THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

On Adjacent Channel Interference-Aware Radio Resource Management for Vehicle-to-Vehicle Communication

ANVER HISHAM

CHALMERS

Communication Systems Group
Department of Electrical Engineering
Chalmers University of Technology

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ANVER HISHAM
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Communication Systems Group
Department of Electrical Engineering
Chalmers University of Technology
SE-412 96 Göteborg, Sweden
Telephone: + 46 (0)31-772 1000
Email: anver@chalmers.se

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Abstract

Safety applications play an essential role in supporting traffic safety and efficiency in next generation vehicular networks. Typical safety applications require vehicle-to-vehicle (V2V) communication with high reliability and low latency. The reliability of a communication link is mainly determined by the received interference, and broadly speaking, there are two types of interferences: co-channel interference (CCI) and adjacent channel interference (ACI). The CCI is cross-talk between transmitters scheduled in the same time-frequency slot, whereas ACI is interference due to leakage of transmit power outside the intended frequency slot. The ACI is typically not a problem in cellular communication since interference is dominated by CCI due to spectrum re-usage. However, ACI is a significant problem in near-far situations, i.e., when the channel gain from the interferer to receiver is high compared to the channel gain from the intended transmitter. The near-far situation is more common in V2V broadcast communication scenario due to high dynamic range of the channel gain and penetration loss by intermediate vehicles. This thesis investigates the impact of ACI on V2V communication and methods to mitigate it by proper radio resource management (RRM), i.e., scheduling and power control.

In [Paper A], we first study ACI models for various transmission schemes and its impact on V2V communication. We propose a problem formulation for a) optimal scheduling as a Boolean linear programming (BLP) problem and b) optimal power control as a mixed Boolean linear programming (MBLP) problem. The objective of the problem formulation is to maximize the connectivity among VUEs in the network. Near-optimal schedules and power values are computed by solving first a) and then b) for smaller-size instances of the problem. To handle larger-size instances of the problem, heuristic scheduling and power control algorithms with less computational complexity are proposed. We also propose a simple distributed block interleaver scheduler (BIS), which can be used as a baseline method.

In [Paper B], we formulate the joint scheduling and power control problem as an MBLP to maximize the connectivity among VUEs. A column generation method is proposed to address the scalability of the network, i.e., to reduce the computational complexity of the joint problem. Moreover, the scheduling problem is observed to be numerically sensitive due to the high dynamic range of channel values and adjacent channel interference ratio (ACIR) values. Therefore, a novel method is proposed to reduce the sensitivity and compute a numerically stable optimal solution at the price of increased computational complexity.

In [Paper C], we extend the RRM problem formulation to include various objectives, such as maximizing connectivity/throughput and minimizing age of information (AoI). In order to account for the fairness, we also formulate the problem to improve the worst-case throughput, connectivity, and AoI of a link in the network. All the problems are formulated as MBLP problems. In order to support a large V2V network, a clustering algorithm is proposed whose computational complexity scale well with the network size. Moreover, a multihop distributed scheduling scheme is proposed to handle zero channel state information (CSI) case.

Keywords: 3GPP, LTE, adjacent channel interference (ACI), combinatorial optimization, convex optimization, channel state information (CSI), medium access control (MAC), power control, radio resource management (RRM), scheduling, traffic efficiency, vehicle-to-vehicle (V2V), vehicle-to-everything (V2X)

List of Publications

Included Papers

This thesis is based on the following appended papers.

[A] A. Hisham, E. G. Ström, F. Brännström, and L. Yan, "Scheduling and Power Control for V2V Broadcast Communications with Co-Channel and Adjacent Channel Interference," in *IEEE Access*, pp. 67041-67058, June 2019.

[B] A. Hisham, Di Yuan, E. G. Ström, and F. Brännström, "Adjacent Channel Interference Aware Joint Scheduling and Power Control for V2V Broadcast Communication" revised version submitted to *IEEE Trans. Intelligent Transport Systems*, Sept. 2019.

[C] A. Hisham, E. G. Ström, and F. Brännström, "Radio Resource Management for V2V Multihop Communication Considering Adjacent Channel Interference" submitted to *IEEE Trans. Intelligent Transport Systems*, Aug. 2019.

Other Works

[a] A. Hisham, W. Sun, E. G. Ström, and F. Brännström, "Power Control for Broadcast V2V Communications with Adjacent Carrier Interference Effects," in *IEEE International Conference on Communications (ICC)*, Kuala Lumpur, May 2016.

[b] A. Hisham, E. G. Ström, F. Brännström, and L. Yan, "Additional Results of Scheduling and Power Control for Broadcast V2V Communications with Adjacent Channel Interference," Tech. Rep., Dec. 2018. URL: https://arxiv.org/src/1708.02444/anc/Additional_Results.pdf

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Acronyms

3GPP	3^{rd} generation partnership project
AAS	active antenna array system
ACI	adjacent channel interference
ACIR	adjacent channel interference ratio
ACLR	adjacent channel interference leakage ratio
ACS	adjacent channel sensitivity
AoI	age of information
BIS	block interleaver scheduler
BLP	Boolean linear programming
BS	base station
C-V2X	cellular based V2X
CAMs	cooperative awareness messages
CCI	co-channel interference
CDF	cumulative distribution function
CSI	channel state information
CSMA	carrier sense multiple access
D2D	device-to-device
DENMs	decentralized environmental notification messages
DPD	digital predistortor
DSRC	dedicated short-range communications
ETSI	European telecommunications stadards institute
FBMC	filter bank multicarrier
FDM	frequency division multiplexing

ITS	intelligent transport system
ITS-S	intelligent transport system stations
LOS	line-of-sight
LP	linear programming
LTE	long term evolution
MAC	medium access control
MBLP	mixed Boolean linear programming
MIQCP	mixed integer quadratically constrained programming
NLOS	non line-of-sight
PA	power amplifier
PHY	physical
QoS	quality of service
RB	resource block
RRM	radio resource management
RSU	roadside unit
SCFDMA	single carrier frequency division multiple access
SINR	signal to interference and noise power ratio
SNR	signal to interference ratio
TDM	time division multiplexing
V2I	vehicle-to-infrastructure
V2N	vehicle-to-network
V2P	vehicle-to-pedestrian
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
VANET	vehicular adhoc network

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Part I

Overview

Chapter 1

Introduction

1.1 V2X Communication

The safety of the passengers have been significantly improved by the active and passive safety features in the vehicles. This is majorly due to the adoptation of optical vision and radar based technologies which help to survey immediate neighborhoods and prevent possible collisions. However, radar and vision based systems are limited by small coverage distances and obstruction by other vehicles. But vehicle-to-everything (V2X) communication can overcome these limitations by supporting non line-of-sight (NLOS) communication over long range among vehicular user equipments (VUEs). For example, both European union and USA are considering mandating V2V technologies in all new light-duty vehicles [1].

