in the proposed system. Section 4.4 organizes the proposed resource allocation algorithm

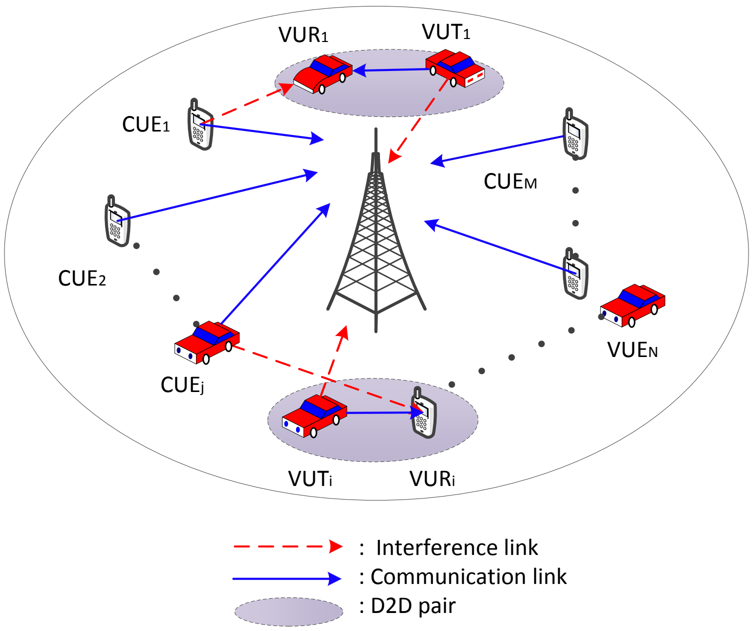


FIGURE 4.1: The system model of underlay V2X communication

into two subsections: Subsection 4.4.1 illustrates the proposed joint power control and proportional fair scheduling scheme from the second time slot to time slot T; Subsection 4.4.2 presents the proposed joint power control and resource allocation method for the first time slot. Section 4.5 presents the simulation results and performance analysis for our proposed scheme. Finally, in Section 4.6, we summarize our main contributions.

4.2 System Model for Underlay V2X Communication with Fairness

4.2.1 System Model of Underlay V2X Communication

Fig. 4.1 illustrates the system model of underlay V2X communication system, where multiple VUEs and CUEs co-exist and D2D-based V2X communication must only reuse the spectral resources that are allocated to CUEs due to severe resource constraints. In order to evaluate the system performance in different communication system model, different from Chapter 3, in this system, the network is fully loaded and all communication links are served by an eNB within its coverage area. We model our system as a single cellular network centered by the eNB with a radius of R. There are M CUEs and N VUTs distributed uniformly within this cell. In addition, we regard the VUE pair as the clustered distribution model where the VUT is denoted as the center of the disk with a radius of r and the corresponding VUR is distributed uniformly on this disk. We define the CUEs' index sets as $\mathcal{C} = \{\text{CUE}_1, \text{CUE}_2, \ldots, \text{CUE}_M\}$ and VUEs' index sets as $\mathcal{V} = \{\text{VUE}_1, \text{VUE}_2, \ldots, \text{VUE}_N\}$, respectively.

In our scheme, only the cellular uplink radio resources are shared by VUEs because the issues of co-channel interference of uplink radio resource are better handled when compared to that of downlink as highlighted in [14, 118]. Conditions of harsh co-channel interference exist in D2D-based V2X enabled cellular networks. Therefore, in order to ensure satisfactory levels of QoS of cellular users, we simplify our model by not considering the scenario in which a single cellular resource can be shared by more than one VUE pair and one cellular user. Besides, all orthogonal radio resources are assumed to be occupied by CUEs in this scheme [36]. Hence, in this case, we ignore the co-channel interference between CUEs.

Our system is considered as a centralized resource planning and scheduling architecture where we assume that traditional cellular links not only experience the fast fading effect caused by multi-path propagation but also experience the slow fading effect introduced by shadowing and path loss. Considering that the Doppler effect causes high signalling overhead at eNB, similar to 3, we only take into account the large-scale fading effect for vehicular links in this chapter. We further assume that eNB has the capability of acquiring the perfect CSI of both vehicular and cellular links, which can be estimated at the receivers and then fed back to eNB.

Definition 2. *We define $g_{j,B,t}$ as the instant channel gain between CUE j and eNB [36] in time slot t shown as:*

$$g_{j,B,t} = G\beta_{j,B,t}\zeta_{j,B,t}L_{j,B,t}^{-\alpha}, \tag{4.1}$$

where, in time slot t, we use G to denote the path loss constant, $\beta_{j,B,t}$ the fast fading gain whose distribution is exponential, $\zeta_{j,B,t}$ the slow fading gain whose distribution is log-normal, α the pathloss exponent, and $L_{j,B,t}$ the distance from cellular user j to eNB. In addition, we use $g_{i,t}$ to denote the channel gains from the VUE transmitter $VUT_{i,t}$ to the VUE receiver $VUR_{i,t}$, $g_{i,j,t}$ the interference links' channel gains between CUE j and VUE i, and $g_{i,B,t}$ the interference links' channel gains between VUE i and the eNB. We also define σ^2 as the power of additive white Gaussian noise.

The most important feature of any cellular network is that the instant data rates of users are, in fact, both user-dependent and time-varying because of channel fading and user mobility characteristics. Hence, we consider the time-varying feature of user's channel condition into our proposed scheme. We model our system in a dynamic context wherein its state is updated in each time slot. Specifically, due to the user's mobility, we assume that the users' locations and CSI changes in every time slot. We further assume that VUE pairs also change because VUE transmitters may choose different VUE receivers to communicate in different time slots. These features make the resource allocation problem for underlay V2X communication very complicated because eNB needs to decide on how to allocate the radio resources over multiple contiguous time slots.

4.2.2 Proportional Fair Scheduling

Our objective is to enhance both the system throughput and the system fairness in unison by using proportional fair scheduling. However, there has been no common view on the definition of fairness [119] so far. Here, we assume that the fairness implies providing equal average data rates to all users over a long-duration service time. We further assume that the demand of data traffic is the same for every user including VUEs and CUEs. Furthermore, in order to measure the system performance over long duration time slots, we assume that each user has an unbounded backlog of data with the minimum SINR requirement. We define the total time slots as T. Here, the system fairness can be enhanced by proportional fair scheduling.

Definition 3. *A scheduling scheme P is proportionally fair if and only if, for any feasible scheduling technique S, we have:*

$$\sum_{i \in U} \frac{R_i^S - R_i^P}{R_i^P} \leq 0, \tag{4.2}$$

where U is the user set, R_i^S is the average data rate of user i for scheduling S and R_i^P is the average data rate of user i for scheduling P. It has been proved in [120] that the proportional fair scheduling P can be expressed as the maximum sum of logarithmic average data rates of users,

$$P = \underset{\mathbf{S}}{\operatorname{argmax}} \sum_{i \in U} \log R_i^S, \tag{4.3}$$

Definition 4. *We define $Q_{i,t}$ as the proportional fairness utility function of user i in time slot t, which is presented as the ratio of instant data rate $r_{i,t}$ in time slot t to the average data rate $R_{i,t-1}$ of user i over the preceding $t-1$ time slots:*

$$Q_{i,t} = \frac{r_{i,t}}{R_{i,t-1}}, \tag{4.4}$$

where the average data rate $R_{i,t}$ is expressed as:

$$R_{i,t} = \begin{cases} \frac{(t-1)R_{i,t-1}+r_{i,t}}{t}, & t > 1, \\ r_{i,1}, & t = 1, \end{cases} \tag{4.5}$$

As proven in [39], equation (4.3) can be further altered to:

$$\begin{aligned} P &= \underset{\mathbf{S}}{\operatorname{argmax}} \sum_{i \in U} \frac{r_{i,t}^S}{(t-1)R_{i,t-1}^S} \\ &= \underset{\mathbf{S}}{\operatorname{argmax}} \frac{1}{t-1} \sum_{i \in U} \frac{r_{i,t}^S}{R_{i,t-1}^S}, \end{aligned} \tag{4.6}$$

Since the time window size $t-1$ is known in time slot t, equation (4.3) can be replaced by maximizing the sum of proportional fairness functions as follows:

$$P = \underset{\mathbf{S}}{\operatorname{argmax}} \sum_{i \in U} \frac{r_{i,t}^S}{R_{i,t-1}^S}, \tag{4.7}$$

Equation (4.7) indicates that the proportional fair scheduler S tends to allocate the radio resource to a user i having a high instant data rate $r_{i,t}^S$ and a relatively low average data rate $R_{i,t-1}^S$, which proves that proportional fair scheduling can improve system throughput and system fairness effectively.

4.2.3 Mathematical Models of Instant Data Rate and Proportional Fairness Function for each VUE and CUE

When VUE pair i and CUE j share the same uplink cellular resource, the SINR $\xi^V_{i,j,t}$, the instant data rate $r^V_{i,j,t}$ and the proportional fairness function $Q^V_{i,j,t}$ of VUE pair i during time slot t can be given as:

$$\xi^V_{i,j,t} = \frac{p^V_{i,j,t} g_{i,t}}{p^C_{i,j,t} g_{i,j,t} + \sigma^2}, t = 1, 2, \ldots, T, \tag{4.8}$$

$$r^V_{i,j,t} = \log_2(1 + \xi^V_{i,j,t}), t = 1, 2, \ldots, T, \tag{4.9}$$

$$Q^V_{i,j,t} = \frac{r^V_{i,j,t}}{R^V_{i,t-1}}, t > 1, \tag{4.10}$$

where $p^V_{i,j,t}$ and $p^C_{i,j,t}$ represent the transmit power of VUE i and CUE j, respectively. $R^V_{i,t-1}$ denotes the average data rate of VUE pair i over the preceding $t-1$ time slots. A window of time slots commences from time slot 1 till a time slot T within which average and instant data rates are computed. Considering that there are no average data rates available for the first time slot, we cannot obtain the proportional fairness function $Q^V_{i,j,1}$ of VUE pair i. Hence, we only consider $Q^V_{i,j,t}$ for the case of $t > 1$.

Similarly, we can also obtain $\xi^C_{i,j,t}$, $r^C_{i,j,t}$ and $Q^C_{i,j,t}$ of CUE j when interfered by VUE pair i as:

$$\xi^C_{i,j,t} = \frac{p^C_{i,j,t} g_{j,B,t}}{p^V_{i,j,t} g_{i,B,t} + \sigma^2}, t = 1, 2, \ldots, T, \tag{4.11}$$

$$r^C_{i,j,t} = \log_2(1 + \xi^C_{i,j,t}), t = 1, 2, \ldots, T, \tag{4.12}$$

$$Q^C_{i,j,t} = \frac{r^C_{i,j,t}}{R^C_{j,t-1}}, t > 1, \tag{4.13}$$

where $R^C_{j,t-1}$ denotes the average data rate of CUE j for the preceding $t-1$ time slots. If the spectral resource of CUE j is not reused by any other user, the SNR $\xi^C_{j,t}$, the instant data rate $r^C_{j,t}$ and the proportional fairness function $Q^C_{j,t}$ of CUE j are shown as:

$$\xi^C_{j,t} = \frac{p^C_{j,t} g_{j,B,t}}{\sigma^2}, t = 1, 2, \ldots, T, \tag{4.14}$$

$$r^C_{j,t} = \log_2(1 + \xi^C_{j,t}), t = 1, 2, \ldots, T, \tag{4.15}$$

$$Q^C_{j,t} = \frac{r^C_{j,t}}{R^C_{j,t-1}}, t > 1, \tag{4.16}$$

where $p^C_{j,t}$ indicates the transmit power of CUE j.

4.3 Problem Formulation for Underlay V2X Communication with Fairness

In this chapter, in order to enhance the system throughput and system fairness in unison, our objective is to maximize the sum of proportional fairness functions of all users while the target SINR of all users is satisfied. Therefore, the problem can be mathematically formulated as:

$$\begin{aligned}(\mathbf{x}^*, \mathbf{p}^*) = \underset{\mathbf{x},\mathbf{p}}{\operatorname{argmax}} \Bigg\{ & \sum_{j=1}^{M} \sum_{i=1}^{N} x_{i,j,t} \frac{r_{i,j,t}^C}{R_{j,t-1}^C} \\ & + \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j,t} \frac{r_{i,j,t}^V}{R_{i,t-1}^V} \\ & + \sum_{j=1}^{M} \left(1 - \sum_{i=1}^{N} x_{i,j,t}\right) \frac{r_{j,t}^C}{R_{j,t-1}^C} \Bigg\},\end{aligned} \tag{4.17}$$

subject to

$$\sum_{i=1}^{N} x_{i,j,t} \leq 1, x_{i,j,t} \in \{0,1\}, \forall j \in \mathcal{C}, \tag{4.17a}$$

$$\sum_{j=1}^{M} x_{i,j,t} \leq 1, x_{i,j,t} \in \{0,1\}, \forall i \in \mathcal{V}, \tag{4.17b}$$

$$\sum_{i=1}^{N} x_{i,j,t}\xi_{i,j,t}^C + \left(1 - \sum_{i=1}^{N} x_{i,j,t}\right) \xi_{j,t}^C \geq \xi_{\min}^C, \forall j \in \mathcal{C}, \tag{4.17c}$$

$$\sum_{j=1}^{M} x_{i,j,t}\xi_{i,j,t}^V \geq \xi_{\min}^V, \forall i \in \mathcal{V}, \tag{4.17d}$$

$$\sum_{i=1}^{N} x_{i,j,t}p_{i,j,t}^C + \left(1 - \sum_{i=1}^{N} x_{i,j,t}\right) p_{j,t}^C \leq P_{\max}^C, \forall j \in \mathcal{C}, \tag{4.17e}$$

$$\sum_{j=1}^{M} x_{i,j,t}p_{i,j,t}^V \leq P_{\max}^V, \forall i \in \mathcal{V}, \tag{4.17f}$$

where $\mathbf{x}$ is a $N \times M$ channel allocation indication matrix. The element $x_{i,j,t}$ is the resource reuse indicator at time slot t. If VUE pair i reuses the spectrum resource of CUE j, $x_{i,j,t} = 1$; otherwise, $x_{i,j,t} = 0$. $\xi_{\min}^C$ is the target SINR of CUEs. $\xi_{\min}^V$ is the target SINR of VUEs. $P_{\max}^C$ denotes the maximum transmit power of cellular links and $P_{\max}^V$ represents the maximum transmit power of vehicular links. We use constraints (4.17a) and (4.17b) to impose a restriction that one single cellular link can be shared by one VUE pair at most while one vehicular link is limited to be reused by only one CUE, constraints (4.17c) and (4.17d) to ensure the minimum SINR requirements for CUEs and VUEs, respectively, and constraints (4.17e) and (4.17f) to limit the maximum transmit power of CUEs and VUEs, respectively.

The optimization problem in equation (4.17) is a MINLP problem which is in general NP-hard [114]. Furthermore, the optimization problem in [53] is the formulation of an integer programming problem which has been proved to be NP-hard. Actually, our optimization problem is more complicated and somewhat general in nature than the one considered in [53] since the one in [53] is only a special instance of our model. This is because the objective in [53] is just to maximize the system performance of cellular users whereas we consider the overall system optimization that includes both the vehicular as well as cellular users. Accordingly, our problem is certainly as hard as an NP-hard problem which cannot be solved in the polynomial time.

4.4 The Proposed Resource Allocation Algorithm

4.4.1 Joint Power Control and Proportional Fair Scheduling

In this section, in order to address the optimization problem in equation (4.17), a new scheme of joint power control and proportional fair scheduling is proposed for the period starting from the second transmit time slot to the current transmit time slot T. According to the average data rates of the first time slot which will be discussed in the following subsection, the proposed scheme will be developed for all the other subsequent time slots. It is feasible that we first obtain the average data rates of preceding $t-1$ time slots, and then substitute them into the optimization problem in equation (4.17) at time slot t. We then further decompose this optimization problem into two main subproblems. The first one is the problem of joint power control for the vehicular transmitter and the cellular transmitter who is sharing the same link with this VUE pair. The goal of the power control problem is to optimize the sum of proportional fairness functions of the VUE pair and its reuse CUE while fulfilling their minimum SINR requirements. The second one is the problem of proportional fair scheduling of radio resources for multiple VUEs and CUEs with a view to improving the system fairness.

In order to guarantee the minimum SINR requirement of every user in underlay V2X communication networks, we need to decide which VUE pair should be allowed to reuse the channel of a cellular user j. To be eligible, the admissible conditions for the candidate pairs need to meet the minimum SINR requirements of both the vehicular link and its reuse cellular link with the restricted transmit power. In time slot t, if a VUE pair i has access to the channel of the CUE j, the admission control conditions can be presented as follows:

$$\begin{cases} \xi_{i,j,t}^{C} \geq \xi_{\min}^{C}, \forall j \in \mathcal{C}, \\ \xi_{i,j,t}^{V} \geq \xi_{\min}^{V}, \forall i \in \mathcal{V}, \\ p_{i,j,t}^{C} \leq P_{\max}^{C}, \forall j \in \mathcal{C}, \\ p_{i,j,t}^{V} \leq P_{\max}^{V}, \forall i \in \mathcal{V}, \end{cases} \tag{4.18}$$

where the first two constraints of equation (4.18) guarantee the minimum SINR requirements of CUEs and VUEs, respectively, when they share with the same radio resource. The last two constraints restrict the maximum transmit power of the cellular link and its reuse vehicular link, respectively. According to these admission control constraints, we can obtain the range of the channel gain $g_{i,j,t}$ between VUE pair i and CUE j at time slot t. Through the instant channel gain model in equation (4.1), we can calculate the minimum distance $L_{i,j,t}^{\min}$ from the transmitter of CUE j to the receiver of VUE pair i as:

Proposition 2. . *CUE j is a reuse candidate of VUE pair i, if $L_{i,j,t} \geqslant L_{i,j,t}^{min}$, where $L_{i,j,t}^{min}$ is given by [36]*

$$L_{i,j,t}^{min} = \begin{cases} \left[\frac{G\beta_{i,j,t}\zeta_{i,j,t}\xi_{min}^{C}\xi_{min}^{V}P_{max}^{C}}{\left(P_{max}^{C}g_{j,B,t}-\xi_{min}^{C}\sigma^2\right)\beta-\xi_{min}^{C}\xi_{min}^{V}\sigma^2}\right]^{\frac{1}{\alpha}} \\ if\frac{P_{max}^{C}g_{j,B,t}}{\sigma^2+P_{max}^{V}g_{i,B,t}} \leq \xi_{min}^{C}, \\ \left[\frac{G\beta_{i,j,t}\zeta_{i,j,t}\xi_{min}^{C}\xi_{min}^{V}\left(\sigma^2+P_{max}^{V}g_{i,B,t}\right)}{g_{j,B,t}\left(P_{max}^{V}g_{i,t}-\xi_{min}^{V}\sigma^2\right)}\right]^{\frac{1}{\alpha}} \\ if\frac{P_{max}^{C}g_{j,B,t}}{\sigma^2+P_{max}^{V}g_{i,B,t}} > \xi_{min}^{C}, \end{cases} \tag{4.19}$$

where $\beta = \frac{g_{i,t}}{g_{i,B,t}}$ represents the vehicular channel gain advantage over traditional user to eNB link.

We assume an admission control matrix $\mathbf{A}$ with the size of $N \times M$ shown below as:

$$\mathbf{A} = \begin{pmatrix} a_{1,1,t} & a_{1,2,t} & \cdots & a_{1,M,t} \\ a_{2,1,t} & a_{2,2,t} & \cdots & a_{2,M,t} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N,1,t} & a_{N,2,t} & \cdots & a_{N,M,t} \end{pmatrix}, \tag{4.20}$$

Let $L_{i,j,t}$ denote the distance from CUE j to VUE pair i. If $L_{i,j,t} \geq L_{i,j,t}^{\min}$, VUE pair i gets the permission from eNB to access the link of CUE j, then the admission control indicator $a_{i,j,t} = 1$; otherwise, $a_{i,j,t} = 0$.

Power control is critical in an underlay V2X communication system because it can facilitate more VUEs to reuse cellular resources, thereby enhancing the overall spectrum utilization. In addition, the QoS requirements of the users can be guaranteed due to the use of proper power control. According to $\mathbf{A}$, we can obtain optimal transmit power of VUEs and CUEs by joint power control. Specifically, when $a_{i,j,t} = 0$, the spectrum of CUE j cannot be reused by VUE pair i. Hence the maximum PF function $Q_{j,t}^{C}$ of CUE j can be achieved when each CUE's transmit power is at its peak maximum power $P_{\max}^{C}$ as follows,

$$P_{\max}^{C} = p_{j,t}^{C^*} = \underset{p_{j,t}^{C}}{\operatorname{argmax}} \frac{\log_2(1+\frac{p_{j,t}^{C}g_{j,B,t}}{\sigma^2})}{R_{j,t-1}^{C}}, t > 1, \tag{4.21}$$

When $a_{i,j,t} = 1$, a VUE pair has access to a CUE's radio resource. The transmit power of VUE pair and its reuse candidate need to be controlled in an appropriate way so as to maximize the sum of their proportional fairness functions. This problem can be formulated as:

$$\left(p_{i,j,t}^{C^*}, p_{i,j,t}^{V^*}\right) = \underset{p_{i,j,t}^{C}, p_{i,j,t}^{V}}{\operatorname{argmax}} \left\{ \frac{\log_2(1+\frac{p_{i,j,t}^{C}g_{j,B,t}}{p_{i,j,t}^{V}g_{i,B,t}+\sigma^2})}{R_{j,t-1}^{C}} + \frac{\log_2(1+\frac{p_{i,j,t}^{V}g_{i,t}}{p_{i,j,t}^{C}g_{i,j,t}+\sigma^2})}{R_{i,t-1}^{V}} \right\}, t > 1, \tag{4.22}$$

subject to

$$\xi^C_{i,j,t} \geq \xi^C_{\min}, \forall j \in \mathcal{C}, \tag{4.22a}$$
$$\xi^V_{i,j,t} \geq \xi^V_{\min}, \forall i \in \mathcal{V}, \tag{4.22b}$$
$$p^C_{i,j,t} \leq P^C_{\max}, \forall j \in \mathcal{C}, \tag{4.22c}$$
$$p^V_{i,j,t} \leq P^V_{\max}, \forall i \in \mathcal{V}, \tag{4.22d}$$

where $R^C_{j,t-1}$ and $R^V_{i,t-1}$ can be calculated iteratively by using equation (4.5). Hence, the values of $R^C_{j,t-1}$ and $R^V_{i,t-1}$ are known at time slot t. Since proportional fair scheduling can achieve a degree of fairness on a long term scale [39], we assume $R^C_{j,t-1} = R^V_{i,t-1}$ for large values of t. Hence, equation (4.22) can be simplified to the following equation:

$$\left(p^{C*}_{i,j,t}, p^{V*}_{i,j,t}\right) = \underset{p^C_{i,j,t}, p^V_{i,j,t}}{\operatorname{argmax}} f(p^C_{i,j,t}, p^V_{i,j,t}), t > 1, \tag{4.23}$$

where $f(p^C_{i,j,t}, p^V_{i,j,t}) = \log_2(1 + \frac{p^C_{i,j,t} g_{j,B,t}}{p^V_{i,j,t} g_{i,B,t} + \sigma^2}) + \log_2(1 + \frac{p^V_{i,j,t} g_{i,t}}{p^C_{i,j,t} g_{i,j,t} + \sigma^2})$.

It has been proved that the optimal power allocation vector $\left(p^{C*}_{i,j,t}, p^{V*}_{i,j,t}\right)$ will have $p^{C*}_{i,j,t}$ or $p^{V*}_{i,j,t}$ equal to the maximum transmit power. When $p^{C*}_{i,j,t} = P^C_{\max}$, equation (4.23) is then convex in terms of $0 \leq p^V_{i,j,t} \leq P^V_{\max}$. Due to symmetry, the same case happens to $p^C_{i,j,t}$. Hence, we can obtain $\left(p^{C*}_{i,j,t}, p^{V*}_{i,j,t}\right)$ in the set Ω of corner points of the admissible area where the transmit power of both CUE j and VUE pair i can meet all constraints in equation (4.18) as follows [36]:

$$\Omega = \begin{cases} \{(P^C_{\max}, P_1), (P^C_{\max}, P_2)\}, \\ if \frac{P^C_{\max} g_{j,B,t}}{P^V_{\max} g_{i,B,t} + \sigma^2} < \xi^C_{\min}, and \frac{P^V_{\max} g_{i,t}}{P^C_{\max} g_{i,j,t} + \sigma^2} \geq \xi^V_{\min}, \\ \\ \{(P_3, P^V_{\max}), (P_4, P^V_{\max})\}, \\ if \frac{P^C_{\max} g_{j,B,t}}{P^V_{\max} g_{i,B,t} + \sigma^2} \geq \xi^C_{\min}, and \frac{P^V_{\max} g_{i,t}}{P^C_{\max} g_{i,j,t} + \sigma^2} < \xi^V_{\min}, \\ \\ \{(P^C_{\max}, P_1), (P^C_{\max}, P^V_{\max}), (P_4, P^V_{\max})\}, \\ if \frac{P^C_{\max} g_{j,B,t}}{P^V_{\max} g_{i,B,t} + \sigma^2} \geq \xi^C_{\min}, and \frac{P^V_{\max} g_{i,t}}{P^C_{\max} g_{i,j,t} + \sigma^2} \geq \xi^V_{\min}, \end{cases} \tag{4.24}$$

where

$$\left(p^{C*}_{i,j,t}, p^{V*}_{i,j,t}\right) = \underset{p^C_{i,j,t}, p^V_{i,j,t} \in \Omega}{\operatorname{argmax}} f(p^C_{i,j,t}, p^V_{i,j,t}), \tag{4.24a}$$

$$P_1 = \frac{(P^C_{\max} g_{i,j,t} + \sigma^2)\xi^V_{\min}}{g_{i,t}}), \tag{4.24b}$$

$$P_2 = \frac{P^C_{\max} g_{j,B,t} - \xi^C_{\min}\sigma^2}{\xi^C_{\min} g_{i,B,t}}, \tag{4.24c}$$

$$P_3 = \frac{P^V_{\max} g_{i,t} - \xi^V_{\min}\sigma^2}{\xi^V_{\min} g_{i,j,t}}, \tag{4.24d}$$

$$P_4 = \frac{(P^V_{\max} g_{i,B,t} + \sigma^2)\xi^C_{\min}}{g_{j,B,t}}, \tag{4.24e}$$

We substitute the transmit power of users in equation (4.17) with the optimal transmit power allocation which can be obtained by power control equation (4.21) and (4.22) described above. Then, the optimization problem can be altered to a problem of proportional fair scheduling for resource management involving multiple VUE pairs and CUEs as follows:

$$\begin{aligned}\mathbf{x}^* = \underset{\mathbf{x}}{\operatorname{argmax}} \Bigg\{ \sum_{j=1}^{M}\sum_{i=1}^{N} x_{i,j,t}\frac{r_{i,j,t}^{C*}}{R_{j,t-1}^{C}} + \sum_{i=1}^{N}\sum_{j=1}^{M} x_{i,j,t}\frac{r_{i,j,t}^{V*}}{R_{i,t-1}^{V}} \\ + \sum_{j=1}^{M}\left(1-\sum_{i=1}^{N}x_{i,j,t}\right)\frac{r_{j,t}^{C*}}{R_{j,t-1}^{C}}\Bigg\}, t>1,\end{aligned} \tag{4.25}$$

subject to

$$r_{i,j,t}^{C*} = \log_2\left(1+\frac{p_{i,j,t}^{C*}g_{j,B,t}}{p_{i,j,t}^{V*}g_{i,B,t}+\sigma^2}\right), \tag{4.25a}$$

$$r_{i,j,t}^{V*} = \log_2\left(1+\frac{p_{i,j,t}^{V*}g_{i,t}}{p_{i,j,t}^{C*}g_{i,j,t}+\sigma^2}\right), \tag{4.25b}$$

$$r_{j,t}^{C*} = \log_2\left(1+\frac{P_{\max}^{C}g_{j,B,t}}{\sigma^2}\right), \tag{4.25c}$$

$$\sum_{i=1}^{N} x_{i,j,t} \le 1, x_{i,j,t} \in \{0,1\}, \forall j \in \mathcal{C}, \tag{4.25d}$$

$$\sum_{j=1}^{M} x_{i,j,t} \le 1, x_{i,j,t} \in \{0,1\}, \forall i \in \mathcal{V}, \tag{4.25e}$$

In equation (4.25), the binary variable $x_{i,j,t}$ is the only remaining variable to be optimized. Therefore, with the optimal power allocation, equation (4.17) turns out to be a 0–1 integer optimization problem of (4.25). The proportional fairness function matrix for VUEs and CUEs is defined as:

$$\mathbf{Q} = \begin{pmatrix} Q_{1,1,t} & Q_{1,2,t} & \cdots & Q_{1,M,t} \\ Q_{2,1,t} & Q_{2,2,t} & \cdots & Q_{2,M,t} \\ \vdots & \vdots & \ddots & \vdots \\ Q_{N,1,t} & Q_{N,2,t} & \cdots & Q_{N,M,t} \end{pmatrix}, t>1, \tag{4.26}$$

where

$$Q_{i,j,t} = \begin{cases} \frac{r_{i,j,t}^{C*}}{R_{j,t-1}^{C}} + \frac{r_{i,j,t}^{V*}}{R_{i,t-1}^{V}}, & a_{i,j,t}=1, \\ \frac{r_{j,t}^{C*}}{R_{j,t-1}^{C}}, & a_{i,j,t}=0, \end{cases} \tag{4.27}$$

The solution to equation (4.25) can be obtained by picking $n = \min(M,N)$ elements from the matrix $\mathbf{Q}$ to maximize the sum of all users' proportional fairness functions, where we can only choose one element from the same row or column. In our proposed scheme, one radio resource can be shared simultaneously by at most one cellular link and one admissible

D2D link. Therefore, the problem in equation (4.25) can be regarded as an one-to-one assignment problem. Different from Chapter 3, in this chapter, our objective is to maximize the sum of proportional fairness functions of all VUEs and CUEs without considering the stable matching between VUEs and their reuse CUEs. Therefore, the optimal solution of equation (4.25) can be achieved by the well-known Hungarian Algorithm [121] with low computational complexity.

The Hungarian Algorithm requires that the cost matrix must satisfy the condition that the number of rows is the same as the number of columns. Hence, we extend the size of $\mathbf{Q}$ to be $\tau \times \tau$ where $\tau = \max(M, N)$. Furthermore, when $N \leq M$, we set the values of additional dummy entries of $\mathbf{Q}$ in the same column j equal to the proportional fairness function of CUE j who is supposed not to be reused by any other user, which means $Q_{i,j,t} = \frac{r^{C*}_{j,t}}{R^{C}_{j,t-1}}$; Otherwise, we set the values of additional dummy entries equal to zero. Given an $\tau \times \tau$ matrix, where an entry i, j gives the cost of matching row i to column j, conventionally, the Hungarian Algorithm determines the optimal assignment of rows to columns such that the cost is minimized. In contrast, our approach is to obtain the maximum cost value by the optimal assignment of rows to columns. Therefore, here, the Hungarian Algorithm has been amended to generate the maximum cost.

4.4.2 Joint Power Control and Resource Allocation for the First Time Slot

According to equation (4.5), we can determine the average data rate at any given time slot by iteratively computing the rates from the preceding time slots. To solve the problem of the objective function (4.17), we need to obtain the average data rates for the preceding $t-1$ time slots. Considering that there are no average data rates for the first time slot, in order to make the system more practical, a joint power control and resource allocation scheme is developed that maximizes the overall throughput of the system by intializing the average data rates in the first time slot. This approach results in the initialization of the average data rates of all of VUEs and CUEs.

If we want to obtain the value of the cumulative average data rate for the previous $t-1$ time slots, we must first initialize the average data rates for the first time slot, which in this case equals its instant data rate. We do not have any past values for the cumulative average data rates of users for the first time slot. Hence we cannot compute the average data rates for this slot. This implies that we cannot deploy the proportional fairness algorithm in the allocation of radio resources in the first time slot. Thus, we adopt the Maximum Carrier to Interference Ratio Algorithm [122] for resource allocation in this time slot. The goal of this algorithm is to obtain the maximum overall throughput without reducing the SINR levels of users. Then, the problem of resource allocation for the initialization phase is mathematically formulated in equation (4.28) with the same constraints that govern equation (4.17).

$$(\mathbf{x}^*, \mathbf{p}^*) = \underset{\mathbf{x},\mathbf{p}}{\operatorname{argmax}} \left\{ \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j,1} r^{V}_{i,j,1} + \sum_{j=1}^{M} \sum_{i=1}^{N} x_{i,j,1} r^{C}_{i,j,1} + \sum_{j=1}^{M} \left(1 - \sum_{i=1}^{N} x_{i,j,1} \right) r^{C}_{j,1} \right\}, \quad (4.28)$$

Similar to the problem highlighted in (4.17), the optimization problem in (4.28) is also a

Mixed-Integer Nonlinear Program (MINLP) problem which cannot be solved directly. In our scheme, we address this problem in three phases. The first phase is the admission control where VUE pairs can be allowed to reuse the cellular resource only if such VUE pairs meet the admission control conditions of equation (4.18). The second phase is the optimal power control whose target is to obtain the maximum overall throughput by properly controlling the transmit power of both VUT and its reuse cellular transmitter. Finally, the third phase involves the channel allocation problem for multiple VUE pairs and CUEs which is solved by the modified Hungarian Algorithm.

In the admission control phase, we can derive the admission control matrix **A** for the first time slot by choosing the same admission control strategy that is mentioned in the above subsection. Based on the outcome from the admission control phase, in the power control phase, we target the maximum sum of throughput of one VUE pair and its reuse cellular user by optimal power control. When $a_{i,j,1} = 0$, VUE pair i cannot be admissible to access the spectral resource of CUE j. Therefore, the instant data rate of CUE j for the first time slot will reach its maximum value with the maximum transmit power,

$$P_{\max}^{C} = p_{j,1}^{C^*} = \underset{p_{j,1}^{C}}{\operatorname{argmax}} \log_2(1 + \frac{p_{j,t}^{C} g_{j,B,1}}{\sigma^2}), \tag{4.29}$$

where $p_{j,1}^{C^*}$ is the optimal transmit power of CUE j without interference from any other user. We can then compute the average data rate of CUE j for the first time slot as: $R_{j,1}^{C} = r_{j,1}^{C^*}$.

When $a_{i,j,1} = 1$, CUE j and VUE pair i share the same uplink resource, where the cellular receiver (eNB) receives the interference signal from VUE transmitter. Meanwhile, the VUE receiver is also interfered by the cellular transmitter. Therefore, in order to improve the reliability of both, vehicular as well as cellular communication, we need to consider the joint power control for CUE j and VUE pair i to maximize the sum of their throughput as follows:

$$\left(p_{i,j,1}^{C^*}, p_{i,j,1}^{V^*}\right) = \underset{p_{i,j,1}^{C}, p_{i,j,1}^{V}}{\operatorname{argmax}} \{\log_2(1 + \frac{p_{i,j,1}^{C} g_{j,B,1}}{p_{i,j,1}^{V} g_{i,B,1} + \sigma^2}) \log_2(1 + \frac{p_{i,j,1}^{V} g_{i,1}}{p_{i,j,1}^{C} g_{i,j,1} + \sigma^2})\}, \tag{4.30}$$

Since the problem in equation (4.30) is the same as the optimization problem depicted in equation (4.23), we can achieve the optimal transmit power allocation in the first time slot using the power control method of equation (4.23).The average data rates of VUE i and CUE j at the first time slot can be obtained, with $R_{i,j,1}^{V} = r_{i,j,1}^{V^*}$ and $R_{i,j,1}^{C} = r_{i,j,1}^{C^*}$, respectively.

In the third phase, the spectral resources of CUEs are allocated to their corresponding VUE pairs. After obtaining the user's optimal transmit power, we simplify the optimization problem in (4.28) into the resource allocation problem of D2D-enabled cellular network as:

$$\mathbf{x}^* = \underset{\mathbf{x}}{\operatorname{argmax}} \left\{ \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j,1} r_{i,j,1}^{V^*} + \sum_{j=1}^{M} \sum_{i=1}^{N} x_{i,j,1} r_{i,j,1}^{C^*} + \sum_{j=1}^{M} \left(1 - \sum_{i=1}^{N} x_{i,j,1}\right) r_{j,1}^{C^*} \right\}, \tag{4.31}$$

subject to

$$r_{i,j,1}^{C^*} = \log_2(1 + \frac{p_{i,j,1}^{C^*} g_{j,B,1}}{p_{i,j,1}^{V^*} g_{i,B,1} + \sigma^2}), \tag{4.31a}$$

$$r_{i,j,1}^{V*} = \log_2(1 + \frac{p_{i,j,1}^{V*} g_{i,1}}{p_{i,j,1}^{C*} g_{i,j,1} + \sigma^2}), \tag{4.31b}$$

$$r_{j,1}^{C*} = \log_2(1 + \frac{P_{\max}^{C} g_{j,B,1}}{\sigma^2}), \tag{4.31c}$$

$$\sum_{i=1}^{N} x_{i,j,1} \leq 1, x_{i,j,1} \in \{0,1\}, \forall j \in \mathcal{C}, \tag{4.31d}$$

$$\sum_{j=1}^{M} x_{i,j,1} \leq 1, x_{i,j,1} \in \{0,1\}, \forall i \in \mathcal{V}, \tag{4.31e}$$

Considering the one-to-one relationship between a single VUE pair and its reuse CUE partner in the first time slot, the problem of resource allocation in (4.31) can be also regarded as a one-to-one assignment problem. We define the rate matrix $\mathbf{R}$ with the size of $N \times M$ as:

$$\mathbf{R} = \begin{pmatrix} r_{1,1,1} & r_{1,2,1} & \cdots & r_{1,M,1} \\ r_{2,1,1} & r_{2,2,1} & \cdots & r_{2,M,1} \\ \vdots & \vdots & \ddots & \vdots \\ r_{N,1,1} & r_{N,2,1} & \cdots & r_{N,M,1} \end{pmatrix}, \tag{4.32}$$

where

$$r_{i,j,1} = \begin{cases} r_{i,j,1}^{C*} + r_{i,j,1}^{V*}, & a_{i,j,1} = 1, \\ r_{j,1}^{C*}, & a_{i,j,1} = 0, \end{cases} \tag{4.33}$$

Here, we also extend $\mathbf{R}$ to be the size of $\tau \times \tau$, where $\tau = \max(M, N)$. We further set the additional dummy entries $r_{i,j,1} = r_{j,1}^{C*}$ when $N \leq M$; Otherwise, the additional dummy entries $r_{i,j,1} = 0$. Then, we utilize the modified Hungarian Algorithm to obtain the maximum total throughput of all VUE pairs and CUEs.

We first propose a new resource allocation algorithm to solve the problem of fairness of the underlay V2X communication in time slots that are of long durations. This algorithm solves the problem of initialization for the first time slot and the resource allocation problem with proportional fairness for subsequent time slots in such a way so as to guarantee system fairness and throughput performance. Specifically, we propose two algorithms to solve the problem of equation (4.17).