V2X communication refers to a set of communication technologies as illustrated in Fig. 1.1, which are as follows,

1. Vehicle-to-vehicle (V2V): communication between vehicles allowing exchange of information related to vehicle attributes and traffic dynamics.

2. Vehicle-to-infrastructure (V2I): communication between a vehicle and an infrastructure unit or a roadside unit (RSU), allowing conveying information between far-away VUEs and application servers.

3. Vehicle-to-pedestrian (V2P): communication between a vehicle and a pedestrian to warn about a vulnerable pedestrian or vehicle.

4. Vehicle-to-network (V2N): communication between a vehicle and a network application server.

The above four V2X communication enhance the cooperative awareness and support autonomous driving applications. Furthermore, V2X communication can be controlled by either a base station (BS) or an intelligent transport system stations (ITS-S). In this thesis, we mainly focus upon V2V communication.

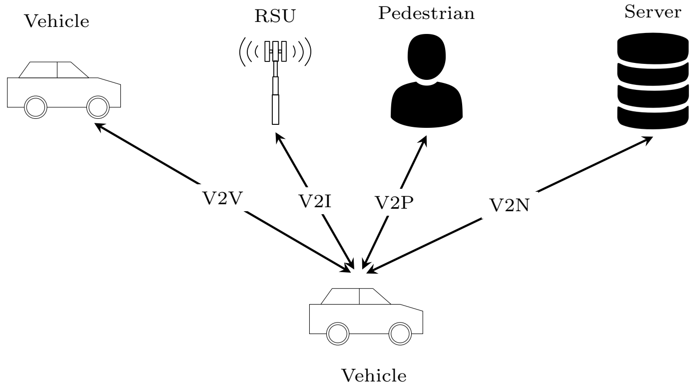


Fig. 1.1: Various types of V2X Communications [2].

1.2 V2X Applications

V2X communication applications are broadly classified as 1) safety related, 2) non-safety related. Safety related applications are primarily for mitigating road accidents, by providing relevant information and assistance to drivers. This can be done by sharing information between vehicles, RSU, and pedestrians, such as vehicle position, velocity, acceleration and intersection position. These information can be used for predicting the probability of collisions with other vehicles or pedestrians. Moreover, RSU can warn vehicles of hazardous locations on roads such as slippery sections or potholes. The 3^{rd} generation partnership project (3GPP) also specifies the following four enhanced safety related scenarios for V2X communication [3],

1. Vehicle platooning: Vehicles automatically join a group and periodically obtain informations from the leading vehicle for carrying on platooning operation.

2. Advanced driving: RSUs and vehicles can collect information from nearby vehicles to coordinate the trajectories to improve driving efficiency and avoid collisions.

3. Extended sensors: Vehicles can improve the perception of its environment by exchanging information from local sensors and cameras.

4. Remote driving: A driver can remotely control a vehicle for people who cannot drive, or when a vehicle is in a dangerous scenario.

Non-safety related applications are traffic efficiency and infotainment, which include traffic coordination, congestion reduction, in-vehicle entertainment, updating local information, map, etc [4]. For example, *speed management* helps the driver to manage speed of the vehicle using regulatory/contextual notifications and allow smooth driving without unnecessary stoppings. Similarly *cooperative navigation* improves traffic efficiency by cooperating among vehicles and adaptive cruise control. Additionally, infotainment services can fetch informations upon local community based services such as fleet management, parking zone, local commerce, etc.

1.3 V2X Standards

Currently, there are two major standard technologies for V2X communication: 1) dedicated short-range communications (DSRC) in USA, 2) intelligent transport system (ITS)-G5 standards developed by European telecommunications stadards institute (ETSI). Both standards physical (PHY) and MAC layer are based on IEEE 802.11p [5], which was the initially approved amendment to IEEE 802.11. However, the difference between these two standards lies in higher layers, e.g., ITS-G5 protocol stack contains an additional facility layer in-between the network and transport layer compared to DSRC.

The IEEE 802.11p standard has PHY layer as regular 802.11 OFDM with 10 MHz channel and medium access control (MAC) layer as carrier sense multiple access (CSMA). However, IEEE 802.11p is a legacy system and has several limitations when it comes to supporting high quality of service (QoS) and mobility for V2X safety-related communication. The main problem with 802.11p system is that, it is mainly optimized for WLAN-type of environment for adhoc communication with very low mobility and high overhead, hence not optimized for vehicles. Additionally, CSMA techniques used in these systems may lead to packet collisions resulting in low reliability and high latency. Therefore, these conventional CSMA approaches are inefficient for broadcast transmission in high density traffics scenarios [6].

Alternatively, 3GPP has been developing cellular based V2X (C-V2X) to support V2X communication requirements. While IEEE 802.11p is an asynchronous scheme, C-V2X scheme is synchronous allowing time division multiplexing (TDM) with lower channel access overhead. Furthermore, C-V2X uses both frequency division multiplexing (FDM) and TDM for multiplexing VUEs, while IEEE 802.11p uses only TDM. Therefore, cellular V2X can provide larger coverage, better data rates and QoS support for V2X communication compared to IEEE 802.11p based standards [7].