4.4.3 The Proposed Resource Allocation Algorithm

Algorithm 3 is developed for the system initialization. In the first time slot, the average data rate of each user is equal to its instant data rate. Considering that there are no average data rates for the first time slot, a joint power control and resource allocation scheme is proposed for this time slot aiming at maximizing the overall throughput of underlay D2D communication networks. The system initialization for the first time slot is completed in three phases, namely the admission control phase, the joint power control phase and the channel allocation phase. In the first phase, the eNB needs to make a decision whether D2D pair i can be admitted to share the spectrum resource of cellular user j or not by the feedback control signal. This phase is called admission control of D2D pairs. Every D2D

Algorithm 3 Joint Power Control and Resource Allocation Algorithm for the 1st Time Slot

Initialize the rate matrix $\mathbf{R}$ as a null matrix
Initialize the admission control matrix $\mathbf{A}$ as a null matrix
Phase 1: Admission control of VUE pairs
for all $i \in N, j \in M$ **do**
  Calculate the minimum distance $L_{i,j}^{\min}$
  if $L_{i,j} \geq L_{i,j}^{\min}$ **then**
    $a_{i,j,1} = 1$
  else
    $a_{i,j,1} = 0$
  end if
end for
Phase 2: Joint power control for admissible VUE pairs and their reuse CUEs
for all $i \in N, j \in M$ **do**
  if $a_{i,j,1} = 1$ **then**
    Calculate optimal transmit power using Eq. (4.30). Obtain $r_{i,j,1}^{V*}$ and $r_{i,j,1}^{C*}$.
    $r_{i,j,1} = r_{i,j,1}^{C*} + r_{i,j,1}^{V*}$
  else
    $r_{i,j,1} = r_{j,1}^{C*}$
  end if
end for
if $N \leq M$ **then**
  for all $i = N + 1 : M, j \in M$ **do**
    $r_{i,j,1} = r_{j,1}^{C*}$
  end for
else
  for all $i \in N, j = M + 1 : N$ **do**
    $r_{i,j,1} = 0$
  end for
end if
Phase 3: Channel allocation for multiple VUEs and CUEs
Obtain the maximum overall throughput for all active VUE pairs and CUEs from the rate matrix $\mathbf{R}$ by the Hungarian Algorithm. Get an optimal channel allocation indication matrix $\mathbf{x}$ for mutiple VUE pairs and CUEs.
for all $i \in N, j \in M$ **do**
  if $x_{i,j,1} = 1$ **then**
    $R_{i,1}^{V} = r_{i,j,1}^{V*}$, $R_{j,1}^{C} = r_{i,j,1}^{C*}$
  else
    $R_{i,1}^{V} = a$, $R_{j,1}^{C} = r_{j,1}^{C*}$ (a is the smallest value of average data rate in the first time slot)
  end if
end for
Obtain the initial values of average data rates matrixs $\mathbf{R_1^V}$ and $\mathbf{R_1^C}$ for all active VUEs and CUEs, respectively.

pair i can discover all the corresponding reuse CUs whose resource can be shared by this D2D pair i in this phase. The admissible condition for D2D pair i reusing the spectrum resource of CU j is that the distance $L_{i,j}$ between cellular transmitter j and D2D receiver i should be larger than the minimum distance $L_{i,j}^{\min}$ between them.

After the admission control phase, each VUE pair i and its reuse CUE j need to control their transmit power properly to mitigate the co-channel interference between them. The objective of the joint power control phase is to maximize the total throughput of every admissible VUE pair and its reuse cellular user while guaranteeing the SINR requirements of both vehicular and cellular links. Based on the optimal power allocation obtained through joint power control phase, the final phase works towards deciding on how to allocate channel resources to multiple VUE pairs and CUEs to optimize the overall system throughput. Since in our system, we only consider that a single cellular resource can be reused by one CUE and one VUE pair at most, the channel allocation problem turns to be an one-to-one assignment problem. This problem can be solved by exhaustively searching all the possible $\binom{M}{N}$ combinations when $N \leq M$ or $\binom{N}{M}$ combinations when $N > M$. But the complexity of this method increases exponentially for large $\tau = \max(M, N)$. Hence, we use the modified Hungarian Algorithm to solve this optimization problem. It can be observed that the complexity of phases 1 and 2 is $O(M \times N)$ whereas the complexity of phase 3 (the Hungarian Algorithm) is $O(\tau^3)$ [46]. Since the complexity of phase 3 dominates, the complexity of Algorithm 3 is $O(\tau^3)$.

Not all VUE pairs can get admitted in the first time slot to reuse cellular spectrum resources. Therefore, in order to complete the initialization of all such pairs, these pairs are assigned the smallest average data rate value. This process helps to improve the system fairness since all such pairs that are denied admission in the first slot get higher priorities assigned to them by the fairness function in subsequent time slots. As a result, their chances of getting admitted in subsequent time slots are quite high. The system initialization in the first time slot results in the initialization of average data rates of all users (VUEs and CUEs). The process of initializing the average data rates in the first time slot is illustrated in Algorithm 3.

Algorithm 4 presents the operational procedure of the proposed resource allocation scheme. The average data rates of all users in the subsequent slots can be calculated in an iterative manner using equation (4.5). Since our system state is discrete and independent in different time slots because of the users' mobility, we conduct the proposed scheme of joint power control and proportional fair scheduling for each subsequent time slot independently, starting from the second time slot and finishing at a chosen time slot T. Our objective for each subsequent time slot except for the first time slot is to achieve the maximum sum of all users' proportional fairness functions.

In each subsequent time slot, we decompose the optimization problem in equation (4.17) into two sub-problems: the first one is the joint power control problem for a single VUE pair and its reuse CUE, by which we can obtain the optimal transmit power allocation vector $(p_{i,j,t}^{C*}, p_{i,j,t}^{V*})$ when VUE pair i is sharing the spectrum resource of cellular user j. The second one is the channel allocation problem which is derived from the original optimization problem depicted in equation (4.17) when the power allocation matrix in equation (4.17) is substituted with the optimal transmit power allocation matrix. Specifically, in our work,

Algorithm 4 Proposed Resource Allocation Algorithm

```
Initialize the PF function matrix Q as a null matrix
Initialize the admission control matrix A as a null matrix
Stage 1: Average data rates initialization by Algorithm 3
Stage 2: Joint power control and proportional fair scheduling for the period
    starting from the second time slot to the time slot T
for all t = 2 to T do
    Obtain the admission control matrix A by admission control strategy
    for all i ∈ N, j ∈ M do
        if a_{i,j,t} = 1 then
            Obtain the maximum sum of proportional fairness functions using Eq. (4.22),
            Q_{i,j,t} = r^{C*}_{i,j,t} / R^C_{j,t-1} + r^{V*}_{i,j,t} / R^V_{i,t-1}
        else
            Obtain the maximum proportional fairness functions using Eq. (4.21).
            Q_{i,j,t} = r^{C*}_{j,t} / R^C_{j,t-1}
        end if
    end for
    if N ≤ M then
        for all i = N + 1 : M, j ∈ M do
            Q_{i,j,t} = r^{C*}_{j,t} / R^C_{j,t-1}
        end for
    else
        for all i ∈ N, j = M + 1 : N do
            Q_{i,j,t} = 0
        end for
    end if
    Obtain the PF function matrix Q. Solve Eq. (4.25) using the Hungarian Algorithm.
    for all i ∈ N, j ∈ M do
        if x_{i,j,t} = 1 then
            R^C_{j,t} = ((t-1)R^C_{j,t-1} + r^{C*}_{i,j,t}) / t , R^V_{i,t} = ((t-1)R^V_{i,t-1} + r^{V*}_{i,j,t}) / t
        else
            R^C_{j,t} = ((t-1)R^C_{j,t-1} + r^{C*}_{j,1}) / t, R^V_{i,t} = ((t-1)R^V_{i,t-1}) / t
        end if
    end for
end for
```

the channel allocation problem is a proportional fair scheduling problem for multiple VUE pairs and their reuse CUEs, which can be solved by the Hungarian Algorithm. In each time slot, the main computational complexity of the proposed algorithm is determined by the Hungarian Algorithm which can be performed up to T times in the proposed scheme. Given that the computational complexity of the Hungarian algorithm is $O(\tau^3)$ for each time slot, the overall computational complexity of our proposed algorithm is $O(T \times \tau^3)$, where $\tau = \max(M, N)$.

4.5 Performance Analysis for Underlay V2X Communication with Fairness

In this section, we present and analyze the simulation results when the time slot $T = 1000$. We make use of the system model of [36] by utilizing the same set of parameters in order for us to meaningfully compare our proposed algorithm with the algorithm proposed in [36]. The related simulation parameters for our model are shown in Table 4.1. For the sake of comparison, the following three algorithms are taken into account.

Algorithm in [36]: The scheduling strategy in [36] uses the Maximum Carrier to Interference Ratio Algorithm to allocate radio resources for underlay D2D communication networks while guaranteeing the minimum SINR requirements of both D2D and cellular links. But it ignores the system fairness.

Algorithm in [39]: This paper presents an optimal proportionally fair scheduling scheme for underlay D2D communication networks where D2D users have to share the same radio resource with the CUEs for D2D communication. However, in this scheme, the users' QoS requirements are not satisfied because of the usage of the pre-defined transmit power.

Optimal Algorithm: The optimal solution to equation (4.17) can be obtained by firstly implementing the optimal power allocation method for each VUE pair and its reuse CUE, and then using the branch-and-bound method to find the optimal reuse CUE for each VUE pair. However, the computational complexity of branch-and-bound method in the worst case scenario is as high as that of an exhaustive search.

In order to evaluate the performance of our system, we measure and analyze the users' service satisfaction degree, the overall network throughput, and the users' fairness against different parameters including the number of VUE pairs, the maximum transmit power of VUEs and the distance between VUE transmitter and VUE receiver. However, due to the exponential growth of the computational complexity of the optimal algorithm with the increasing number of users, we only compare the system performance of our proposed algorithm with algorithms in [36] and [39] in terms of the increasing number of VUE pairs. Here, we measure the QoS satisfaction degree by the ratio of the number of CUEs (VUEs) satisfying the minimum SINR requirements to the total number of CUEs (admissible VUEs). The overall throughput is the sum of the throughput of all of VUEs and CUEs. We measure users' fairness using Jain's fairness index [123], which is described as:

$$F = \frac{\left|\sum_{i=1}^{K} R_i\right|^2}{K \sum_{i=1}^{K} R_i^2}. \tag{4.34}$$

where K is the number of users and R_i is the average service rate of user i. This index measures the fairness between different users in terms of their average data rates. We assume this system to be completely fair if the average service rate of every user is likely to be uniform in this system, i.e. average data rates of all users are equal. This results

TABLE 4.1: Simulation Parameters for Underlay V2X Communication with Fairness

Parameter	Value
Cell radius, R	500m
VUE pair distance, r	20-100m
Uplink bandwidth	3MHz
Noise spectral density	-174dBm/Hz
Passloss constant, G	10^{-2}
Pathloss model for cellular links	$128.1 + 37.6\log(d[\text{km}])$
Pathloss model for vehicular links	WINNER+B1
Multiple-path fading	Unit mean
Shadowing standard deviation	8 dB (CUEs), 4 dB (VUEs)
SINR threshold, $\xi^C_{\min}$, $\xi^V_{\min}$	8 dB (CUEs), 10 dB (VUEs)
Maximum power, $P^C_{\max}$,	23dBm
Maximum power, $P^V_{\max}$,	10-30dBm

in the system's Jain's fairness index of 1. But as the difference in average data rates of different users increases, the system experiences a decrease in fairness. Accordingly, the fairness index decreases and eventually will become zero. Hence, the range of the fairness index varies between 0 and 1; 1 means absolutely fair and 0 means completely unfair. In other words, an increase in the value of fairness index results in an increase in the degree of system fairness.

4.5.1 QoS Satisfaction Degree

We first consider the QoS satisfaction degree as a parameter to determine the performance of both VUEs and CUEs in Fig. 4.2-4.4 . It can be observed that all users meet the minimum SINR requirements in both the proposed algorithm and the algorithm in [36] irrespective of the increase in the number of VUE pairs, the maximum transmit powers of VUEs or the distance between VUE transmitter and VUE receiver. However, only a small portion of users in [39] can meet their minimum SINR as the underlying parameters change. This is because both the proposed algorithm and the algorithm in [36] use an optimal power control strategy to mitigate the problem of the co-channel interference for underlay V2X communication while the algorithm proposed in [39] does not take any measures to deal with this issue. In the model of [39], users transmit data with a fixed maximum transmit power, which results in a strong interference between VUEs and CUEs.

Fig. 4.2 shows the QoS satisfaction degree versus different numbers of VUE pairs with $M = 20, P^C_{\max} = P^V_{\max} = 24$dBm. As shown in the graph, the values of QoS satisfaction degree of all users both in the proposed algorithm and the algorithm in [36] are equal to 1 which means that all users in these two schemes can meet their minimum QoS requirements.

However, in the model of [39], as the number of VUE pairs grows up, the value of QoS satisfaction degree of VUEs increases slightly at first and then remains stable at the value of 1 while the QoS satisfaction degree of CUEs first decreases and then keeps stable after the number of VUE pairs reaches 20. This is primarily due to the one-to-one reuse relationship between VUE pairs and CUEs. The maximum number of VUE pairs which can reuse the spectrum resources of CUEs is equal to the maximum number of CUEs. When the number of VUE pairs is less than that of CUEs, an increase in the number of VUE pairs results in an automatic increase in the number of corresponding reuse CUEs, which causes a corresponding decrease in the QoS satisfaction level of CUEs as shown in the model of [39]. Furthermore, as the number of VUE pairs increases, the scheduler has more opportunities to choose the right set of VUE pairs which can make the system perform better. Hence, the value of QoS satisfaction level of VUEs increases slightly to 1 when the number of VUE pairs becomes larger than the maximum number of available reuse CUEs.

Fig. 4.3 presents the QoS satisfaction degree for different maximum transmit power of VUE users, where $M = 20, P^C_{\max} = 24\text{dBm}, r = 20\text{m}$. VUEs can have higher instant data rates than before because of the rise in the transmit power of VUE transmitters, while this higher transmit power also causes stronger interference to the reuse CUEs. That's why the QoS satisfaction degree of VUEs rises gradually while that of CUEs steadily decreases as shown in the model in [39]. However, in the proposed scheme, both vehicular and cellular links can meet their minimum SINR requirements because of the optimal power allocation.

Fig. 4.4 shows the QoS satisfaction degree for the increasing distance r between VUT and VUR, where $M = 20$, $P^C_{\max} = P^V_{\max} = 24\text{dBm}$. We can see that the increase in the distance r has no effect on the QoS satisfaction levels of users in both our proposed algorithm and the algorithm in [36]. But the VUEs in the scheme of [39] experience a dramatic decrease in the QoS satisfaction level. One key factor is that an increase in r will introduce a great path loss in vehicular links, thereby reducing the data rates of VUEs. However, the interference signal from VUTs to eNB remains stable because the distances between VUTs to eNB do not change in our scheme. Hence, the QoS satisfaction levels of CUEs in the scheme of [39] remain stable.

4.5.2 System Throughput

Next, the performance of the overall system throughput against different parameters is depicted in Fig. 4.5-4.7. As shown in the figures, the model described in [39] has the highest system throughput. This is mainly due to two factors. The main reason is that, although the authors in [39] take into account the co-channel interference between VUEs and CUEs, they do not take any measures to handle this issue and there is no admission control for VUE pairs to guarantee the QoS of users. Consequently, the number of VUE pairs who get access to the cellular resources in [39] is much larger than that of other algorithms. Another factor is that both VUEs and CUEs in the model of [39] transmit signal with the maximum power. Therefore, D2D-based V2X communication can introduce much higher reuse gains to the cellular network in [39] when compared to other algorithms.

Fig. 4.5 compares the changes in the network throughput against the varying number of VUE pairs, where $M = 20, P^C_{\max} = P^V_{\max} = 24\text{dBm}$. As we can see in Fig. 4.5 , when

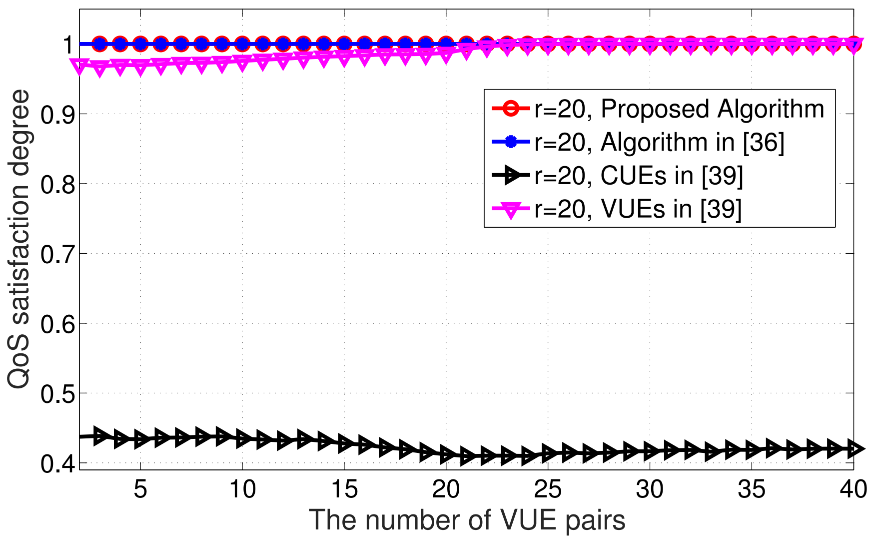


Figure 4.2: The QoS satisfaction degrees for different numbers of VUE pairs.

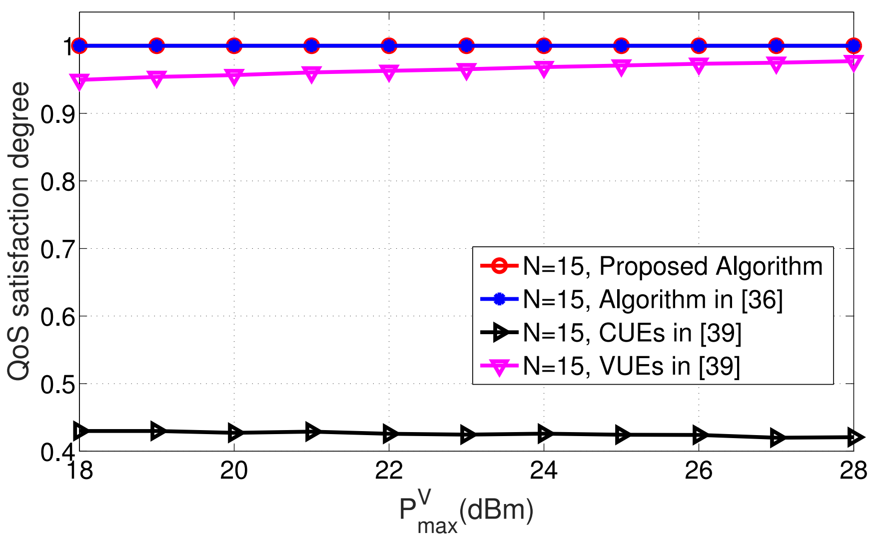


Figure 4.3: The QoS satisfaction degrees for the different maximum transmit power of VUEs.

compared to pure cellular network users, underlay V2X communication networks experience a dramatic rise in the overall network throughput because D2D communication as a proximity service can bring high reuse gains into the cellular network. We can also see that the system throughput of the proposed algorithm is quite close to that of the model in [36] which aims at maximizing the overall system throughput. Moreover, after the number of VUE pairs reaches 20, the system throughput rises slowly because of the limited available spectrum resources. And the reason why the system throughput can still go up is that, with an increase in the number of VUE pairs, more and more VUE pairs can be chosen to make the system performance better.

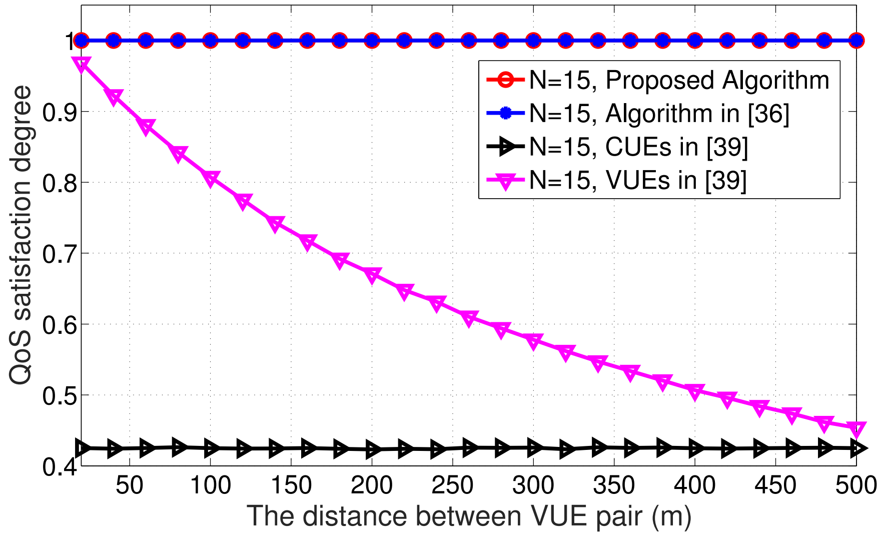


Figure 4.4: The QoS satisfaction degrees for the increasing distance between VUT and VUR.