1.4 D2D in V2X

Direct device-to-device (D2D) communication proposed in C-V2X can improve V2X communication performance in terms of 1) proximity gain, 2) hop gain, and 3) reuse gain [8, 9]. The proximity gain comes from the relatively short communication range between D2D transceivers which improves data rate and low power consumption. Two nodes (vehicles/pedestrians/RSU) in V2X can communicate via a more efficient D2D link through centralized scheduling. This leads to the so-termed hop gain by avoiding 2-hops (i.e., uplink and downlink via BS) communication. The reuse gain comes from the fact that different V2X links can simultaneously share the same radio resources, which can significantly improve the network spectrum efficiency. Doppler et al. [10] indicated that overall throughput in the network with D2D communications can increase data rate up to 65% compared to the case where all D2D traffic is transmitted through the traditional cellular mode. Also, the D2D operation can be fully transparent to users and the central controller (e.g., the BS/ITS-S) can do the pairing and accessing. In other words, the central controller can conceal the complexity of setting up the D2D connections from vehicles or pedestrians.

The coexistence of D2D and cellular communications is defined under two basic spectrum sharing approaches: (i) the spectrum underlay, where D2D transmissions reuse spectrum portions utilized by cellular transmitters and (ii) the spectrum overlay, where temporary empty spectrum portions are used for D2D. The key challenge in both cases is the mitigation of the generated interferences. These two approaches are compared based on transmission capacity and throughput respectively by Huang et al. [11] and Yu et al. [12]. Both these studies conclude that the spectrum sharing between wireless networks improves the spectrum usage efficiency, however, in spectrum underlay case, more sophisticated interference cancellation techniques and interference coordination are required to improve the performance. Moreover, there exists an optimum density for D2D links in the underlay mode, since high density leads to extensive interference, and low density result in limited resource reuse. In this thesis, we consider spectrum overlay where V2V communication uses dedicated spectrum separate from the cellular spectrum.

1.5 Objectives of the Thesis

In this thesis, we are considering V2V communication for safety related applications. Typically, safety related applications come with low data rates, but stringent requirements on reliability and latency. However, in V2V communication reliability and latency are largely determined by the received interference.

Broadly speaking, there are two types of interferences: co-channel interference (CCI) and adjacent channel interference (ACI). CCI is cross-talk between transmitters scheduled in the same time-frequency slot, whereas ACI is interference due to leakage of transmit power outside the intended frequency slot within a timeslot. Therefore, ACI will affect transmissions that are scheduled at different frequency slots within a timeslot.

When both the transmitter and interferer have similar channel gains, the received ACI is significantly low compared to the signal power. Therefore, in a typical cellular communication systems, the communication performance is majorly limited by CCI instead of ACI. However, V2V channel gains are quite dynamic mainly due to the intermediate blocking vehicles: measurements indicate that blocking vehicles can introduce high penetration losses upto 10 dB for each blocking vehicle [13–16]. Hence, a transmitting vehicle need to use a high transmit power to reach a vehicle that is blocked by other vehicles, and this causes a near-far situation, i.e., interference power becomes much higher than the received signal power, making ACI a significant component. Moreover, unlike CCI, the received ACI is harder to cancel using interference cancellation techniques [17], which makes ACI a key factor in determining the performance in V2V communication.

In an ACI-limited communication network, a link's performance is heavily dependent on the scheduling of nearby frequency slots as well, therefore, ACI-unaware radio resource management (RRM) (i.e., scheduling and power-control) might be underperforming. However, ACI-aware RRM can play a key role in mitigating the effects of ACI and improve the performance. The main objective of this thesis is to first analyze the impact of ACI in V2V communication, and then design effective RRM solutions to mitigate its effects. The scalability issue of the RRM algorithms is also addressed in this thesis by proposing novel heuristic and clustering schemes for the network, which help in reducing the computational complexity. Furthermore, the low values of ACI make the problem more sensitive and harder to solve to find the optimal solutions. Therefore, novel methods have been suggested to reduce the sensitivity and improve the robustness of the solutions in this thesis.

1.6 Outline

The thesis is organized as follows. We start by discussing the vehicular channel topology, channel model, and V2V requirements in Chapter 2, which are vital for efficient design of RRM algorithms. In Chapter 3, characteristics and causation of ACI are presented and the impact of ACI is quantified using simulations. In the same chapter, we also explain the ACI models in more details. In Chapter 4, we provide a brief introduction upon the problem formulation for joint scheduling and power control. We address scalability issues by explaining heuristic, clustering, and distributed algorithms which reduces the computational complexity. We also address the sensitivity issue of the problem formulation in ths same chapter. Finally, the contributions of this thesis and future directions are summarized in Chapter 5.

1.7 Notation

We use the following notation throughout the thesis and all the attached papers. Lowercase and uppercase letters, e.g., x and X, represent scalars. Lowercase boldface letters, e.g., $\mathbf{x}$, represent a vector where x_i is the i^{th} element and $|\mathbf{x}|$ is its dimensionality. The uppercase boldface letters, e.g., $\mathbf{X}$, denote matrices where $X_{i,j}$ indicates the $(i,j)^{\text{th}}$ element. Calligraphic letters, e.g., $\mathcal{X}$, represent sets, $|\mathcal{X}|$ denote its cardinality, and $\emptyset$ denotes an empty set. We use $a \bmod b$ for the remainder of a when divided by b. The notations $\lceil\cdot\rceil$, and $\lfloor\cdot\rfloor$, $\lfloor\cdot\rceil$ represents ceil, floor, and round operations, respectively. The Boolean OR, AND and NOT operations are denoted by $\vee$, $\wedge$, and $\neg$, respectively. The notation $\mathbb{1}\{statement\}$ is either 1 or 0, depending upon if the *statement* is true or false.

Chapter 2

V2V Scenario and Requirements

2.1 V2V Scenario

2.1.1 Vehicular Topology

One of the most distinguishing feature of vehicular networks simulation lies in the mobility of users, which is the result of the interaction of complex macroscopic and microscopic dynamics. Therefore, the relevance of mobility modeling in the simulation of vehicular networks is widely acknowledged in the research community and substantial progress has been made in tracing the quality of car movements. The simplistic stochastic models employed in early works [1], [2] have been replaced by random mobility over realistic road topologies [3] at first, and by microscopic vehicular models borrowed from transportation research [4] later on. These features were then included in dedicated simulation environments and integrated with road signalization [5], [6]. Since then, vehicular mobility simulators have been growing in their complexity and features [7], allowing to accurately simulate the individual movement of vehicles over realistic road topologies. For example, the authors in [18] provide an urban vehicular mobility model using a real-world measurement of road topology and traffic demand in the city of Köln, Germany.

To characterize inter-vehicular distances, many statistical models have been considered, such as, exponential, negative exponential, shifted exponential, gamma, lognormal, semi-poisson, etc [18–21]. Researchers conclude that the vehicular topologies are different in different scenarios. For example, in a dense traffic scenario, VUEs usually keep a fixed distance with the adjacent VUEs. However, for sparse traffic, it is more appropriate to model distribution of VUEs as a Poisson point process on a line, i.e., inter-VUE distance as an exponential distribution [22]. Moreover, adjacent VUEs maintain a minimum distance between them. Therefore, the distance d between any two adjacent VUEs in a line is modeled as a shifted exponential distribution with the minimum distance $d_{\min}$ and the average distance d_{avg} (i.e., $\mathrm{E}[d] = d_{\text{avg}}$). The probability density function of d is shown in Fig. 2.1, which is given as,

$$f(d) = \begin{cases} (1/(d_{\text{avg}} - d_{\text{min}})) \exp(-\frac{d-d_{\text{min}}}{d_{\text{avg}}-d_{\text{min}}}), & d \geq d_{\text{min}} \\ 0, & \text{otherwise} \end{cases} \tag{2.1}$$

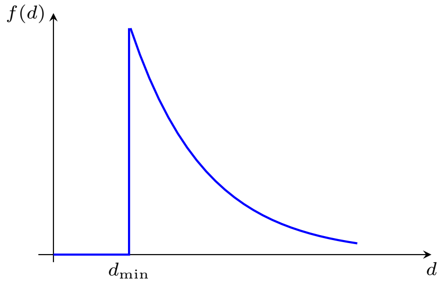


Fig. 2.1: Probability density function of distance

2.1.2 Vehicular Channel Model

As in the development of any wireless system, knowledge of the propagation channel is vital for designing V2V communication systems since its properties will ultimately dictate system performance. Because of the characteristics of vehicles traveling at high speed in limited moving area, the V2V propagation environment is significantly different from the traditional cellular systems. The biggest difference is that in V2V communication both the transmitter and receiver are in motion and equipped with low elevation antennas. Furthermore, V2V channel is usually fast varying with time-varying Doppler. Therefore, it is important to develop a practical and easy-to-use V2V channel model to understand the unique V2V channel characteristics and design the vehicle communication system accordingly.

Similar to other wireless systems, it has been found that the pathloss coefficient in V2V links depends upon the type of environment and carrier frequency. For example, compared to rural environment, in urban environment there would be large number of scatterers near the transmitting and receiving vehicles, which also may be moving. Pathloss results have been derived through measurement campaigns for highway [23], [24], [25], rural [23], [24], urban [24], and suburban [26] environments. However, the number of measurements in those works may not be sufficient to make general statements about the pathloss behavior in these environments.

In [27], Karedal et al. present parameterized pathloss models for V2V communications based on extensive sets of measurement data collected mainly under line-of-sight (LOS) conditions in four different propagation environments: highway, rural, urban, and suburban. The measurement setup is based on the setup proposed in [25] and close to the frequency 5.9 GHz. The spectrum around 5.9 GHz has been proposed to allocate for traffic safety applications by the Safety Spectrum Coalition (which represents a group of industries for transportation technologies and safety advocates) [1]. The results show that the pathloss exponent is low (i.e., $n = 1.77$), i.e., pathloss slowly increases with increasing distance, even better than free-space propagation. This is due to the availability of more received energy due to multipaths, in addition to LOS path. Moreover, there is a tendency for two ray propagation model in a rural environment, since the LOS path and ground reflection are dominant due to the few scatterers of the environment. However, in urban/suburban/highway scenarios, this tendency is less. For the simulation purpose in this thesis, we chose a channel model for highway scenario based on measurements done in [27], which is,

$$\mathrm{PL}(d) = \mathrm{PL}_0 + 10n\log_{10}(d/d_0) + X_{\sigma_1} \tag{2.2}$$

where d is the distance, $n = 1.77$ is the pathloss exponent, $\mathrm{PL}_0 = 63.3\,\mathrm{dB}$ is the pathloss at a reference distance $d_0 = 10\,\mathrm{m}$, and X_{σ_1} represents the shadowing effect modeled as a zero-mean Gaussian random variable with standard deviation $\sigma_1 = 3.1\,\mathrm{dB}$. The penetration loss caused by a single vehicle has been widely studied: measurements show that an obstructing truck causes 12–13 dB [14], a bus 15–20 dB [16], a van 20 dB [15], and a car 10 dB [13] penetration loss. However, presently there is a lack of enough measurements for the penetration loss caused by multiple obstructing vehicles. Real-time measurements in [28] shows that multiple obstructing vehicles cause higher shadowing.

2.2 V2V Requirements

2.2.1 Periodic and Aperiodic Messages in V2V

Typical vehicular safety and traffic efficiency applications require continuous status information about surrounding vehicles and road condition. Direct V2V communication can provide up-to-date local information and emergency informations to the vehicle using periodic and event-driven messages. To this end, ETSI is proposing both cooperative awareness messages (CAMs) for periodic messages, and decentralized environmental notification messages (DENMs) for aperiodic messages. The CAMs are a kind of heartbeat messages periodically broadcasted by each vehicle to its neighbors to provide information of presence, position, velocity, acceleration, etc. The CAMs are sent by all vehicles with frequency 2–10 Hz with a latency requirement of 100 ms, depending upon the application [29, Table 1]. Meanwhile DENMs are event-triggered messages broadcasted to alert vehicles of a detected hazardous event, and the transmission can be repeated and persisted as long as the event is present [30]. However, both periodic and aperiodic messages in V2V are broadcast and localized in its nature, i.e., requiring cooperation between vehicles in close proximity. The conditions under which CAMs and DENMs are transmitted and the message format are described in ETSI proposals in [29, 30], although the implementation details are left for the developers.