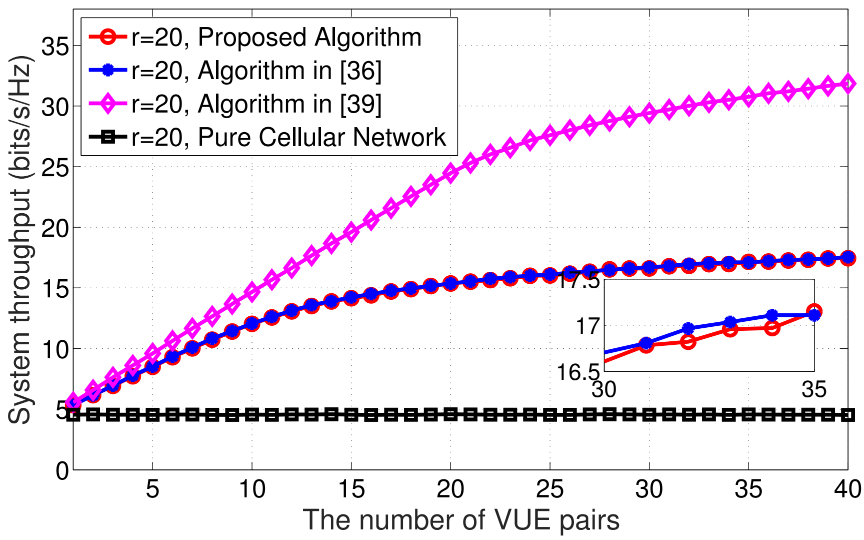


Figure 4.5: The system throughput versus increasing number of VUE pairs.

Fig. 4.6 and 4.7 compare the system throughput for the different transmit power and the distance r between VUT and VUR, respectively. In Fig. 4.6 $M = 20, r = 20, P^C_{\max} = 24$dBm while in Fig. 4.7 $M = 20, P^C_{\max} = P^V_{\max} = 24$dBm. As shown in the graph, the system throughput of the proposed algorithm is almost same with that of the optimal algorithm and very close to that of the algorithm proposed in [36] although the objective of the model in [36] is to maximize the overall throughput. When comparing these two graphs, it can be observed that the network throughput is likely to increase as the maximum transmit power of VUEs increase. By contrast, the throughput decreases as the distance r between VUE pair rises. This is because the instant data rates of VUEs grows with the increase in the

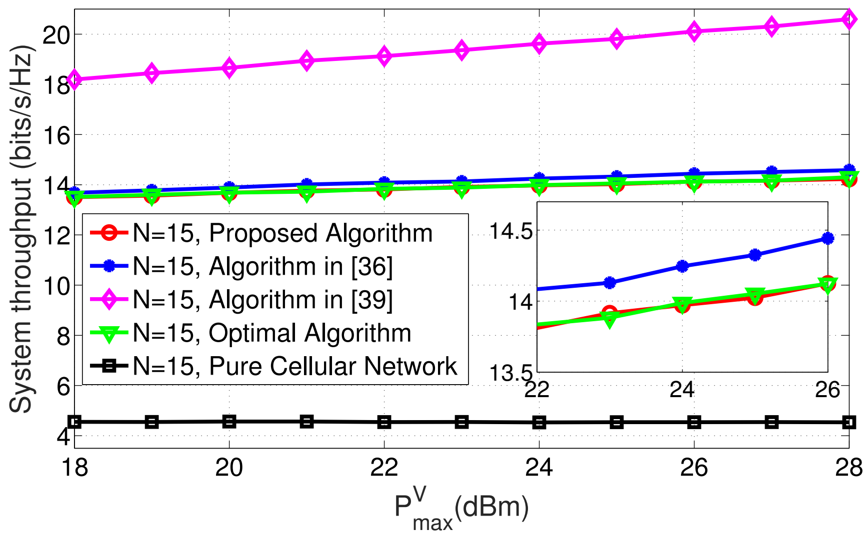


FIGURE 4.6: The system throughput against the increasing maximum transmit power of VUEs.

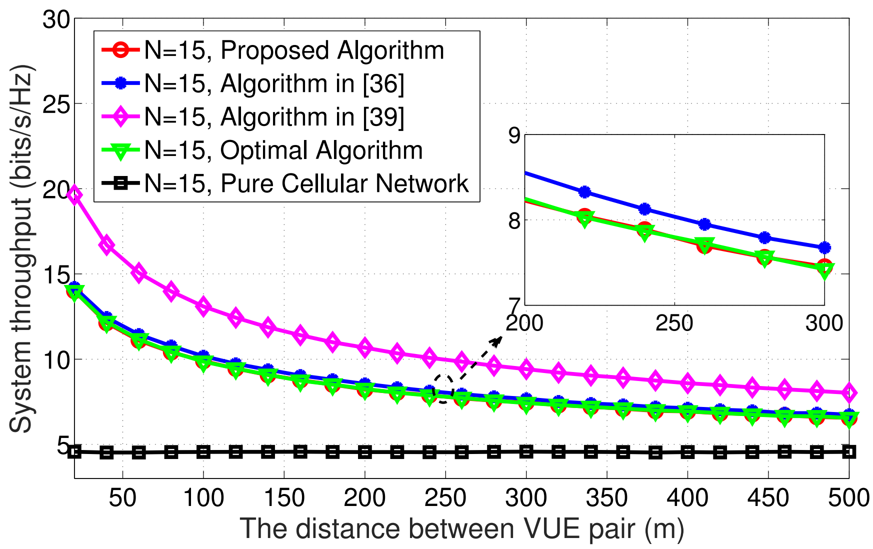


FIGURE 4.7: The system throughput versus the different distance r between VUT and VUR.

transmit power. However, the data rates of VUEs tend to decrease with the increasing r which causes a significant increase in the path loss of vehicular links.

4.5.3 System Fairness

The system fairness is also an important performance metric in our work. When the average data rates of users are equal, the system is completely fair while the system tends to become unfair when the average data rates of users vary from one to another by a certain margin. Figs. 4.8-4.10 reveal that, in terms of system fairness performance, the proposed algorithm

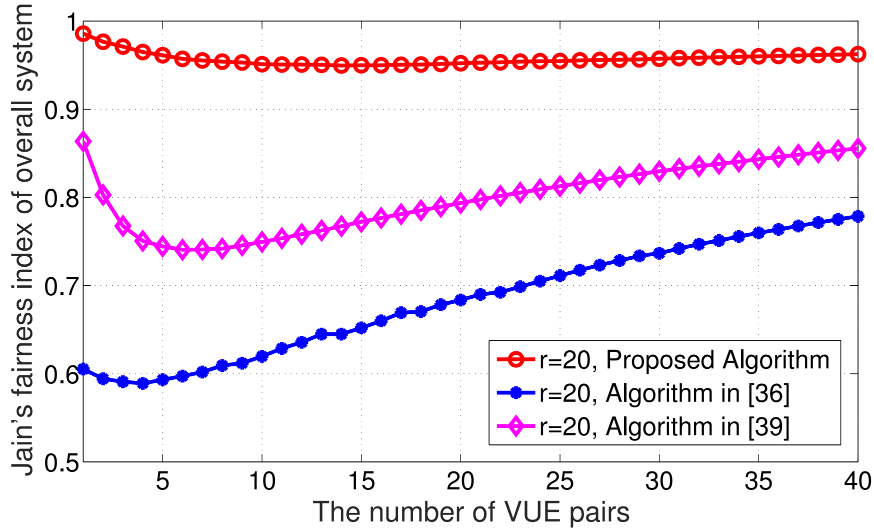


Figure 4.8: The system fairness for different numbers of VUE pairs.

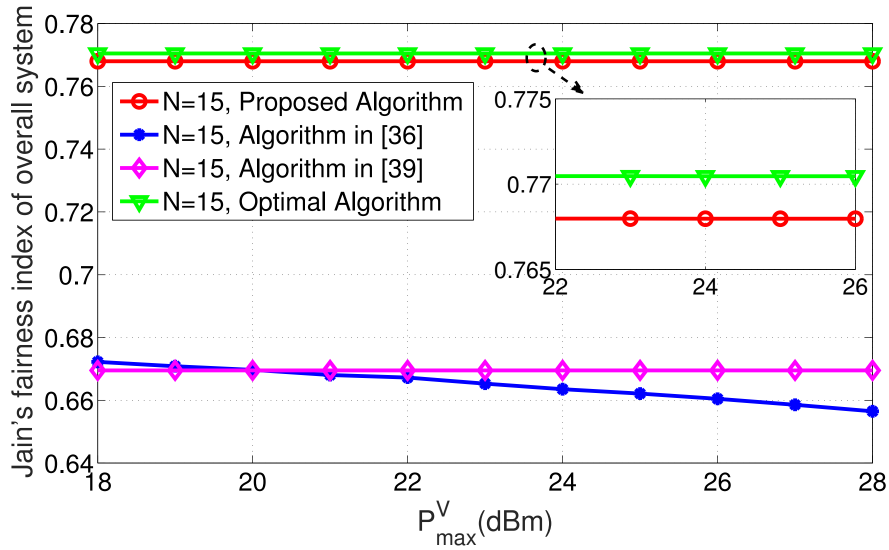


Figure 4.9: The system fairness for the different maximum transmit power of VUEs.

is a little bit lower than that of the optimal algorithm, but it significantly outperforms the algorithms in [36] and [39]. The main reason for this is that the scheduler in [36] prefers to give high-quality channel resources to users with good link conditions. Accordingly, some users will be starved due to poor channel conditions. However, we use the proportional scheduler to allocate resources to users in a manner that guarantees a high degree of fairness to all users. Although the scheme in [39] also adopts the proportional fair scheduler, the difference between the average data rates of VUEs and CUEs is still big because VUEs can obtain a pretty high instant data rates with the maximum transmit power while introducing the strong interference to CUEs.

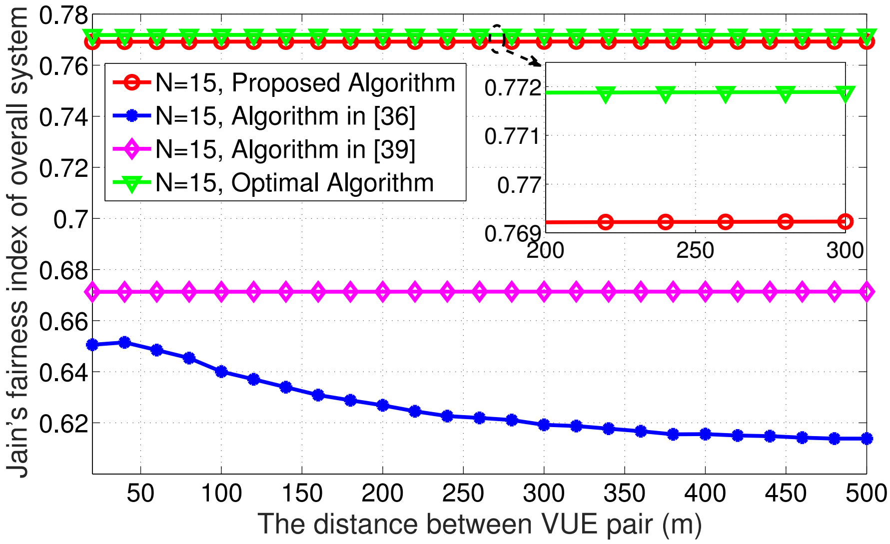


FIGURE 4.10: The system fairness for the increasing distance between VUT and VUR.

Fig. 4.8 compares the system fairness against an increasing number of VUE pairs, where $M = 20, P^C_{\max} = P^V_{\max} = 24$dBm. According to the figure, it is shown that the system fairness first drops down when there are only a few of VUE pairs. But when the number of VUE pairs rises, the fairness increases gradually. The reason why the system fairness initially drops down is that the system maintains a relatively high degree of fairness when only one cellular resource is reused by one VUE pair. With the increase in the number of VUE pairs, the number of corresponding reuse CUEs increases which in turn results in an increase in the number of users with diverse data rates. Hence, the system fairness is reduced at the beginning. But as the number of active VUE pairs increase, the system fairness can be further enhanced by improving the scheduling process in eNB.

Fig. 4.9 depicts the system fairness for the different maximum transmit power of VUEs, where $M = 20, r = 20, P^C_{\max} = 24$dBm. From Fig. 4.4 (b), we can see that, only in the model of [36], the system fairness drops gradually with the increase of the transmit power of VUEs. When the transmit power of VUEs increase, the instant data rates of VUEs rise while the instant data rates of CUEs decrease because of the strong interference from VUTs. The objective of the model in [36] is to maximize the overall throughput while ignoring the system fairness. However, in the proposed algorithm, although the transmit power of VUEs goes up, the users' fairness can be guaranteed by the proportional fair scheduler. Therefore, the increasing transmit power of VUEs has no obvious influence on the system fairness of the proposed scheme.

Fig. 4.10 compares the system fairness for the increasing distance r between VUT and VUR, where $M = 20, P^C_{\max} = P^V_{\max} = 24$dBm. From this figure, we can also see that the system fairness of the proposed algorithm remains almost unaffected by increasing values of r. By contrast, the system fairness in the model of [36] initially increases and then tends to decrease with increasing values of r. This is because the increasing distance between VUT and VUR cause the decrease in the instant data rates of VUEs. When r is small, the instant data rates of VUEs are higher when compared to the instant data rates of CUEs. The difference between the average data rates of VUEs and CUEs can be reduced by the increasing distance r. Therefore, the system fairness of the model in [36] is improved when r is small. However, when r is large, the instant data rates of VUEs become small because of the increase in the path loss of vehicular links while the instant data rates of CUEs remain stable. Consequently, the difference between the average data rates of VUEs and CUEs increase with the increasing r, which then causes a decrease in the system fairness.

As shown in Figs. 4.8-4.10, the proposed algorithm significantly outperforms the algorithms in [36] and [39] in terms of system fairness performance. Reference [36] is published in the journal of IEEE Transactions on Communications while reference [39] is published in the journal of IEEE Transactions on Wireless Communications. Both journals are the major archival journals which are committed to the timely publication of very high-quality, peer-reviewed, original papers that advance the theory and applications of wireless communication systems and networks. Furthermore, the related work of this chapter has already been published in a high-quality journal-IEEE Transactions on Vehicular Technology which consists of high-quality technical manuscripts on advances in the state-of-the-art of vehicular technology. Therefore, the work done in this chapter sits on the leading position in the related field.

4.6 Summary

In this chapter, we have proposed a new joint power control and resource scheduling scheme for underlay V2X communication to simultaneously improve both the system throughput and the system fairness. We have formulated the resource allocation problem with proportional fairness by optimizing the sum of all users' proportional fairness functions and proposed a resource allocation algorithm with low computation complexity and overheads. The proposed algorithm takes into consideration time slots of long duration and is implemented in two stages: stage 1 realizes the initialization of the average data rates of all users by the proposed joint power control and resource allocation method; stage 2 develops the proposed joint power control and proportional fair scheduling scheme from the second time slot to time slot T to improve both the system throughput and fairness over a period of time. The performance results reveal that our resource allocation scheme with proportional fairness achieves a significant performance gain in terms of both the system throughput and the system fairness without degrading the QoS levels of both VUEs and CUEs.

5 Resource Allocation for V2X Communication with Imperfect CSI

5.1 Preface

In contrast to the discussion on one-to-one matching between VUEs and CUEs in the last two chapters, here we propose a novel V2X communication scheme in which each VUE is allowed to get access to multiple CUEs' resources while each CUE's resource can be reused by one VUE at most. The proposed scheme not only can guarantee the QoS of CUEs, but also can significantly improve the system performance of V2X communication. Considering the high mobility of vehicles, in each TTI, we base the resource allocation of V2X communication on the imperfect CSI to track the fast variations of the channel state caused by the Doppler effect. Our objective is to maximize the sum ergodic capacity of all VUEs under minimum SINR requirements of CUEs and the restriction of maximum transmit power of VUEs while the reliability of vehicular links is guaranteed by keeping the outage probability of each vehicular link less than a fixed small threshold. To reduce the signalling overhead of the network, we propose a low-complexity Lower Bound-based One-to-Many matching (LB-O2M) algorithm to solve the resource allocation problem of the proposed scheme. The numerical results demonstrate the proposed scheme efficiently and effectively enhances the system performance of D2D-based V2X communication network.

The rest of this chapter is organized as follows: Section 5.2 illustrates the system model and channel model for the proposed D2D-based V2X communication system; Section 5.3 formulates the optimization problem of the system; Section 5.4 presents the power control problem with the imperfect CSI, describes the feasible region of admissible VUEs and develops the Lower Bound-based power control method to achieve an closed-form maximum ergodic capacity of each VUE; Section 5.5 presents the proposed one-to-many two-sided matching channel allocation algorithm; Section 5.6 evaluates the system performance of the

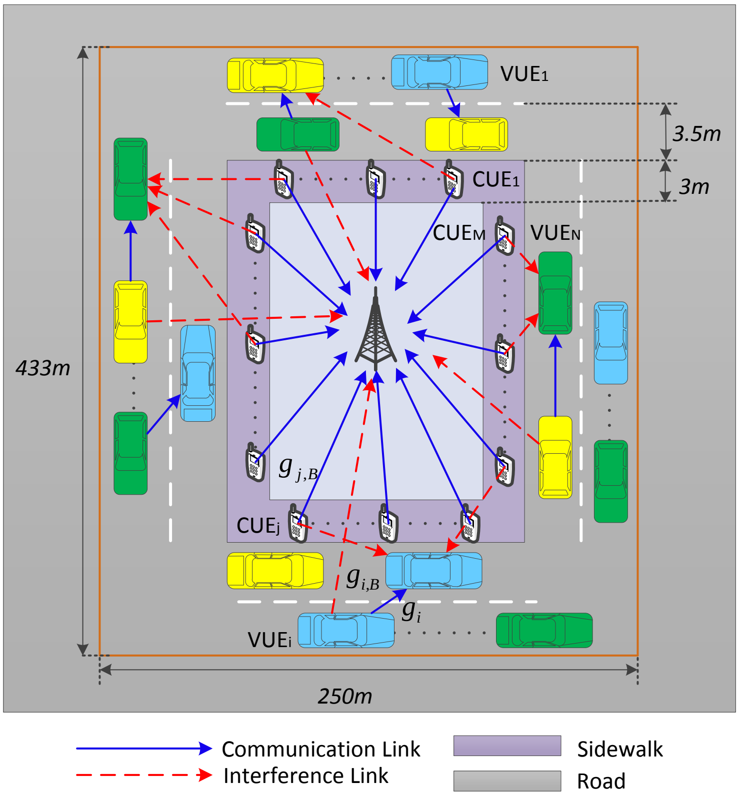


FIGURE 5.1: The system model of one-to-many matching V2X communication

proposed algorithm by different numerical simulation results; In section 5.7, we present a brief conclusion where we summarise key contributions of our work in this chapter.

5.2 System Model for V2X Communication with Imperfect CSI

5.2.1 System Model for One-to-Many Matching V2X Network

The details of the proposed system model are shown in Fig. 5.1, where a multi-user OFDMA D2D-based V2X communication network is considered. In this system, all communication links are served by an eNB within its coverage area. The road configuration for D2D-based V2X communication is defined as same as that of Chapter 3. There are M traditional CUEs distributed uniformly in the cell and N VUE transmitters dropped at different points on lanes uniformly. The sets of CUEs and VUEs are defined as $\mathcal{C} = \{\text{CUE}_1, \text{CUE}_2, \ldots, \text{CUE}_M\}$ and $\mathcal{V} = \{\text{VUE}_1, \text{VUE}_2, \ldots, \text{VUE}_N\}$, respectively. We define one subband in each TTI as one RB. We further assume that there are K vacant RBs. The vacant RBs set is defined as $\mathcal{F} = \{F_1, F_2, \ldots, F_K\}$. To effectively improve the data rates of VUEs, in this system model, for each VUE pair, V2X communication can be realized by using multiple resources which can be vacant RBs or the spectrum resources occupied by CUEs, such that the data rates of VUEs can reach as high as possible under the restriction of the maximum transmit power. Furthermore, in order to guarantee the QoS of CUEs, we assume that the resources allocated to CUEs are orthogonal from one to another and each CUE only allows one VUE at most to share its resource. Since D2D-based V2X communication is proximity-based service, the clustered distribution model [57] is considered for each VUE pair to guarantee the reliable connection between VUE transmitter and VUE receiver. In this clustered model, VUR is distributed uniformly in a circle with the centre of its corresponding VUT. To avoid the relative mobility between VUT and its VUR, we further assume that the movement direction and the vehicle speed are same for each VUT and its VUR. We further assume that the speeds of all vehicles remain the same in all lanes.

5.2.2 Channel Model of Different Communication Links

We assume that both cellular and vehicular links are independent block-fading channels, which implies the CSI can be approximately constant in each TTI [124]. Furthermore, to make the channel model more realistic, both large-scale fading and small-scale fading are taken into account for the CSI. Large-scale fading is caused by two major factors: path loss and shadowing fading while the small-scale fading is introduced by the effect of multi-path propagation. For example, g_i is defined as the channel gain between VUE transmitter i and its corresponding receiver, which can be expressed as [16]:

$$g_i = |h_i|^2 LF_i \tag{5.1}$$

where $LF_i = G\zeta_i d_i^{-\alpha}$ represents the large-scale fading channel gain of VUE i. G is defined as the path loss constant, ζ_i the shadowing fading gain with a log-normal distribution, α the path-loss exponent, and d_i the distance from VUE transmitter i to its receiver; h_i represents the small-scale fading effect. Similarly, the expressions of the interference channel gain from VUE transmitter i to eNB $g_{i,B}$, the channel gain between CUE j and eNB $g_{j,B}$, and the interference channel gain from CUE j to VUE i $g_{i,j}$ can be obtained.

Since the large-scale fading effect can be approximately considered constant in each TTI, we assume that the information of large-scale fading of all communication links can be perfectly obtained at eNB. However, with respect to the small-scale fading, for different communication situations, we have different assumptions. Considering the links $g_{j,B}$ and $g_{i,B}$ connected to the eNB directly as shown in Fig. 5.1, we assume that the information of the small-scale fading of these two links can be accurately obtained at eNB. Furthermore, we also assume eNB can obtain the perfect knowledge of g_i of VUE pair i. There are two main reasons for this assumption. One is that there is no relative motion between VUE transmitter and its corresponding receiver, which means the Doppler effect can be ignored for this case. The other is that the channel information of each VUE pair is already reported to eNB in the process of D2D discovery stage before D2D communication was established [125]. We further assume that the perfect small-scale fading information h for the aforementioned situations is independent and identically distributed (i.i.d) according to $\mathcal{CN}(0,1)$.

However, with respect to the interference link $g_{i,j}$ from CUE transmitter j to VUE receiver i, the small-scale fading $h_{i,j}$ is greatly influenced by the Doppler Shift because of the high mobility of vehicles. Furthermore, $g_{i,j}$ is reported to eNB periodically with a feedback latency T. In this case, as described in the Lemma 1 of the work in [126], eNB is only able to achieve an estimated channel gain of small-scale fading of $\tilde{h}_{i,j}$ ($\sim \mathcal{CN}(0,1)$) and the distribution of estimation error $e_{i,j}$ ($\sim \mathcal{CN}(0,1)$). Therefore, we model the small-scale fading channel estimation of $h_{i,j}$ by using the first-order Gauss-Markov process [127] in each TTI as follows:

$$h_{i,j} = \epsilon \tilde{h}_{i,j} + \sqrt{1-\epsilon^2} e_{i,j}, \tag{5.2}$$

we assume that the estimated channel gain of $\tilde{h}_{i,j}$ is i.i.d and subject to $\mathcal{CN}(0,1)$ such that $|\tilde{h}_{i,j}|^2$ has the exponential distibution with unit mean. Furthermore, $e_{i,j}$ is also i.i.d as $\mathcal{CN}(0,1)$ and independent and uncorrelated of $\tilde{h}_{i,j}$. The coefficient ϵ ($0 < \epsilon < 1$) quantifies the channel correlation between the two consecutive time slots and we assume that time correlation coefficient ϵ is same for all VUEs. According to Jakes statistical model for fading channel [128], ϵ is given as:

$$\epsilon = J_0(2\pi f_D T), \tag{5.3}$$

where J_0 is the zero-order Bessel function of the first kind. $f_D = v f_c / c$ is the maximum Doppler frequency where v indicates the vehicle speed, f_c the carrier frequency, and $c = 3 \times 10^8$m/s. T is period feedback latency. Generally, both transmitter and receiver can know the accurate ϵ.

Based on the aforementioned discussion, in the case of VUE pair i working on the vacant RB k, the received signal can be expressed as:

$$y_{i,k} = \sqrt{p_{i,k}^V L F_i} h_i s_i + n, \tag{5.4}$$

the corresponding signal-to-noise ratio (SNR) $\xi_{i,k}^V$ of VUE i is given as:

$$\xi_{i,k}^V = \frac{p_{i,k}^V g_i}{\sigma^2}. \tag{5.5}$$

When VUE i share the same resource with CUE j, considering the co-channel interference from CUE to VUE receiver, the received signal by VUE receiver i is given as:

$$y_{i,j} = \sqrt{p_{i,j}^V L F_i} h_i s_i + \sqrt{p^C L F_{i,j}} h_{i,j} s_{i,j}^C + n, \tag{5.6}$$

the corresponding SINR $\xi_{i,j}^V$ of VUE i is expressed as:

$$\xi_{i,j}^V = \frac{p_{i,j}^V g_i}{p_{i,j}^C L F_{i,j} (\epsilon^2 |\tilde{h}_{i,j}|^2 + (1-\epsilon^2)|e_{i,j}|^2) + \sigma^2}, \tag{5.7}$$

and the SINR of reuse CUE j is given as:

$$\xi_{i,j}^C = \frac{p^C g_{j,B}}{p_{i,j}^V g_{i,B} + \sigma^2}, \tag{5.8}$$

where $y_{i,k}$ is the received signal at VUE i from vacant RB k and $y_{i,j}$ is the received signal at VUE i which is sharing the resource with CUE j. s_i is the transmitted signal from VUE transmitter i. $s_{i,j}^C$ is the transmitted interference signal from reuse CUE j to VUR i. We further assume that $E[|s_i|^2] = 1$ and $E[|s_{i,j}^C|^2] = 1$ [129]. $p_{i,k}^V$ represents the transmit power of VUE i works on the vacant RB k and $p_{i,j}^V$ indicateds the transmit power of VUE i sharing the same resource with CUE j, respectively. p^C is the transmit power of CUE. In order to simplify the system model, we assume that the transmit power of CUE is fixed with the maximum transmit power, i.e., $p^C = P_{\max}^C$. VUE i is the Guassian noise with zero mean and variance σ^2, i.e., $n \sim \mathcal{CN}(0, \sigma^2)$, where σ^2 is the power of additive white Gaussian noise [129].

5.3 Problem Formulation for V2X Communication with Imperfect CSI

To make a significant improvement in the sum ergodic capacity of all VUEs, the proposed scheme is designed for the scenario where each VUE can get access to multiple resources which could either be vacant RBs or be the uplink resources occupied by CUEs, such that the data rates of VUEs can reach as high as possible under the restriction of the maximum transmit power. Furthermore, to shield CUEs from the severe co-channel interference and guarantee the SINR requirements of CUEs, in the proposed scheme, each CUE only allows one VUE to share its resource and the transmit power of CUEs are fixed with their maximum transmit power, i.e., $p^C = P_{\max}^C$. With the imperfect CSI obtained by eNB, our objective is to maximize the sum ergodic capacity of all VUEs with the constraints of outage probability of VUEs and minimum SINR requirements of CUEs. The mathematical formula of the resource allocation problem for the proposed D2D-based V2X communication scheme is given as:

$$(\mathbf{x}^*, \mathbf{p}^*) = \underset{\mathbf{x},\mathbf{p}}{\operatorname{argmax}} \left\{ \sum_{i=1}^{N} \sum_{k=1}^{K} x_{i,k}^{(1)} \log_2\left(1 + \xi_{i,k}^V\right) + \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j}^{(2)} E[\log_2\left(1 + \xi_{i,j}^V\right)] \right\}, \tag{5.9}$$

subject to

$$\sum_{i=1}^{N} x_{i,k}^{(1)} \leq 1, x_{i,k}^{(1)} \in \{0,1\}, \forall k, \tag{5.9a}$$

$$\sum_{i=1}^{N} x_{i,j}^{(2)} \leq 1, x_{i,j}^{(2)} \in \{0,1\}, \forall j, \tag{5.9b}$$

$$\sum_{k=1}^{K} x_{i,k}^{(1)} p_{i,k}^V + \sum_{j=1}^{M} x_{i,j}^{(2)} p_{i,j}^V \leq P_{\max}^V, \forall i, \tag{5.9c}$$

$$\Pr\{\xi_{i,j}^V \leq \xi_{\min}^V\} \leq p_0, \forall i, \tag{5.9d}$$

$$\xi_{i,j}^C \geq \xi_{\min}^C, \forall j, \tag{5.9e}$$

where $\mathbf{x} = \{\mathbf{x^{(1)}}, \mathbf{x^{(2)}}\}$ is defined as the channel allocatin matrix for V2X communication, in which $\mathbf{x^{(1)}}$ $(N \times K)$ is the channel allocation matrix for VUEs working in vacant RBs communication scenario while $\mathbf{x^{(2)}}$ $(N \times M)$ is for VUEs working in resue communication scenario. If VUE i works in the vacant RB k, $x_{i,k}^{(1)} = 1$; otherwise, $x_{i,k}^{(1)} = 0$. Likewise, if VUE i reuse the same resource with CUE j, $x_{i,j}^{(2)} = 1$; otherwise, $x_{i,j}^{(2)} = 0$. $\mathbf{p} = \{\mathbf{p^V}, \mathbf{p^C}\}$ is the transmit power matrix of UEs, where $\mathbf{p^V}$ is for VUEs and $\mathbf{p^C}$ is for CUEs, respectively. $P_{\max}^V$ is the maximum transmit power of VUEs. $\xi_{\min}^C$ and $\xi_{\min}^V$ are the minimum SINR thresholds of CUEs and VUEs, respectively. $\Pr\{\cdot\}$ defines the probability of the input and p_0 the acceptable outage probability.

Constraint (5.9a) restricts the use of an RB to just one VUE. Constraint (5.9b) restricts that the resource of each CUE can be reused by only one VUE. Constraint (5.9c) indicates the sum of the transmit power of VUEs is limited to its maximum transmit power. With respect to the imperfect CSI of interference links for V2X communication, we introduce the outage probability constraint (5.9d) to guarantee the reliability of V2X communicaiton. Furthermore, the minimum SINR requirement of CUEs is guaranteed by (5.9e).

The original problem in (5.9) is a Mixed-Integer Nonlinear Program (MINLP) problem for which an optimal solution is hard to obtain. Therefore, we divide this problem into two subproblems: the power control problem and one-to-many matching channel allocation problem. We propose a Lower LB-O2M algorithm to solve these two subproblems jointly. Specifically, we first focus on the power control of each VUE pair under the constraints of the outage probability of VUE and the minimum SINR requirement of its reuse CUE. By using the Lower Bound-based power control method, we can achieve an closed-form optimal power allocation for all possible combinations of VUEs and resources with low computational complexity. Based on these power allocation results, we then use the proposed one-to-many (O2M) matching method to find the optimal resources for each VUE such that the sum ergodic capacity of all VUEs can be maximized.

5.4 Power Control with Imperfect CSI

5.4.1 Power Control for Different V2X Communication Cases

In this section, we will discuss how to find the optimal transmit power of VUEs and CUEs to maximize the achievable data rate of each VUE with the imperfect CSI. For different V2X communication cases, the power control problem of VUEs can be formulated in the following two cases:

Case I: Power Control for V2X Communication in Vacant RBs

When VUE i occupies a vacant RB k, VUEs communicate with one another without being subject to co-channel interference. In this case, we get the maximum throughput of VUE i at its maximum transmit power as shown in the equation below:

$$P_{\max}^V = p_{i,k}^{V*} = \underset{p_{i,k}^V}{\operatorname{argmax}} \left\{ \log_2 \left(1 + \frac{p_{i,k}^V g_i}{\sigma^2} \right) \right\}, \tag{5.10}$$

Case II: Power Control for V2X Communication in Reuse RBs

When VUE pair i shares the same resource with CUE j, VUE transmitter i introduces the interference signal to eNB while CUE j send the interference signal to VUE receiver with imperfect CSI. In this case, we use the constraints of minimum SINR threshold and outage probability to guarantee the QoS of CUEs and VUEs, respectively. The optimization problem of the ergodic capacity of each VUE can be formulated as:

$$p_{i,j}^{V*} = \underset{p_{i,j}^{V}}{\operatorname{argmax}} \left\{ E\left\{ \log_2\left(1 + \frac{B_1}{B_2 + B_3 X}\right)\right\}\right\}. \tag{5.11}$$

subject to

$$0 \leq p_{i,j}^{V} \leq P_{\max}^{V}, \forall i, \tag{5.11a}$$

$$Pr\{\xi_{i,j}^{V} \leq \xi_{\min}^{V}\} \leq p_0, \forall i, \tag{5.11b}$$

$$\xi_{i,j}^{C} = \frac{p^C g_{j,B}}{p_{i,j}^{V} g_{i,B} + \sigma^2} \geq \xi_{\min}^{C}, \forall j, \tag{5.11c}$$

where $B_1 = p_{i,j}^{V} g_i$, $B_2 = p_{i,j}^{C} L F_{i,j} \epsilon^2 |\tilde{h}_{i,j}|^2 + \sigma^2$ and $B_3 = p_{i,j}^{C} L F_{i,j}(1 - \epsilon^2)$. $X = |e_{i,j}|^2$ is a exponential random variable with unit mean, i.e., $X \sim \exp(1)$. To solve the optimization problem in equation (5.9), it is necessary to derive an accurate expression for the ergodic capacity of VUEs and then find the optimal power allocation solution in its feasible region. Due to the imperfect CSI of the interference link from CUE to VUE receiver, as shown in equation (5.11), we first start by deriving the accurate expression of the ergodic capacity of the VUE. Based on the Lemma 2 proved in [130], we can obtain the following lemma:

Lemma 1. *For $X \sim \exp(\alpha)$ it holds that,*

$$E[\ln(1 + PX)] = \phi(P\alpha) \tag{5.12}$$

where $\phi(x) = e^{1/x} E_1(1/x)$, $E_1(x) = \int_x^\infty \frac{1}{t} e^{-t} dt$, $x > 0$.

As explained in Appendix B.1, when VUE i and CUE j share the same resource, the ergodic capacity value of VUE i can be calculated as:

$$E\left\{\log_2\left(1 + \frac{B_1}{B_2 + B_3 X}\right)\right\} = \log 2\left(\frac{(B_1 + B_2)}{B_2}\right) + \frac{\phi\left(\frac{B_3}{B_1 + B_2}\right)}{\ln 2} - \frac{\phi\left(\frac{B_3}{B_2}\right)}{\ln 2} \tag{5.13}$$

5.4.2 Feasible Region for Admissible VUEs

According to constraints (5.11a) to (5.11c), the feasible region $\mathcal{F}_{i,j}^{V}$ of equation (5.11) is derived as:

$$\mathcal{F}_{i,j}^{V} = \left\{ p_{i,j}^{V} \in \mathcal{F}_{i,j}^{V} : P_1 \leq p_{i,j}^{V} \leq P_{\max}^{V}, p_{i,j}^{V} \leq P_2 \right\}, \tag{5.14}$$

where

$$P_1 = \frac{(B_2 - B_3 \ln p_0)\xi_{\min}^{V}}{g_i}, \tag{5.14a}$$

$$P_2 = \frac{p^C g_{j,B} - \xi_{\min}^{C} \sigma^2}{g_{i,B}}, \tag{5.14b}$$

The proof of the feasible region can be found in Appendix B.2. If $P_2 < P_1$, VUE i is not allowed to get access to the resource of CUE j. The feasible region of equation can be further decomposed into two sub cases as follows:

Case 1: If $P_1 \leq P_2 \leq P_{\max}^V$, the feasible region of problem (5.11) is given as:

$$\mathcal{F}_{case1}^V = \left\{ p_{i,j}^V \in \mathcal{F}_{i,j}^V : P_1 \leq p_{i,j}^V \leq P_2 \right\}. \tag{5.15}$$

Case 2: If $P_1 \leq P_{\max}^V \leq P_2$, the feasible region of problem (5.11) is derived as:

$$\mathcal{F}_{case2}^V = \left\{ p_{i,j}^V \in \mathcal{F}_{i,j}^V : P_1 \leq p_{i,j}^V \leq P_{\max}^V \right\}. \tag{5.16}$$

5.4.3 SA-based Power Control

The problem in equation (5.13) is a non-linear optimization problem. Due to the randomness of UEs locations, it is difficult to certify whether equation (5.13) is convex with variable $p_{i,j}^V$ in the feasible region. That is to say, it is not easy to obtain the optimal transmit power of VUEs to reach the maximum ergodic capacity in equation (5.13).

Heuristic simulated annealing (SA) method proposed by S. Kirkpatrick et al. [131] (1983) is able to obtain an acceptably good solution to the non-linear bound-constrained optimization problem. This method uses a probabilistic technique to approximate the global optimum of a given objective function which may have several local minima [132]. It works by modelling the physical process of heating metal until it melts and then cooling it slowly to form a crystallisation with minimal energy. Therefore, SA algorithm can be used to obtain an acceptable optimum of equation (5.13). Algorithm 5 gives a brief description of SA-based power control method. The procedure of the basic simulated annealing algorithm can be depicted as iterative and evolutionary and includes two loops: an outer Cooling Loop and a nested inner Thermal Equilibrium Loop. The outer Cooling Loop cools the temperature down until the minimum temperature is reached and the search is stopped. With a given temperature, the inner Thermal Equilibrium Loop stops when it achieves thermal equilibrium, which implies either the threshold of maximum number of iterations possible is reached or an acceptable optimal solution has been found.

As shown in Algorithm 5, we find that the convergence of SA algorithm is determined by the following critical parameters. For the outer loop, there are the initial temperature $Temp_{\max}$, the final freezing temperature $Temp_{\min}$ and the cooling ratio η. For the inner loop, there is the maximum number of iteration length L for each given temperature [133]. If we assume that the final freezing temperature $Temp_{\min} = 1$, we can obtain the computational complexity of the outer loop is $O(\log(Temp_{\max}))$ [132]. Furthermore, for each given temperature, the inner loop is executed $O(L)$. Therefore, the computational complexity of SA is $O(L \times \log(Temp_{\max}))$. Apparently, directly finding an acceptably good solution to the problem in (5.13) by SA is time-consuming. Therefore, in the following section, we consider an approximation to simplify (5.13) so that the complexity can be reduced.