2.2.2 Latency and Reliability Requirements

The latency and reliability requirements for various V2V applications (explained in Section 1.2) are not yet been finalized by 3GPP, even though, there are many proposals to 3GPP [3]. Additionally, the requirements heavily depend upon the level of automation as well. For example, vehicle platooning has a proposed reliability requirement of 99.99% with a latency of 10–20 ms depending on the degree of automation. The advanced driving and remote driving applications have proposals for high reliability requirement (99.999%), but latency requirement for the former is less stringent (10–100 ms) compared to the latter (5 ms). Extended sensors are proposed to have moderately high latency (3-50 ms) and reliability (99–99.999%) requirements for higher degree of automation.

There is an implicit trade-off between latency and reliability; it is harder to support low latency with high reliability. Fig. 2.2 shows an illustration of a cumulative distribution function (CDF) of a packet delay τ. Assume that a communication system has a latency requirement $\tau^{\max}$, i.e., a packet has to be successfully received within time period $\tau^{\max}$. The reliability is defined as the probability that the actual latency is less than or equal to the latency requirement, i.e., $\Pr\{\tau \leq \tau^{\max}\}$. When the latency is more than the required latency, the packet is considered as discarded, and the corresponding probability is called the outage probability $P^{\text{out}} = \Pr\{\tau > \tau^{\max}\}$. Observe that the outage probability is complementary of the reliability. Similarly, $\Pr\{\tau = \infty\}$ is the probability of packet drop, as illustrated in Fig. 2.2.

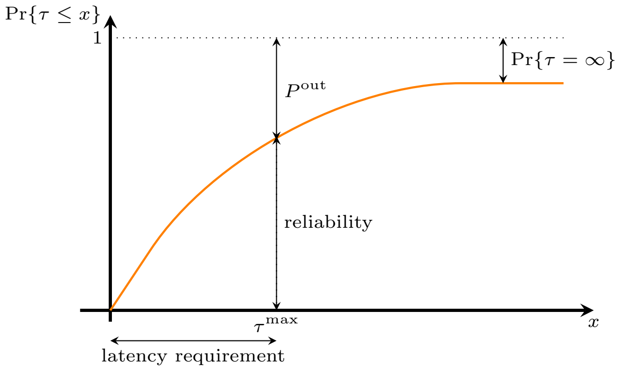


Fig. 2.2: Association between latency and reliability requirements

Assume that the reliability requirement is such that $P_{\text{req}}^{\text{out}}$ is the maximum tolerable outage probability. Since outage probability is a function of instantaneous SINR (γ) of a link, the reliability requirement can be satisfied by achieving a certain γ, i.e., by ensuring $\Pr\{\rho \log_2(1+\gamma) \leq N^{\text{bits}}\} \leq P_{\text{req}}^{\text{out}}$, where ρ is the number of complex symbols used for transmission and N^{bits} is the packet size. The value of γ is calculated based on instantaneous channel values which include small scale fading as well. In [31, Lemma 1], Sun et al. proved that achieving an average SINR ($\bar{\gamma}$) above a certain threshold value can ensure that the outage probability is less than the required outage probability. The proof relies on the fact that SINR is a convex function of the channel values and log is a concave and increasing function, hence the channel capacity, i.e., $\log_2(1+\text{SINR})$ is a concave function of channel values. Therefore, applying Jensen's inequality $\log_2(1+$

$\bar{\gamma}) \geq \mathrm{E}(\log_2(1+\gamma))$ where $\mathrm{E}(\cdot)$ is expectation function. Therefore, outage probability requirement (i.e., $\Pr\{\rho \log_2(1+\gamma) \leq N^{\text{bits}}\} \leq P^{\text{out}}_{\text{req}}$) can be satisfied by ensuring average SINR above a certain threshold value.

2.2.3 AOI Requirement

A common requirement in real-time V2V applications is freshness of data, which can be generally measured using a parameter known as age of information (AoI) [32]. The AoI is defined as the time elapsed since the generation of the latest status update received at an intended receiver. AOI is a more relevant metric capturing the requirement of applications to receive the current state information from all other nearby vehicles. For example, the service requirement for enhanced V2X scenarios require status updates every 20–100 ms, according to 3GPP [3].

The latency and AOI in a communication system are fundamentally different metrics. For, e.g., a low packet arrival frequency results in a short queuing delay (hence lower latency) because the queue is almost empty, but the destination may end up having old data due to less frequent updates. On the other hand, a very high update frequency will increase the queuing delay as well as age, since the updates are becoming old during their long waiting time in the queue. In [32], authors show that minimizing AOI cannot be achieved by maximizing throughput, instead an optimal packet arrival rate is required. In other words, minimizing average AoI yields an operating point which lies between maximum throughout and minimum delay. Most existing works optimizing AOI assumes stochastic packet arrival times [33–35]. However, the RRM schemes in this thesis does not assume any packet arrival times, therefore, they can be used for any known packet arrival process.

Chapter 3

Adjacent Channel Interference

A comprehensive knowledge of ACI is important to understand and mitigate its impact on V2V communication. In this chapter, we make an analysis of ACI and its impact on wireless communication in general.

3.1 Cause of ACI

ACI consists of two components: 1) Leakage power from the power amplifier (PA) in a transmitter, 2) Receiver's sensitivity to the power in unwanted channels. Typically, component 1) is more significant than 2), hence, in this section we explain more about the former component.

The leakage power in a transmitter is caused by the nonlinearity of PA. A typical PA output response is nonlinear as shown as the red curve in Fig. 3.1, which causes higher bit error rate and more distortion. This distortion causes transmit power leaking into neighboring channels resulting in ACI [36].