Algorithm 5 Simulated Annealing-based Power Control

Set $Temp_{\max}$ as the initial temperature, $Temp_{\min}$ final freezing temperature, $Temp$ the current temperature and η the cooling ratio, $0 < \eta < 1$;
For the thermal equilibrium loop, set L as the maximum number of iterations and μ and $\mu_{\max}$ as the positive integers;
Based on the feasible region of (5.14), generate a random p_0^V as an initial solution $p_{i,j}^V$ of equation (5.13);
Set $Temp = Temp_{\max}$, $p_{i,j}^V = p_0^V$ and $\mu = 0$;
while $Temp > Temp_{\min}$ **do**
  for $i = 1 : L$ **do**
    Substitute $p_{i,j}^V$ into equation (5.13), calculate its corresponding ergodic capacity r_{old};
    Generate a random neighbouring solution p^V by making a small perturbation to $p_{i,j}^V$, and compute the new solution's ergodic capacity r_{new} ;
    Compare the new solution's ergodic capacity (r_{new}) with the old one (r_{old}):
    if $r_{\text{new}} > r_{\text{old}}$ **then**
      Accept the new solution;
      Set $p_{i,j}^V = p^V$, $\mu = 0$;
    else if $r_{\text{new}} < r_{\text{old}}$ **then**
      Accept the new solution with a certain probability, which helps the algorithm to explore more possible global solutions instead of being trapped in local maxima;
      Set $p_{i,j}^V = p^V$, $\mu = \mu + 1$;
    end if
    if $\mu > \mu_{\max}$ **then**
      Set the optimal transmit power $p_{i,j}^{V^*} = p_{i,j}^V$;
      A near-optimal solution is found. Stop the thermal equilibrium loop;
    end if
  end for
  The algorithm systematically lowers the temperature by setting $Temp = \eta Temp$;
end while
Obtain $p_{i,j}^{V^*}$.

5.4.4 Lower Bound-based Power Control

In this section, to further reduce the complexity, we introduce the lower bound of the ergodic capacity to solve the problem (5.13). As proved below, the ergodic rate in (5.13) is convex with respect to X. Hence, by Jensen's inequality [134], the lower bound of equation (5.13) can be expressed as:

$$\begin{aligned} E\left\{\log_2\left(1+\frac{B_1}{B_2+B_3X}\right)\right\} &\geq \log_2\left(1+\frac{B_1}{B_2+B_3E[X]}\right) \\ &= \log_2\left(1+\frac{B_1}{B_2+B_3}\right) \end{aligned} \tag{5.17}$$

Proof:

$$f(X) = \log_2\left(1 + \frac{B_1}{B_2 + B_3 X}\right), \tag{5.18}$$

By differentiating $f(X)$ with respect to X, we have its corresponding second derivative:

$$\frac{\partial^2 f}{\partial X^2} = \frac{B_1 B_3^2 (B_1 + 2(B_2 + B_3 X))}{(B_2 + B_3 X)^2 (B_1 + B_2 + B_3 X)^2 \ln 2} > 0. \tag{5.19}$$

As shown in equation (5.19), the value of the second derivative is larger than 0. Therefore, we can conclude that $f(X)$ is convex with X. The proof is concluded.

Apparently, the lower bound function (5.17) is much simpler than the original optimization function (5.13). We then focus on maximizing the lower bound function to obtain the optimal power allocation:

$$p_{i,j}^{V^*} = \underset{p_{i,j}^V}{\text{argmax}} \left\{ \log_2\left(1 + \frac{p_{i,j}^V g_i}{B_2 + B_3}\right) \right\}. \tag{5.20}$$

Since the logarithm function shown in equation (5.20) monotonically increases with respect to $p_{i,j}^V$, the maximum value of the objective function of (5.20) can be reached at maximum $p_{i,j}^{V^*}$ based on the feasible region of (5.15) and (5.16), which is shown as:

$$p_{i,j}^{V^*} = \begin{cases} P_2, & if P_1 \le P_2 \le P_{\max}^V, \\ P_{\max}^V, & if P_2 \ge P_{\max}^V, \end{cases} \tag{5.21}$$

The computational complexity of the proposed lower bound method is $O(1)$, which reduces the system computational complexity significantly when compared to the SA algorithm.

5.5 One-to-Many Matching Channel Allocation for V2X Communication

5.5.1 Problem Formulation for One-to-Many Matching Channel Allocation

By leveraging the Lower Bound-based power control method proposed in the last section, we can evaluate the closed-form optimal transmit power allocation to reach the maximum data rate of each VUE for all possible combinations of VUEs and resources (vacant resources and reuse resources). By substituting these power allocation results into the original optimization problem (5.9), the MINLP problem can be simplified into a 0-1 integer programming problem with only one variable $\mathbf{x}$, shown as:

$$\mathbf{x}^* = \underset{\mathbf{x}}{\text{argmax}} \left\{ \sum_{i=1}^{N} \sum_{k=1}^{K} x_{i,k}^{(1)} r_{i,k}^{V^*} + \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j}^{(2)} \overline{r}_{i,j}^{V^*} \right\}, \tag{5.22}$$

subject to

$$\sum_{i=1}^{N} x_{i,k}^{(1)} \leq 1, x_{i,k}^{(1)} \in \{0,1\}, \forall k, \tag{5.22a}$$

$$\sum_{i=1}^{N} x_{i,j}^{(2)} \leq 1, x_{i,j}^{(2)} \in \{0,1\}, \forall j, \tag{5.22b}$$

$$\sum_{k=1}^{K} x_{i,k}^{(1)} p_{i,k}^{V*} + \sum_{j=1}^{M} x_{i,j}^{(2)} p_{i,j}^{V*} \leq P_{\max}^{V}, \forall i, \tag{5.22c}$$

$$r_{i,k}^{V*} = \log_2 \left(1 + \frac{P_{\max}^{V} g_i}{\sigma^2}\right), \tag{5.22d}$$

$$\overline{r}_{i,j}^{V*} = \log_2 \left(1 + \frac{p_{i,j}^{V*} g_i}{B_2 + B_3}\right), \tag{5.22e}$$

5.5.2 One-to-Many Two-sided Matching Algorithm Design

As mentioned above, the proposed scheme is suitable for the scenario where each VUE pair can use multiple resources such that the data rate of VUE can increase as high as possible under its maximum transmit power constraint. Furthermore, in order to guarantee the QoS of CUEs, we assume that the resource of each CUE can be reused by one VUE at most. Therefore, considering VUEs and spectrum resources as two disjoint sets, the channel allocation problem in (5.22) can be regarded as a one-to-many two-sided matching problem.

The college admissions problem is a one-to-many matching problem, in which a number of students apply to a number of colleges and one college can recruit a fixed number of students with a certain quota while one student can be admitted by only one college. How to design a one-to-many matching mechanism to maximize the welfare of both students and colleges is a very challenging task. David Gale and Lloyd Shapley [117] have already designed a stable one-to-many matching mechanism by which both students and colleges get matched in such a way that no such pair exists in which a student A of the first matched set which prefers some given college B of another matched set over the college to which A is already matched and vice versa. Note that, in the proposed scheme, as shown in constraints (5.22a)-(5.22c), a VUE can get access to multiple spectrum resources under the constraint of the maximum transmit power while each resource can be allocated to one VUE at most. This is in accordance with a one-to-many matching in the matching theory.

Inspired by college admission problem, we propose an enhanced GS algorithm which is tailored to the one-to-many matching resource allocation problem of the proposed scheme. We assign VUEs the role of colleges, and spectrum resources the role of students respectively. A matching is referred to an assignment of spectrum resources to VUEs under the two-sided preferences framework. Different from the traditional one-to-many matching algorithm adopted in [32], to facilitate the practical application in V2X communication, as shown in constraint (5.22c), the proposed algorithm takes into account the maximum transmit power of VUEs to limit the number of spectrum resources VUEs can get access to instead of a fixed number of resources. That is to say, the number of spectrum resources occupied by

VUEs depends on the practical transmit power and the instant CSI of vehicular links. For each VUE i, the one-to-many matching resource allocation problem with the limitation of its maximum transmit power is formulated as:

$$\mathbf{x_i^*} = \underset{\mathbf{x_i}}{\mathrm{argmax}} \left\{ \sum_{k=1}^{K} x_{i,k}^{(1)} r_{i,k}^{V*} + \sum_{j=1}^{M} x_{i,j}^{(2)} \overline{r}_{i,j}^{V*} \right\}, \tag{5.23}$$

subject to

$$\sum_{k=1}^{K} x_{i,k}^{(1)} p_{i,k}^{V*} + \sum_{j=1}^{M} x_{i,j}^{(2)} p_{i,j}^{V*} \leq P_{\max}^{V}, \tag{5.23a}$$

The problem (5.23) is a 0-1 integer programming problem which can be solved by the well-known Branch-and-Bound algorithm [135]. By solving the problem in (5.23), we can obtain the optimal resources for VUE i.

5.5.3 Utility Matrix and Preference List Establishment

One key advantage of the matching theory is to establish a suitable preference list which can tackle the complex and heterogeneous QoS requirements of matching players in two distinct sets. The goal of the proposed one-to-many matching algorithm is to match vacant RBs set $\mathcal{F}$ and reuse spectrum resources of CUEs set $\mathcal{C}$ to VUEs set $\mathcal{V}$ such that the sum ergodic capacity of all VUEs can be maximized under the constraint of maximum transmit power of VUEs. We then define $\mathcal{F}_{\mathcal{O}}$ as the set of all resources including both vacant and reuse resources. That is to say, $\mathcal{F}_{\mathcal{O}}$ consists of vacant RBs set $\mathcal{F}$ and reuse spectrum resource set $\mathcal{C}$. Therefore, we define a utility function matrix $\mathcal{U}$ that evaluates the ergodic capacities of all VUEs in all different resources to measure the preference of both VUEs set and resource set. Considering that there are N VUEs and $K+M$ resources, the size of the $\mathcal{U}$ is $N \times (K+M)$ given as:

$$\mathcal{U} = \begin{pmatrix} u_{1,1} & u_{1,2} & \cdots & u_{1,K} & \cdots & u_{1,K+M} \\ u_{2,1} & u_{2,2} & \cdots & u_{2,K} & \cdots & u_{2,K+M} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ u_{I,1} & u_{I,2} & \cdots & u_{I,K} & \cdots & u_{I,K+M} \end{pmatrix}. \tag{5.24}$$

Based on the optimal power allocation results discussed in the power control section (Section 5.4), we can obtain the utility function $u_{i,j}$ as follows: In the case of $j \leq K$, $u_{i,j}$ can be calculated by equation (5.10). In the case of $K+1 \leq j \leq K+M$, if VUE i is admissible to get access to the reource of CUE j, $u_{i,j}$ can be calculated by equation (5.11); Otherwise, $u_{i,j} = 0$. The utility function matrix $\mathcal{U}$ provides the preference framework for the two-sided VUEs set and resource set. Based on the individual preferences of VUEs and resources, the proposed one-to-many algorithm can provide a stable and optimal matching between both VUEs set $\mathcal{V}$ and resource set $\mathcal{F}_{\mathcal{O}}$. The stable matching for the proposed scheme is defined as follows:

Definition 5. *A matching is stable if there are no two spectrum resources j and j' which are allocated to VUEs i and i', respectively, such that $u_{i,j'} > u_{i,j}$ and $u_{i',j} > u_{i',j'}$, which means VUE i prefers resource j' and VUEs i' prefers resource j.*

Algorithm 6 Proposed Resource Allocation Algorithm

Define $\mathbf{F_{UM}}$ as the set of unmatched resources including vacant and reuse resources;
Define $\mathbf{Pro_j}$ as the proposition vector of resource j, where if resource j proposes to VUE i, $Pro_{i,j} = 1$; otherwise $Pro_{i,j} = 0$;
Calculate the optimal power allocation of VUEs by using the Lower Bound-based power control method discussed in section 5.4;
Establish the preference list of VUEs and resources by matching matrix $\mathcal{U}$;
while $\mathbf{F_{UM}} \neq \varnothing$ and $\mathbf{Pro_j} \neq \varnothing$ **do**
    Choose any resource j from $\mathbf{F_{UM}}$;
    Resource j makes an offer to its highest ranked VUE i;
    $Pro_{i,j} = 1$;
    Among the applicants, VUE i picks up the q highest-ranked resources under its maximum transmit power restriction by using the optimal solution $\mathbf{x_i^*}$ of the problem (5.23) and put them on the waitlist. The rest of the applicants are rejected;
    if Resource j is selected by VUE i **then**
        Remove resource j from $\mathbf{F_{UM}}$;
    end if
    for all $m \in M$ **do**
        if VUE i does not chooose resource m **then**
            Add resource m into $\mathbf{F_{UM}}$;
        end if
    end for
end while
Obtain the optimal one-to-many matching matrix $\mathbf{x}^*$.

5.5.4 Proposed Resource Allocation Algorithm

Since the utility function is obtained by the Lower Bound (LB) method proposed in the power control stage, we name the proposed matching algorithm as LB-O2M algorithm. The specific details of the proposed algorithm are presented as follows: Step1: Each resource ranks the VUEs in the descending order of its preference value, ignoring the VUEs which are not admissible. Likewise, each VUE ranks the resources in order of its preference eliminating those resources which cannot be accessed under the constraints of (5.11a)-(5.11c); Step2: Each resource makes an offer to its highest-ranked VUE; Step3: Among the applicants, each VUE picks up the q highest-ranked resources under its maximum transmit power restriction by using the optimal solution $\mathbf{x_i^*}$ of the problem (5.23) and put them on the waitlist. The rest of the applicants are rejected; Step4: The rejected resources are assigned to their next highest ranked VUEs; Step5: The VUE then re-ranks resources among all applicants and those who are on the waitlist. Repeat step 3-5 and the procedure will be stopped until all resources are either matched to VUEs or have proposed to all VUEs on their preference list. By using LB-O2M algorithm, the matching between VUEs and resources can reach the stable state.

TABLE 5.1: Simulation Parameters

Parameter	**Value**
Cell radius, R	500 m
VUE pair distrance, r	$20-100$ m
Carrier frequency	2 GHz
Uplink Bandwidth	10 MHz
Bandwidth of each RB	180 kHz
Noise spectral density	-174 dBm/Hz
Path-loss model for CUEs	$128.1+37.6\log(d[\text{km}])$
Multiple-path fading	Unit mean
Shadowing standard deviation	8 dB (CUEs), 4 dB (VUEs)
SINR threshold of CUEs, $\xi^C_{\min}$	$5-15$ dB
SINR threshold of VUEs, $\xi^V_{\min}$	10 dB
Reliability for VUEs, p_0	10^{-3}
Channel feedback latency, T	0.5 ms
Maximum power of CUEs, $P^C_{\max}$	23 dBm
Maximum power of VUEs, $P^V_{\max}$	19-26 dBm
The number of CUEs, M	5,8
The number of VUEs, N	1-8
The number of vacant RBs, K	1
The absolute vehicle speed	60km/h

5.6 Performance Analysis for V2X Communication with Imperfect CSI

5.6.1 Scenarios and Parameters for V2X Communication with Statistical CSI

In this section, we configure an urban road scenario for V2X communication as described in 3GPP TR 36.885[13], where the path-loss model for VUEs is WINNER+B1 Manhattan grid layout (note that the antenna height is 1.5m) and the path-loss model for CUEs is set as Macrocell propagation model of the urban area. Considering the different data traffic requirements of CUEs, in the proposed scheme, the spectrum resources are randomly allocated to CUEs. The major parameters used for the proposed scheme are summarized in Tabel 5.1 [13, 16, 136].

We present the numerical results of different algorithms and parameters to evaluate the system performance of the proposed algorithm in terms of the sum ergodic capacity of all

VUEs and the sum ergodic capacity of the overall network which includes all VUEs and CUEs, respectively. For the sake of comparison, the numerical results of the SA-based one-to-many matching algorithm and the one-to-one matching algorithm proposed in [16] are also considered:

SA-based one-to-many (SA-O2M) matching algorithm: Unlike the Lower Bound algorithm that was proposed for power control, this algorithm use heuristic simulated annealing method to obtain an acceptable optimal power allocation. Based on these results, the proposed one-to-many matching algorithm can achieve an acceptable optimal solution for the original problem in equation (5.9).

Algorithm in [16] : The algorithm proposed in [16] is developed by joint spectrum and power allocation under the delayed CSI feedback. It is designed for the one-to-one matching communication scenario where each CUE's resource can be reused by one VUE at most and each VUE can only be allowed to share the resource with one CUE.

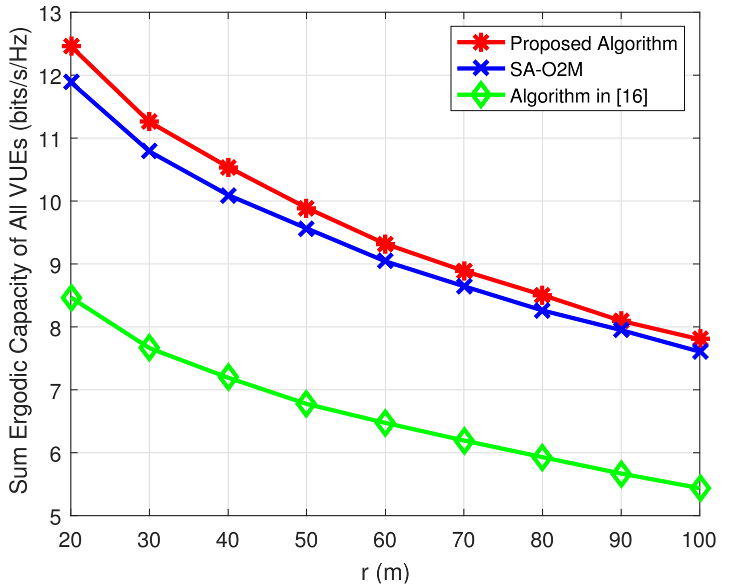
Since SA-based one-to-many matching algorithm is time-consuming as the number of users increases, for the simulation, both the number of VUEs and CUEs are limited to less than 10. Parameter r is defined as the radius of the D2D-based V2X clustered model, which is equal to the maximum communication distance between VUT and VUR. We further assume the radius r to be same for all VUE pairs. For each VUE pair, since the VUE receiver is distributed uniformly in the circle, the locations of VURs are different for different VUE pairs and the communication distance for each VUE pair is also different. Therefore, for simulation, we change communication distances for all VUE pairs by changing r.

5.6.2 Impact of Different Parameters on the System Performance

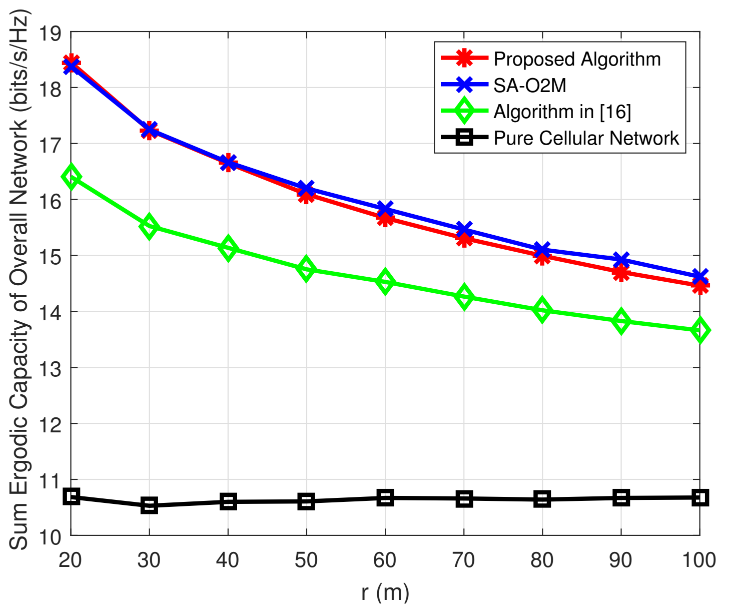
Fig.5.2 compares the system performance of different algorithms against increasing distance r. As shown in Fig.5.2, as r increases, both the sum ergodic capacity of all VUEs (Fig.5.2(a)) and the sum ergodic capacity of the overall network (Fig.5.2(b)) decrease gradually. This is because the increase in r introduces a large path-loss to vehicular link, which results in the decrease in the capacity of VUEs. Accordingly, the reuse gains introduced by VUEs are also degraded. Hence, the sum capacity of the overall network decreases with an increase in r.

Fig.5.2(a) illustrates the sum ergodic capacity of all VUEs against various r. As shown in the figure, the proposed algorithm achieves the best performance among all three algorithms, which demonstrates that, when compared to SA-O2M algorithm, the proposed algorithm not only has the lower computational complexity but also performs better. The performance of both the proposed algorithm and SA-O2M algorithm outperforms the Algorithm in [16] dramatically. The main reason for this is that, by using the proposed algorithm and SA-O2M algorithm, each VUE is able to reuse multiple CUEs' resources which can introduce high reuse gains, especially when the networks have enough available cellular resources. However, the system model in [16] only allows one VUE to share the resource with one CUE at most, which limits the improvement in the sum capacity of all VUEs.