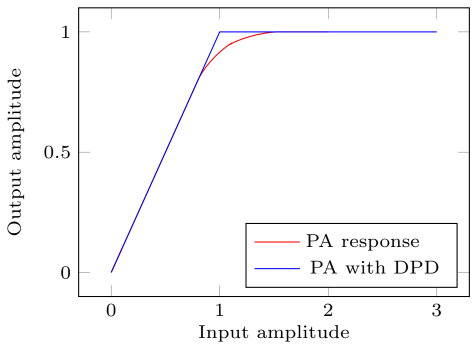


Fig. 3.1: Illustration of PA response with and without DPD

To avoid excessive leakage, the PA must be backed off from its saturation point. The amount of back off depends on the input signal peak-to-average-power-ratio (PAPR); the higher the PAPR the more back off is required. However, backing off from the saturation point leads to low power efficiency for PAs. Power efficiency of PAs is of paramount importance since it is the major contributing factor for the large energy consumption in wireless networks [37]. Due to PA's inefficiency in converting direct current (DC) power into radio frequency (RF) power, typical PAs in a BS produce a large amount of heat which requires an air conditioning unit to cool down, further increasing the energy consumption. Therefore, power efficiency and linearity are conflicting requirements of PAs, hence the operating point should reflect the optimal tradeoff between them.

In order to improve efficiency-linearity tradeoff, system designers prefer to operate PAs at high-efficiency levels and later remove the resulting distortions [38]. Over the past years, many techniques have been investigated for improving the linearity of PAs [39]. However, in recent years, advanced methods such as digital predistortor (DPD) have been proposed [38–40]. The idea of DPD is to distort the input signal to PAs so that the combined response of DPD and PA would be linear (see Fig. 3.1, blue curve). However, irrespective of DPD, the clipping behaviour of PAs causes ACI, and an example of resulting ACI is presented in Section 3.3.

3.2 ACI Measurement Metrics

ACI is measured by first tuning a transmitter to a frequency channel f, and then measuring the total received power by a receiver in an adjacent channel f'. Assume that T_f and $T_{f'}$ are the transmitted and leakage power of the transmitter respectively, when the transmitter is tuned to transmit in f. The leakage power of a PA is measured by using a metric called adjacent channel interference leakage ratio (ACLR), which is the ratio of the power transmitted within the assigned channel to the power of the unwanted emission in the adjacent channel, i.e, $T_f/T_{f'}$.

On the other hand, receivers sensitivity to the received power in adjacent channels is measured by a parameter known as adjacent channel sensitivity (ACS). Assume that the transmitter uses an ideal PA, hence no leakage power, i.e., $T_{f'} = 0$. However, the receiver still receives some power $R_{f'}$ in channel f' due to the receivers sensitivity to the adjacent channel f. The ACS is defined as the ratio between the received power in the desired channel f to the received power in the adjacent channel f', i.e., $HT_f/R_{f'}$, where H is the channel power gain of the Tx-Rx link.

Similarly, the parameter adjacent channel interference ratio (ACIR) is defined as the ratio of the total Rx signal power in the desired channel to the total received ACI power. Note that the total received ACI is sum of leakage power from the transmitter and the sensitivity of the receiver to the unwanted channel, therefore, the following equations hold,

$$\text{Rx Signal Power} = HT_f \tag{3.1}$$

$$\text{ACI} = HT_{f'} + R_{f'} \tag{3.2}$$

$$\text{ACIR} = \frac{HT_f}{HT_{f'} + R_{f'}} \tag{3.3}$$

$$\text{ACLR} = \frac{T_f}{T_{f'}} \tag{3.4}$$

$$\text{ACS} = \frac{HT_f}{R_{f'}} \tag{3.5}$$

$$\Rightarrow \frac{1}{\text{ACIR}} = \frac{1}{\text{ACLR}} + \frac{1}{\text{ACS}} \tag{3.6}$$

However, ACS is a significantly higer value compared to ACLR, therefore, ACIR $\simeq$ ACLR [41].

To understand this point more clearly, see Fig. 3.2, where VUE i is transmitting a packet to VUE j while VUE k is transmitting in a nearby frequency slot. The received SINR of the packet from VUE i to j is worsened by ACI from VUE k. As illustrated in Fig. 3.3, ACIR is the ratio between the average in-band received power from the transmitter k to the average received out of band power from transmitter k's signal in the frequency band allocated for transmitter i. Observe from the same figure that the signal to interference ratio (SNR) of the link from VUE i to j is determined by the ACI from VUE k.

3.3 ACI Models

The ACI majorly depends on the power amplifier and the waveform used for transmission in a communication system. LTE uses the waveform OFDM for downlink transmission and single carrier frequency division multiple access (SCFDMA) for uplink transmission. There are many waveform proposals from the research community for 5G new radio (NR) systems, which include Windowed-OFDM, Filtered-OFDM and filter bank multicarrier (FBMC) waveforms. Most of these new waveforms are generated by modifying existing OFDM waveform in many possible ways; sub-carrier wise filtering or pulse shaping, filtering of groups of sub-carriers, allowing successive symbols to overlap in time, dropping cyclic-prefix, replacing cyclic-prefix with nulls or with another sequence, etc.. Some of these new proposed waveforms come with reduced ACI. However, OFDM is still the most preferred candidate for 5G [42], due to its low implementation cost, better compatibility with MIMO and multi-antenna technologies, robustness to oscillator phase noise and doppler, etc. Moreover, OFDM is well-localized in time domain which is crucial for supporting low latency applications.

The in-band V2V communication is scheduled in cellular uplink resources, hence would be using SCFDMA as the transmission scheme. In Fig. 3.4, we plot the leakage power of an SCFDMA scheme with a power amplifier with 1% clipping threshold as blue curve. The red-colored step curve in the same figure shows the SCFDMA-ACI averaged

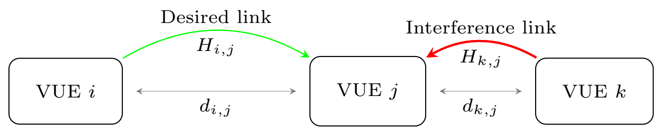


Fig. 3.2: System model

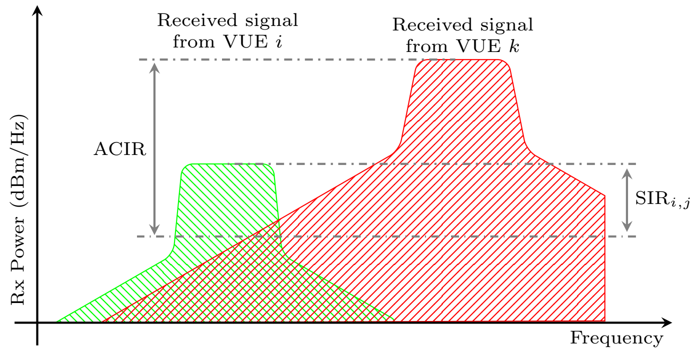


Fig. 3.3: Received power spectral density at receiving VUE j.

over each frequency slot. In other words, the curves in Fig. 3.4 indicate the inverse ACLR

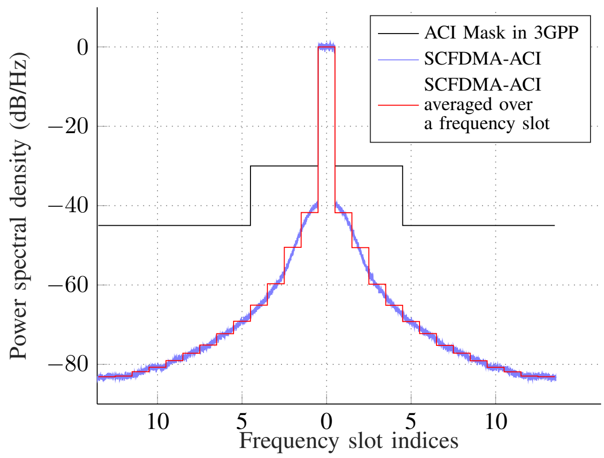


Fig. 3.4: Inverse ACIR model

values for each frequency slot.

Regulatory requirements are stringent on ACLR metric in order to reduce the interference and allow co-existence between networks. Reducing leakage power is also important from the perspective of frequency spectrum usage since operators pay millions of dollars for exclusive rights of a small portion of the spectrum. For example, the black step curve in Fig. 3.4 is the ACI mask specified by 3GPP [43].

3.4 ACI Impact on Cellular Communication

The impact of ACI when different communication technologies coexist in adjacent frequency bands have been extensively studied in [44–47] to name a few papers. In [48], authors analyze throughput degradation in downlink due to ACI when neighboring BSs use adjacent frequency bands, and conclude that the degradation is 2% for a single antenna system with an ACLR value of 30 dB. The throughput degradation is high (4%) when BSs are using 3D-MIMO due to the vertical sectorization brought in by active antenna array system (AAS). In uplink, when neighbouring BSs are far apart, cell-edge users have to transmit at high power resulting in severe ACI causing performance degradation for nearby users [49].

The ACI from the digital terrestrial television broadcast affect LTE uplink systems, therefore, proper network and spectrum planning have to be undertaken, e.g., broadcast system can be located at LTE cell edge [50]. On the other hand, if LTE BS and broadcast system are co-located, then ACIR value has to be atleast 115 dB in order to limit the uplink throughput loss within 5% [44]. In GSM system, Gaussian filter is used to reduce out of band emission power to less than 1% . The leakage power can be reduced further by increasing the roll-off factor of the Gaussian filter.

Presently, 3GPP is standardizing the requirements for Electromagnetic compatibility (EMC) for the interference management between 5G NR and other communication technologies [51].

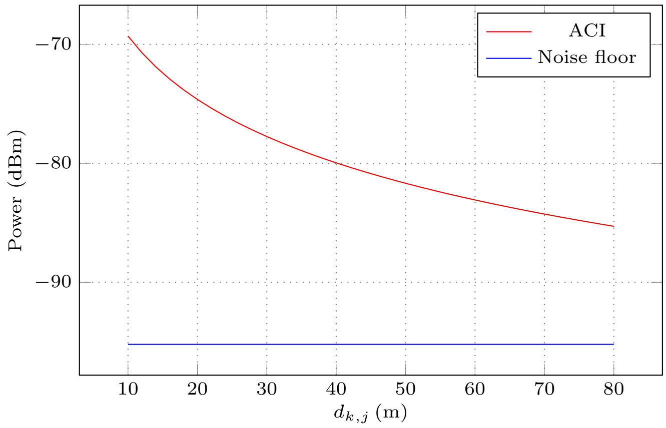
3.5 ACI Impact on V2V Communication

In V2V communication with CSMA MAC, a potential transmitter may falsely assume that the channel is busy due to the ACI from a transmitter tuned to an adjacent channel, which causes the transmitter to defer its transmission resulting in channel access delays [52, 53]. In [53], the authors analyze both physical layer and MAC layer impacts of ACI in vehicular adhoc network (VANET).

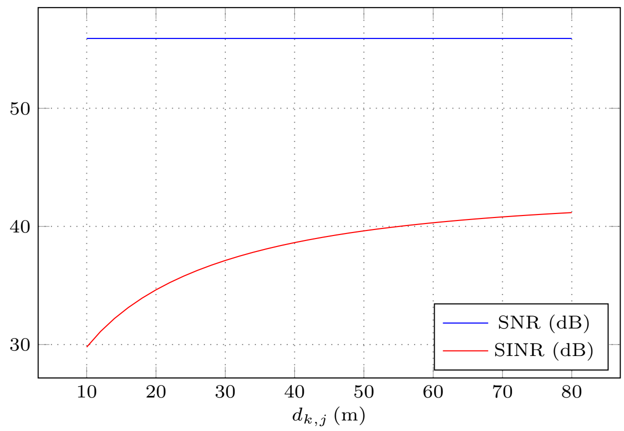
In general ACI is problematic in V2V communication in so-called near-far situations, i.e., when there is weak desired signal and a strong interfering signal. These situations occurs in direct V2V broadcast communication since (i) the transmit powers tend to be similar in broadcast communication, (ii) all transmitted signals are of interest to all receivers, and (iii) the obstruction by intermediate vehicles cause high penetration loss [13–16] resulting in high dynamic range in channel gains. This implies that the received power ratio from a nearby and far-away transmitter is high, especially when there are multiple blocking vehicles, and ACI can therefore be a significant problem while detecting the far-away signals. The rest of this section shows an investigation upon ACI impacts on V2V using simulations, both in the absence and presence of CCI.