Fig.5.2(b) compares the sum ergodic capacity of overall network against various r. From this figure, we can observe that, when compared to the pure cellular network, D2D-based



(a) The sum ergodic capacity of all VUEs against various r.



(b) The sum ergodic capacity of overall network against various r.

FIGURE 5.2: System performance with different distance r, where $P_{\max}^{C} = P_{\max}^{V} = 23\text{dBm}, M = 8, N = 4, \xi_{\min}^{C} = 10$ dB.

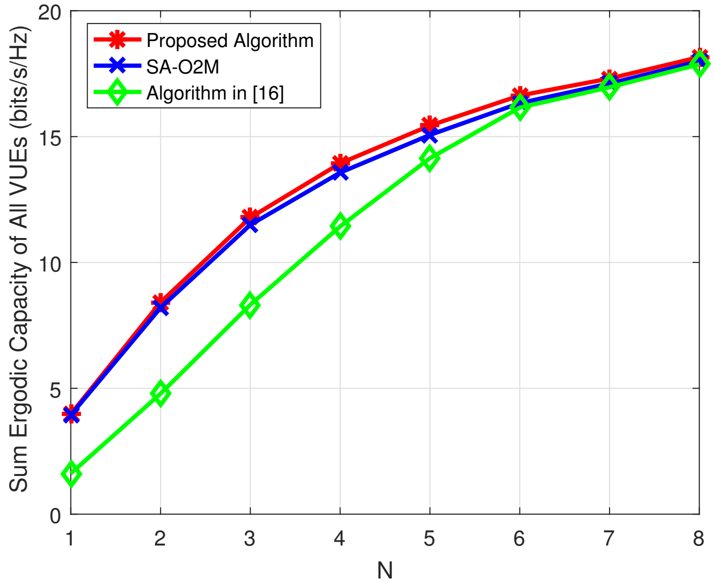
V2X communication can enhance the sum ergodic capacity of the overall network dramatically. This demonstrates that, by leveraging the proximity service-D2D technology, V2X communication can bring high reuse gains to the conventional cellular network. We can also see that the sum capacity of the overall network is higher than the sum capacity of all VUEs. This is reasonable because the overall network includes not just VUEs but also CUEs. It is also very interesting that, when compared to Fig.5.2(a), the difference gap between the proposed algorithm and the Algorithm in [16] is reduced obviously. The main reason for this is that the number of reuse CUEs in the model of [16] is less than that of the proposed scheme. Consequently, the sum capacity of all CUEs in the model of [16] is larger than that of the proposed scheme. Hence, the difference gap between the proposed algorithm and the Algorithm in [16] becomes smaller when compared to Fig.5.2(a).

Fig.5.3 evaluates the system performance of different algorithms under different communication scenarios where the number of VUE pairs can be any case (less than, equal to or greater than the number of CUEs). The parameters are set as $P^C_{\max} = P^V_{\max} = 23\text{dBm}, M = 5, r = 20\text{m}, \xi^C_{\min} = 10$ dB. It can be observed that the sum ergodic capacity of the network experiences a noticeable increase with the increase in the number of VUE pairs. As the number of VUE pairs increases, the number of admissible VUEs also increases. Consequently, the sum capacity of the system goes up. We can also see that, when the number of VUE pairs is larger than that of CUEs, the gap between all three algorithms become small. This is because when the number of VUE pairs is large enough, the paucity of cellular resources makes each VUE can only get access to one spectrum resource such that the sum capacity of all VUEs can be maximized. In this case, all three algorithms perform similar performances.

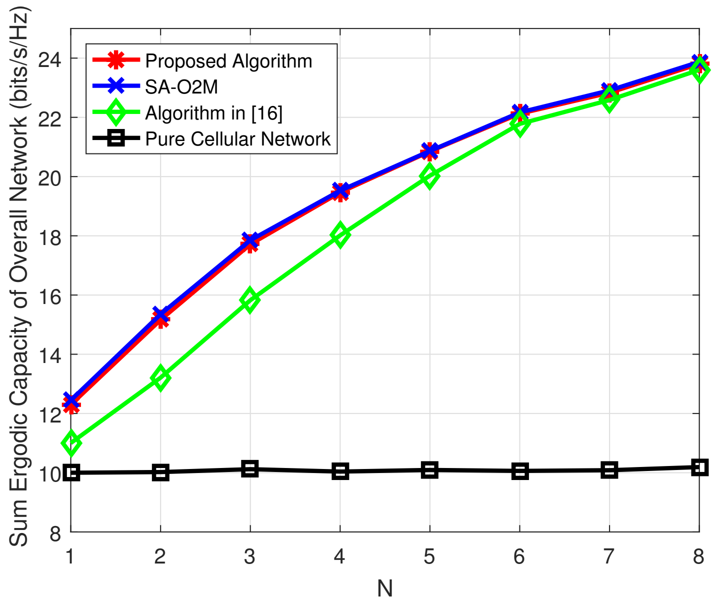
Fig.5.3(a) compares the sum ergodic capacity of all VUEs for different algorithms with the increasing number of VUE pairs N. As observed from the figure, when the number of VUE pair is not greater than 2 and there are enough cellular resources, VUEs have big probabilities to get access to the cellular links with better CSI. In this case, the performance of the proposed algorithm and SA-O2M algorithm is quite similar. As the number of VUE pairs keeps rising, we can further find that the proposed algorithm has a better performance than other two algorithms. Fig.5.3(b) presents the sum ergodic capacity of the overall network for the different number of VUE pairs. As we can see, the sum capacity of the overall network of the proposed algorithm and SA-O2M algorithm is very close and both of their performances are greater than that of the Algorithm in [16].

Fig.5.4 elaborates the effect of the maximum transmit power of VUEs $P^V_{\max}$ on the system performance, where $P^C_{\max} = 23\text{dBm}, M = 8, N = 4, r = 20\text{m}, \xi^C_{\min} = 10$ dB. From Fig.5.4(a), we can observe that the sum ergodic capacity of all VUEs has an obvious increase with the increasing $P^V_{\max}$. However, the sum capacity of the overall network experiences a slight increase. This occurs because the high transmit power of VUEs brings high data rates to vehicular links, but it also introduces high co-channel interference to the cellular links, which reduces the capacity of the reuse CUEs. Furthermore, as we can see, when the VUE communication distance is not big, such as $r = 20$m, and there are adequate available cellular resources for V2X communication, such as $M = 8, N = 4$, the proposed algorithm has an excellent performance which outperforms other two algorithms significantly.

Fig.5.5 depicts the performance degradation in the system capacity with the rise in the SINR threshold of CUEs $\xi^C_{\min}$. Fig.5.5(a) shows that the increasing $\xi^C_{\min}$ leads to a gradual reduction in the sum ergodic capacity of all VUEs. In general, the low $\xi^C_{\min}$ value indicates that the SINR constraints of CUEs are easily satisfied. In this case, VUEs can get permission to reuse CUEs' resources easily. Accordingly, the number of admissible VUEs is large such that the sum ergodic capacity of VUEs is high. However, the big $\xi^C_{\min}$ value makes it difficult for CUEs to satisfy their SINR requirements, which requires VUEs to transmit



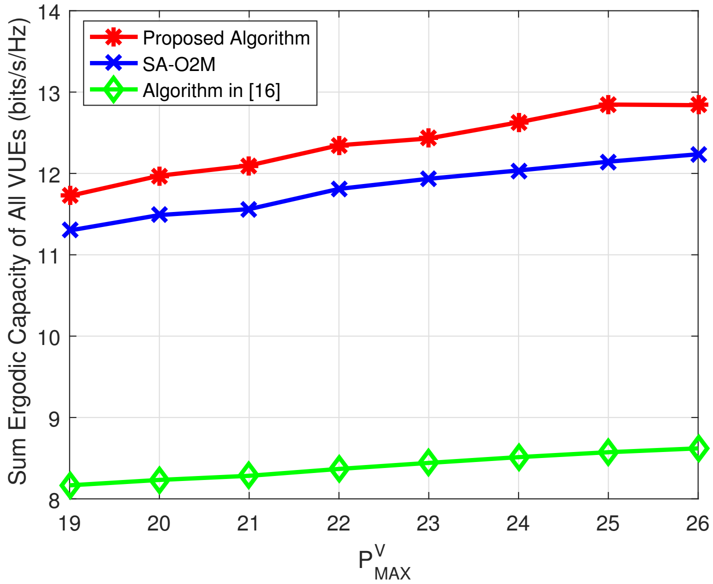
(a) The sum ergodic capacity of all VUEs versus increasing N.



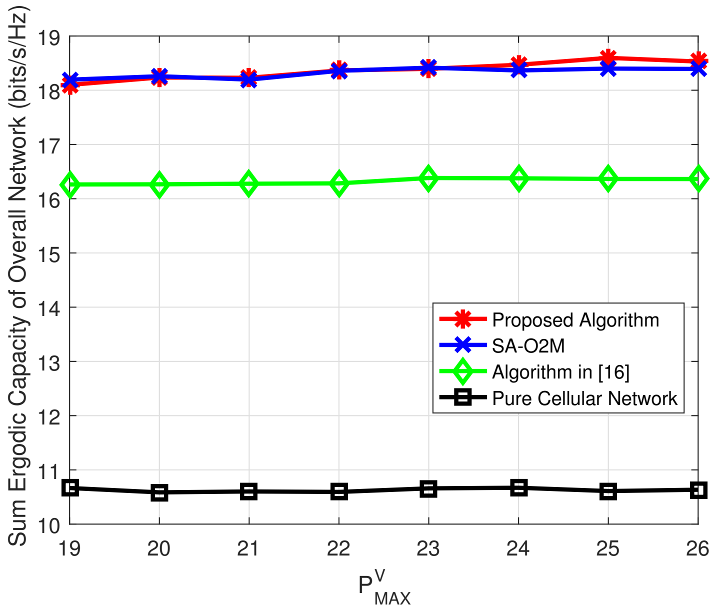
(b) The sum ergodic capacity of overall network versus increasing N.

FIGURE 5.3: System performance with different number of VUE pairs N, where $P^C_{\max} = P^V_{\max} =$ 23dBm, $M = 5, r = 20$m, $\xi^C_{\min} = 10$ dB.

their data with a very low transmit power. But, this leads to the degradation in the number of admissible VUEs because a lot VUEs cannot meet their own QoS requirements with the low transmit power. Accordingly, the sum ergodic capacity of VUEs decreases when the SINR threshold of CUEs is high. When compared to Fig.5.5(a), Fig.5.5(b) presents that the sum ergodic capacity of the overall network is degraded slightly with the increase in $\xi^C_{\min}$.



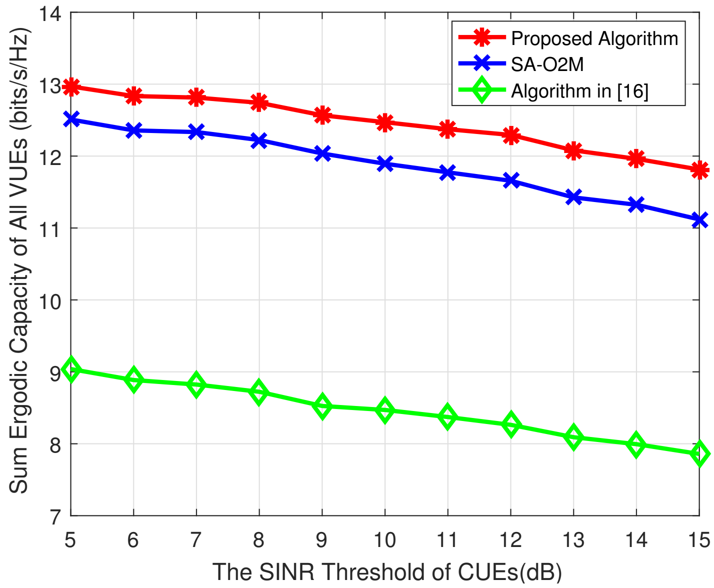
(a) The sum ergodic capacity of all VUEs for different $P^V_{\max}$.



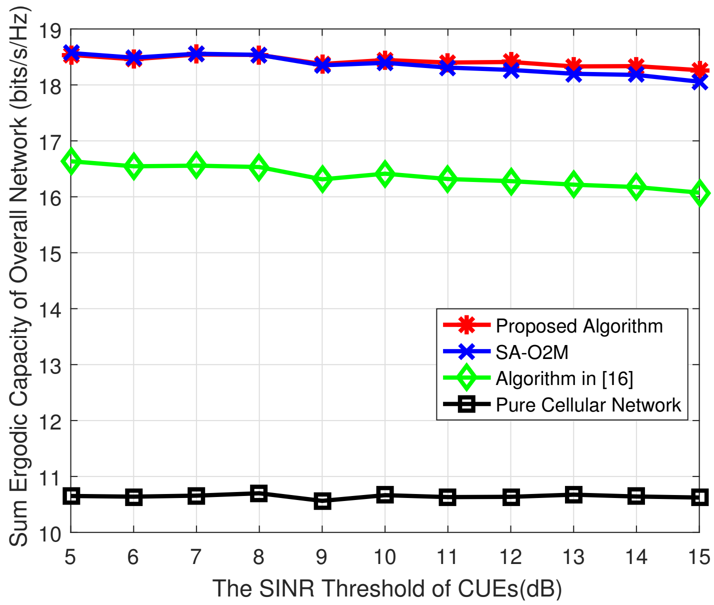
(b) The sum ergodic capacity of overall network for different $P^V_{\max}$.

Figure 5.4: System performance with maximum transmit power of VUEs $P^V_{\max}$, where $P^C_{\max} = 23\text{dBm}, M = 8, N = 4, r = 20\text{m}, \xi^C_{\min} = 10$ dB.

The main reason for this is that, due to the increase in the SINR threshold of CUEs, the number of admissible VUEs decreases leading to the reduction in the number of reuse CUEs. As a result, the sum capacity of all CUEs increases. Furthermore, since the decrease rate of the sum capacity of all VUEs is greater than the increase rate of the sum capacity of all CUEs in the network, the overall system experiences a slight decrease.



(a) The sum ergodic capacity of all VUEs for different $\xi_{\min}^{C}$.



(b) The sum ergodic capacity of overall network for different $\xi_{\min}^{C}$.

FIGURE 5.5: System performance with different SINR threshold of CUEs, $\xi_{\min}^{C}$, where $P_{\max}^{C} = P_{\max}^{V} = 23\text{dBm}, M = 8, N = 4, r = 20\text{m}$.

In this paper, our goal aims at maximizing the sum ergodic capacity of all VUEs. The proposed algorithm can effectively and efficiently realize our goal when compared to other existing algorithms, which has been demonstrated in Fig.5.2(a), 5.3(a), 5.4(a) and 5.5(a). By contrast, from Fig.5.2(b), 5.3(b), 5.4(b) and 5.5(b), we can further observe that the proposed algorithm and the SA-O2M algorithm have very close system performance in terms of the sum ergodic capacity of the overall network. The main reason for this is that, to improve the performance of VUEs, the cost of the proposed algorithm is to reduce the welfare of CUEs due to the co-channel interference issues. By contrast, since the performance enhancement of VUEs by using the SA-O2M algorithm is not good as that of the proposed algorithm, to some extent, the welfare of CUEs can be guaranteed better by using the SA-O2M algorithm. Furthermore, the sum ergodic capacity of the overall network is influenced by both VUEs and CUEs. Therfore, it is reasonable that the proposed algorithm and the SA-O2M algorithm have similar system performances in terms of the overall network.

5.7 Summary

In this chapter, we have studied the joint power control and channel allocation problem for D2D-based V2X communication. In order to guarantee the QoS of CUEs and to improve the system performance of V2X communication, we have proposed a novel communication scheme where each VUE is allowed to get access to multiple CUEs' resources, but the resource of each CUE can be reused by only one VUE. Furthermore, to track the fast channel variations of vehicular links incurred due to the high mobility of vehicles, we have considered the Doppler effect into the small-scale fading of vehicular links. Our objective is to the sum ergodic capacity of all VUEs with the imperfect CSI while satisfying the QoS requirements of both vehicular and cellular links. A low-complexity Lower Bound-based One-to-Many matchings algorithm has been developed to solve this optimization problem while the reliability of vehicular links is guaranteed by maintaining the outage probability of vehicular links smaller than a very small threshold and the QoS of CUEs is ensured by the minimum SINR requirements. Simulation results have demonstrated that the proposed one-to-many matching scheme can effectively enhance the overall system performance of D2D-based V2X communication with low complexity. Furthermore, results also show that the proposed algorithm outperforms the one-to-one matching scheme without degrading the QoS of CUEs.

6 Conclusions and Future Research Directions

In this thesis, we have investigated the resource allocation optimization problems for different application requirements of safety-related and non-safety-related V2X services. All these optimization problems studied are Mixed-Integer Nonlinear Program problem which is NP-hard, thereby making it difficult to obtain an optimal solution in the polynomial time. Even though meta-heuristic method and game-theoretic method can be used to solve the NP-hard problem, they are not able to guarantee that the globally optimal solution can be found. Furthermore, in general, these methods are time intensive due to large number of iterations. Consequently, these methods cannot satisfy the low latency requirement of V2X communication. Furthermore, Branch-and-Bound algorithm is considered to be an effective method to find the final optimal solution of the NP-hard problem. However, in the worst-case scenario, the computational complexity of BB algorithm is quite high and is comparable to that of an exhaustive search, which tends to grow exponentially with a corresponding increase in the number of users.

Therefore, in this thesis, to reduce the computational complexity, we decompose the original optimization problem into two subproblems: power control problem and channel allocation problem. We then employ the proposed algorithms by adopting Convex Optimization theory, Graph theory and Matching theory to solve these two subproblems jointly with low computational complexity. Besides, by using the proposed algorithms, we can obtain the globally optimal solution or sub-optimal solution for the system. The numerical results demonstrate the proposed algorithms can efficiently and effectively enhance the system performance of V2X networks and perform better when compared to other existing works.

6.1 Summary of Contributions

In order to develop an efficient and effective resource management scheme to mitigate and eliminate the interference problem in D2D-based V2X communication, in Chapter 1, we first analyzed the current research issues and technical challenges for D2D-based V2X communication and discussed the different QoS requirements of safety-related and non-safety-related V2X communication, respectively. We then summarised and evaluated the latest research progress in this area in Chapter 2. Then Chapters 3-5 have presented our contributions summarized as follows:

In Chapter 3, we have proposed a scheme of joint power control and resource allocation mode selection to support safety-related V2X services under different network load conditions. Considering different resource allocation modes: the dedicated mode, reuse mode and Mode 4, we have proposed power control strategies to specifically cater to these different modes in order to maximize the information value of a single VUE while mitigating the co-channel interference between VUE and its reuse PUE. To further improve the QoS of VUEs in terms of the ProSe Per-Packet Priority and the communication link quality, we have proposed two new algorithms, the VRBPA algorithm and the ORBPA algorithm for the light network load scenario and heavy network load scenario, respectively, with a view to maximizing the sum of information values of all VUEs. This is accomplished through the use of joint resource scheduling of three resource allocation modes under different network load scenarios. The simulation results demonstrate that our proposed scheme can not only provide better performance in terms of the information value of VUEs but can also enhance the spectral efficiency of PUEs significantly when compared to other such schemes.

We then have investigated the resource management problem for non-safety-related V2X communication in Chapters 4 and 5. Considering that there are no stringent requirements of high reliability and low latency for non-safety-related V2X services, we studied the resource management problems of Chapters 4 and 5 with a view to improving the system fairness and system throughput, respectively.

In particular, in Chapter 4, we have proposed a new joint power control and resource scheduling scheme for underlay D2D-based V2X communication. The goal of this scheme is to simultaneously improve both the system throughput and system fairness. Accordingly, we have formulated the resource allocation problem with proportional fairness by optimizing the sum of all users' proportional fairness functions. To solve this problem, we have proposed a resource allocation algorithm with low computation complexity and overheads, which takes into consideration time slots of long duration. The algorithm is designed in two stages: Stage 1 realizes the initialization of the average data rates of all users by the proposed joint power control and resource allocation method; Stage 2 develops the proposed joint power control and proportional fair scheduling scheme from the second time slot to time slot T to improve both the system throughput and fairness over a period of time. The performance results reveal that our resource allocation scheme achieves a significant enhancement in terms of both system fairness and system throughput without degrading the QoS levels of both VUEs and CUEs.

In Chapter 5, we have studied the joint power control and channel allocation problem for D2D-based V2X communication with the goal of improving the sum ergodic capacity of all VUEs. Considering that the traditional cellular users existing in the network have a higher priority than VUEs, the QoS of cellular links should not be affected or degraded because of the channel reuse of VUEs. Therefore, in order to guarantee the QoS of CUEs and improve the system performance of V2X communication, we have proposed a novel communication scheme where each VUE is allowed to get access to multiple CUEs' resources, but the resource of each CUE is supposed to be occupied by only one VUE at most. Furthermore, to track the fast channel variations of vehicular links caused by high mobility of vehicles, we have considered the Doppler effect into the small-scale fading of vehicular links. To reduce the overhead of eNB, a low-complexity Lower Bound-based One-to-Many matching algorithm has been proposed to maximize the sum ergodic capacity of all VUEs while guaranteeing the QoS requirements of both vehicular and cellular links. Specifically, the communication link reliability of VUEs is guaranteed by keeping the outage probability of vehicular links smaller than a very small threshold and the QoS of CUEs is ensured by the minimum SINR requirements. Simulation results have demonstrated that the proposed one-to-many matching scheme can effectively enhance the overall system performance of D2D-based V2X communication with low complexity. Furthermore, it also shows that the proposed algorithm outperforms the one-to-one matching scheme without degrading the QoS of CUEs.

6.2 Future Research Directions

Unlike the traditional mobile networks, V2X communication requires high throughput, high reliability and ultra-low latency. As a result, several related issues emerge that need to be explored further and addressed.

(1)Millimeter Wave: Millimetre wave (mmW) communication as a key technology in 5G networks has attracted a lot of attention from worldwide researchers. Automated driving, one of the important applications of the 5G network, is under investigation by both academia and industry. To provide a safer and more efficient traffic environment for automated driving, an increasing number of advanced onboard sensors with high complexity are being integrated into vehicles, resulting in the transmission of tremendous amount of data to eNB. Furthermore, the current 4G cellular technologies cannot meet the users' soaring demands due to a significant increase in data traffic load compounded by the paucity of available spectrum resources. By using the extremely high frequencies between 30 and 300GHz, Millimeter wave communication is able to provide ultra-high data rates (several Gbps) for V2X communication [137, 138]. However, Millimetre wave communication has the characteristics of high path loss, Line-of-Sight transmission, beam directionality, and low signal penetration [139]. Therefore, there are a few but significant challenges that require immediate attention.

(2) Energy efficiency: Energy efficiency (EE) is referred to as the transmitted capacity per unit of energy [140]. The increasing number of sensors incorporated into vehicles to enable V2Xcommunication causes a huge amount of energy consumption. Therefore, the enhancement of energy efficiency as an essential aspect should be taken into consideration for V2X communication. Two solutions that address this problem exist. One method we can use is the proper power control and resource allocation by which we can improve the overall throughput and save the overall power consumption. Another method is the simultaneous wireless information and power transfer (SWIPT) technology which is one of the key enablers of the 5G network. This technology enables sensors to harvest energy from the ambient radio frequency signal to recharge batteries instead of their fixed power sources. However, considering the fact that both the information and energy may be delivered by the same RB, the tradeoff of resources between them should be properly designed to improve energy

efficiency [141].

(3) Network Slicing: Network slicing enables multiple logical networks for different users to multiplex over a shared physical infrastructure and has the capability of customizing the network for an application based on its specific requirements [142]. Network slicing is implemented by leveraging the programmability of network functions offered by network functions virtualization (NFV) [143] and software-defined networking (SDN) [144]. This technology provides tailored slices to meet the different needs of a variety of V2X use cases. For example, the slice for automated driving meets the low-latency and high-reliability needs and the slice for infotainment application offers high data rates for users. However, network slicing for V2X is still a challenging issue, such as how to design the network slices when multiple slices exist simultaneously for V2X communication [72].

(4) Security: With the development of V2X communication, more and more vehicles are interconnected with one another and with other entities such as pedestrians, RSU and core network. However, the integration of wireless communication technology and the inherent broadcast nature of wireless communication make vehicles vulnerable to various types of cyber-attacks [145]. The security issue caused by diverse cyber-attacks is the main challenge for V2X communication, but has not been fully explored in the literature. The malicious entities may eavesdrop, forge and replay the information exchanged between vehicles and other VUEs, which may lead to serious consequences, especially for safety-related V2X communication [146]. Therefore, the provisioning of secure V2X communication is a major concern that needs urgent attention to safeguard VUEs [147].

In summary, our future work will focus on how to leverage the benefits of advanced 5G technology to improve the system performance of V2X communication by considering different V2X applications requirements. This work is envisioned to provide a safer driving environment, more efficient traffic scheduling, more enjoyable user experience and advanced automated driving support.

A

Appendices for Chapter 3

A.1 Proof of the Non-Convex MINLP Problem in (3.12)

We prove the non-convex MINLP problem in (3.12) by verifying the positive semidefinite property of its Hessian matrix. The formulation in (3.12) is composed of the sum of information values of all VUEs working in different resource allocation modes. Therefore, we will demonstrate the positive semidefinite property of Hessian matrix for different resource allocation modes separately. Before the demonstration, we first transform the optimization problem in (3.12) from the maximum form to the minimum standard form as follows:

$$\begin{aligned} f(\mathbf{x},\mathbf{p}) = \min \Bigg\{ &- \sum_{i=1}^{N} x_i^{(1)} \theta_i^{(1)} \log_2 \left(1 + \frac{p_i^{(1)} h_i}{\sigma_N^2}\right) \\ &- \sum_{i=1}^{N} x_i^{(2)} \theta_i^{(2)} \log_2 \left(1 + \frac{p_i^{(2)} h_i}{\sigma_N^2}\right) \\ &- \sum_{i=1}^{N} \sum_{j=1}^{M} x_{i,j}^{(3)} \theta_i^{(3)} \log_2 \left(1 + \frac{p_{i,j}^{(3)} h_i}{p_{i,j}^{C} h_{i,j} + \sigma_N^2}\right) \Bigg\}, \end{aligned} \tag{A.1}$$

Ignoring co-channel interference, the information value of VUE i for the Mode 4 and dedicated mode can be expressed using the following function as follows:

$$f(x_i, p_i^V) = \min \left\{ - x_i \theta_i \log_2 \left(1 + \frac{p_i^V h_i}{\sigma_N^2}\right) \right\}, \tag{A.2}$$

However, when VUE i works in the reuse mode, it will be interfered by its reuse partner

PUE j. In this case, the information value of VUE i can be computed as:

$$f(x_i, p_i^V, p_{i,j}^C) = \min\left\{ -x_i\theta_i \log_2\left(1 + \frac{p_i^V h_i}{p_{i,j}^C h_{i,j} + \sigma_N^2}\right)\right\}, \tag{A.3}$$

where x_i is the resource allocation mode selection indicator. To simplify the notation, we define $x = x_i$, $y = p_i^V$, $z = p_{i,j}^C$, $a = h_i$, $b = h_{i,j}$, and $c = \sigma_N^2$. Then the function (A.2) can be re-written as follows:

$$f(x, y) = \min\left\{ -\theta_i x \log_2\left(1 + \frac{ay}{c}\right)\right\}, \tag{A.4}$$

by differentiating $f(x, y)$ of (A.4) with respect to x, we have

$$\frac{\partial f}{\partial x} = -\theta_i \log_2\left(1 + \frac{ay}{c}\right), \tag{A.5}$$

then, the corresponding second derivative is calculated as:

$$\frac{\partial^2 f}{\partial x^2} = 0. \tag{A.6}$$

Likewise, by differentiating $f(x, y)$ of (A.4) with respect to y, we have

$$\frac{\partial f}{\partial y} = -\frac{\theta_i acx}{(ay + c)\ln 2}, \tag{A.7}$$

and the second derivative of $f(x, y)$ with y can be given as:

$$\frac{\partial^2 f}{\partial y^2} = \frac{\theta_i a^2 cx}{(ay + c)^2 \ln 2} > 0, \tag{A.8}$$

Therefore, if VUE works in the Mode 4 or in the dedicated mode, then the resulting Hessian matrix is positive semidefinite. We then re-write function (A.3) as:

$$f(x, y, z) = \min\left\{ -x\theta_i \log_2\left(1 + \frac{ay}{bz + c}\right)\right\}, \tag{A.9}$$

Similarly, we differentiate $f(x, y, z)$ of equation (A.9) with respect to x, y, and z, respectively. The second derivative of $f(x, y, z)$ in terms of x is first obtained as:

$$\frac{\partial^2 f}{\partial x^2} = 0, \tag{A.10}$$

We then obtain the second derivative of $f(x, y, z)$ in terms of y as shown below:

$$\frac{\partial^2 f}{\partial y^2} = \frac{\theta_i a^2 (bz + c)x}{(ay + bz + c)^2 \ln 2} > 0, \tag{A.11}$$

Finally, we obtain the second derivative of $f(x, y, z)$ in terms of z as follows:

$$\frac{\partial^2 f}{\partial z^2} = -\frac{\theta_i abxy(aby + 2b^2 z + 2bc)}{(ay + bz + c)^2 (bz + c)^2 \ln 2} < 0, \tag{A.12}$$

Our objective function in equation (3.12) is composed of the sum of information values of all VUEs working in different resource allocation modes. However, as shown in equation (A.12), the Hessian matrix of $f(x, y, z)$ is not positive semidefinite for the VUEs working in the reuse mode. Therefore, the problem (3.12) is a non-convex optimization problem. Furthermore, equation (3.12) has both binary variables and continuous variables, which further confirms that this problem is a non-convex MINLP problem.

A.2 Proof of the Convex MINLP Problem in (3.13)

In fact, the optimization problem (3.13) is composed of three parts: part 1 is the sum of information values of all VUEs working in Mode 4; part 2 is for the VUEs working in dedicated mode, and part 3 is for reuse mode. As explained in Appendix A, part 1 and part 2 are convex with the variable matrices $\mathbf{x}$ and $\mathbf{p}$. Therefore, we only need to demonstrate the convexity of the optimization function of part 3. Since part 3 is the sum of information values of all VUEs working in reuse mode, we only need to verify the convexity of the information value function of one arbitrary VUE. When VUE i is allocated to the reuse mode, from (3.13), we can derive the equation of its information value as follows,

$$f(x_{i,j}^{(3)}, p_{i,j}^{(3)}) = \min \left\{ -x_{i,j}^{(3)} \theta_i^{(3)} \log_2 \left(1 + \frac{H}{I} \right) \right\}, \tag{A.13}$$

As in Appendix A, we define $x = x_{i,j}^{(3)}$, $y = p_{i,j}^{(3)}$. Then the function (A.13) can be re-written as follows:

$$f(x, y) = \min \left\{ -x\theta_i^{(3)} \log_2 \left(\frac{H + I}{I} \right) \right\}, \tag{A.14}$$

where

$$H = h_i h_{j,B} y, \tag{A.14a}$$
$$I = \xi_{\min}^C h_{i,B} h_{i,j} y + \xi_{\min}^C \sigma_N^2 h_{i,j} + \sigma_N^2 h_{j,B},. \tag{A.14b}$$

We then differentiate by parts to first obtain the second derivative of $f(x, y)$ with respect to x shown as:

$$\frac{\partial^2 f}{\partial x^2} = 0, \tag{A.15}$$

and then proceed to obtain the second derivative w.r.t to y as follows:

$$\frac{\partial^2 f}{\partial y^2} = \frac{x\theta_i^{(3)} J(H'I + HI' + 2II')}{(HI + I^2)^2 \ln 2} > 0, \tag{A.16}$$

where

$$J = h_i h_{j,B}(\xi_{\min}^C \sigma_N^2 h_{i,j} + \sigma_N^2 h_{j,B}), \tag{A.16a}$$

$$H' = h_i h_{j,B}, \tag{A.16b}$$

$$I' = \xi_{\min}^C h_{i,B} h_{i,j}, . \tag{A.16c}$$

We can see that the Hessian matrix of $f(x, y)$ of VUEs working in the reuse mode is positive definite, which means part 3 is also convex. Since the sum of convex functions is still convex, the objective function of problem (3.13) is proven to be convex. Furthermore, constraint functions in the problem (3.13) are also convex which proves the optimization problem in (3.13) is a convex MINLP problem.

B
Appendices for Chapter 5

B.1 The Ergodic Rate of a Single VUE

The ergodic rate of a single VUE can be expressed as:

$$
\begin{aligned}
&\ln 2E[\log_2\left(1+\xi_{i,j}^{V}\right)] \\
&= E\left\{\ln\left(1+\frac{B_1}{B_2+B_3X}\right)\right\} \\
&= E\left\{\ln\left(\frac{B_1+B_2+B_3X}{B_2+B_3X}\right)\right\} \\
&= E\left\{\ln\left(B_1+B_2+B_3X\right)-\ln\left(B_2+B_3X\right)\right\} \\
&= E\left\{\ln\left((B_1+B_2)\left(1+\frac{B_3X}{B_1+B_2}\right)\right)\right\} \\
&\quad - E\left\{\ln\left(B_2\left(1+\frac{B_3X}{B_2}\right)\right)\right\} \\
&= E\left\{\ln\left(\frac{(B_1+B_2)}{B_2}\right)\right\}+E\left\{\ln\left(1+\frac{B_3X}{B_1+B_2}\right)\right\} \\
&\quad - E\left\{\ln\left(1+\frac{B_3X}{B_2}\right)\right\}
\end{aligned} \tag{B.1}
$$

where $X \sim \exp(1)$. Based on Lemma 1, the ergodic rate of VUE i in equation (B.1) is given as:

$$
\begin{aligned}
&E[\log_2\left(1+\xi_{i,j}^{V}\right)] \\
&\quad = \log 2\left(\frac{(B_1+B_2)}{B_2}\right)+\frac{\phi(\frac{B_3}{B_1+B_2})}{\ln 2}-\frac{\phi(\frac{B_3}{B_2})}{\ln 2}
\end{aligned} \tag{B.2}
$$

B.2 Proof of the Feasible Region of equation (5.11)

By substituting the PDF of X into the outage probability constraint of (5.11b), we can get the feasible power region of outage probability as:

$$\begin{aligned} Pr\{\xi_{i,j}^V \leq \xi_{\min}^V\} &= Pr\left\{\frac{B_1}{B_2 + B_3 X} \leq \xi_{\min}^V\right\} \\ &= 1 - Pr\left\{X \leq \frac{B_1 - B_2\xi_{\min}^V}{B_3\xi_{\min}^V}\right\} \\ &= 1 - \int_0^{\frac{B_1 - B_2\xi_{\min}^V}{B_3\xi_{\min}^V}} e^{-x}dx \\ &= \exp\left(-\frac{B_1 - B_2\xi_{\min}^V}{B_3\xi_{\min}^V}\right) \leq p_0 \end{aligned} \tag{B.3}$$

Then we have the equivalent result of the inequality function in equation (B.3) as:

$$\begin{aligned} &-\frac{B_1 - B_2\xi_{\min}^V}{B_3\xi_{\min}^V} \leq \ln p_0 \\ &\Rightarrow \frac{p_{i,j}^V g_i - B_2\xi_{\min}^V}{B_3\xi_{\min}^V} \geq -\ln p_0 \\ &\Rightarrow p_{i,j}^V \geq \frac{(B_2 - B_3\ln p_0)\xi_{\min}^V}{g_i} = P_1, \end{aligned} \tag{B.4}$$

Furthermore, since $0 \leq p_0 \leq 1$, we can obtain $\ln p_0 \leq 0$ such that $\frac{(B_2 - B_3\ln p_0)\xi_{\min}^V}{g_i} > 0$. Hence, by combining constraints (5.11a) and (5.11b), we can obtain:

$$\left\{P_1 \leq p_{i,j}^V \leq P_{\max}^V\right\}, \tag{B.5}$$

In order to satisfy the minimum SINR requirement of reuse CUE j, the transmit power of VUE i is also limited by constraint (5.11c):

$$\begin{aligned} &\frac{p^C g_{j,B}}{p_{i,j}^V g_{i,B} + \sigma^2} \geq \xi_{\min}^C \\ &\Rightarrow p_{i,j}^V \leq \frac{p^C g_{j,B} - \xi_{\min}^C\sigma^2}{g_{i,B}\xi_{\min}^C} = P_2 \end{aligned} \tag{B.6}$$

which concludes the proof.

List of Symbols

The following list is neither exhaustive nor exclusive, but may be helpful.

Table B.1: Symbols

Symbol	**Definition**
M	Number of PUEs/CUEs
N	Number of VUE pairs
L	Number of licensed vacant RBs
U	Number of unlicensed vacant RBs
K	Number of vacant RBs
$\mathcal{C}$	Set of PUEs/CUEs
$\mathcal{V}$	Set of VUE pairs
$\mathcal{F}_{\mathcal{L}}$	Set of vacant licensed RBs
$\hat{\mathcal{F}}_{\mathcal{U}}$	Set of vacant unlicensed RBs
$\mathcal{F}$	Set of vacant RBs
$\mathcal{F}_{\mathcal{O}}$	Set of all resources including both vacant and reuse resources
v	Absolute vehicle speed
Θ	PPPP set of VUEs
$g_{j,B}$	Channel gain between PUE/CUE j and eNB
g_i	Channel gain between VUT i and VUR i
$g_{i,j}$	Inteference channel gain from PUE/CUE j to VUR i
$g_{i,B}$	Inteference channel gain from VUT i to eNB
$g_{j,B,t}$	Channel gain between CUE j and eNB in time slot t
$g_{i,t}$	Channel gain between VUT i and VUR i in time slot t
$g_{i,j,t}$	Inteference channel gain from CUE j to VUR i in time slot t
$g_{i,B,t}$	Inteference channel gain from VUT i to eNB in time slot t
$h_{i,j}$	Small-scale fading channel estimation
$\tilde{h}_{i,j}$	Estimated channel gain of small-scale fading
$e_{i,j}$	Estimation error
ϵ	Time correlation coefficient
σ^2	The power of additive White Gaussian Noise
Inf_i	Information value of VUE i
$\mathbf{p^{(1)}}$	Transmit power vector for VUEs working in Mode 4
$\mathbf{p^{(2)}}$	Transmit power vector for VUEs working in dedicated mode

Continued on next page

Table B.1 – *Continued from previous page*

Symbol	**Definition**
$\mathbf{p^{(3)}}$	Transmit power vector for VUEs working in reuse mode
T	Total time slots
$Q_{i,t}$	Proportional fairness utility function of VUE i in time slot t
$r_{i,t}$	Instant data rate of VUE i
$R_{i,t-1}$	Average data rate of VUE i over the preceding $t-1$ time slots
p^V	Transmit power of VUEs
p^C	Transmit power of PUEs/CUEs
$\xi_{\min}^C$	Minimum SINR of PUEs/CUEs
$\xi_{\min}^V$	Minimum SINR of VUEs
$P_{\max}^C$	Maximum transmit power of PUEs/CUEs
$P_{\max}^V$	Maximum transmit power of VUEs
$\left(p_{i,j}^{C^*}, p_{i,j}^{V*}\right)$	Optimal power allocation vector
$L_{i,j,t}^{\min}$	Minimum distance from the transmitter of CUE j to VUR i
$\mathbf{A}$	Admission control matrix
LF_i	Large-scale fading channel gain of VUE i
J_0	Zero-order Bessel function of the first kind
f_D	Maximum Doppler frequency
T	Period feedback latency
f_c	the carrier frequency
y_i	Received signal at VUE i
s_i	Transmitted signal from VUT i
$\Pr\{\cdot\}$	Probability of the input
p_0	Acceptable outage probability
$p_{i,j}^{V*}$	Optimal power allocation for VUE i
$\mathcal{F}_{i,j}^V$	Feasible region of VUEs

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