3.5.1 In the absence of CCI

In the absence of CCI, the SINR of a link is solely determined by ACI and noise. For quantifying the value of received ACI, we take an example scenario where VUE i is



(a) Comparing ACI for various distances $d_{k,j}$ to noise floor



(b) SINR and SNR when $d_{i,j} = 10\,\mathrm{m}$

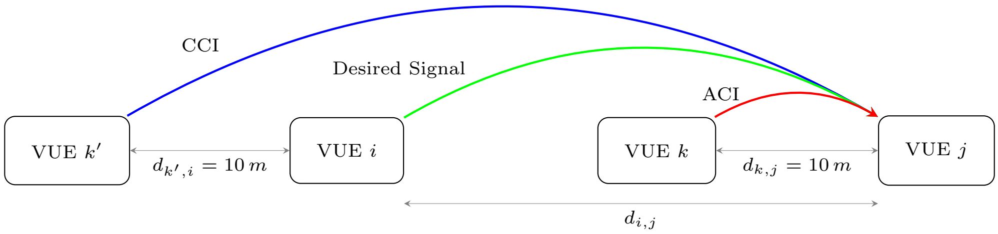
Fig. 3.5: Effects of ACI

transmitting a packet to VUE j while VUE k is interfering the reception as illustrated in Fig. 3.2. For this study, we assume VUE i and k are transmitting in adjacent frequency slots, and the leakage power to adjacent frequency slot is 30 dB less than the in-band power, i.e., ACLR = 30 dB as per ACI mask specified by 3GPP (see Fig. 3.4). The Tx-Rx distance is set to 10 m (i.e., $d_{i,j} = 10$ m) while VUE j to k distance ($d_{k,j}$) is varied. The channel parameters are taken from [27], and noise floor from 3GPP recommendation [43]. We assume that both VUE i and k are transmitting on its maximum power 24 dBm [43].

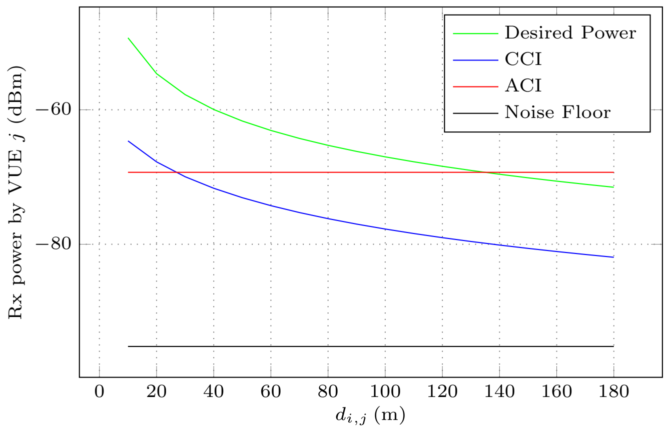
In Fig. 3.5(a), we compare the ACI received by VUE i from VUE k with noise power for various distances from interferer ($d_{k,j}$). Observe that ACI is significantly higher than noise power for lower distances from the interferer. In Fig. 3.5(b), we compare SINR with SNR for various distances from interferer, i.e., $d_{k,j}$. Clearly, SINR is far less compared to SNR indicating a high influence of ACI, and ACI would be more when there are multiple interferers. The impact of ACI is further justified by the performance gap of RRM schemes in the presence and absence of ACI, as shown in the attached papers.

3.5.2 In the presence of CCI

To illustrate the effect of ACI in the presence of CCI, we consider a near-far scenario example as shown in Fig. 3.6, where VUE i is transmitting a message to VUE j, while VUE k is transmitting in the adjacent frequency slot and VUE k' transmitting in the same frequency slot. Hence, the reception is affected by both ACI from VUE k and CCI from VUE k'. Assume that distance from VUE k to j, as well as VUE k' to i are fixed to 10 m, but distance from VUE i to j (i.e., $d_{i,j}$) is varied as shown in Fig. 3.6 (a). Fig. 3.6 (b) shows the received ACI and CCI by VUE j for various Tx-Rx distances, i.e., $d_{i,j}$. It is observed that CCI is less compared to ACI due to the high penetration loss (10 dB/vehicle) of two intermediate vehicles between VUE k' and VUE j. Moreover, observe that the signal power becomes lower than ACI when Tx-Rx distance ($d_{i,j}$) is more than 133 m. In conclusion ACI is problematic even in the presence of CCI in the near-far scenario as illustrated here.



(a) System model



(b) Rx power for various distances $d_{i,j}$ to noise floor

Fig. 3.6: Comparison of ACI with CCI

Chapter 4

Radio Resource Management in V2V Communication

The V2V communication scenario is different from conventional D2D systems, since 1) V2V safety-critical applications are not typically interested in high data rates, but have stringent requirement on latency and reliability [54], 2) the near-far situations are common in V2V communication making ACI a significant factor as explained in Section 3.5. Therefore, the RRM strategies devised for D2D communication, e.g., [55–60], may not be sufficient for V2V communication.

There are many studies on RRM for V2V communication that consider reliability, latency requirements [12, 54, 61] and support broadcast services [62, 63]. Out-of-cellular coverage scenario for V2V has been studied both theoretically [64], and simulation-based [65]. Infrastructure-based scheduling is studied in [66], while a distributed autonomous scheduling approach is proposed in [63]. Location-based scheduling for a highway platooning scenario is investigated in [67, 68], and [69] proposes RRM strategies to improve connectivity among VUEs based on inter-VUE distances and mobility. A study on the capability of the IEEE 802.11p standard to satisfy stringent V2V requirements is done in [70, 71], where the authors conclude that the IEEE 802.11p standard may not be sufficient. Instead, the authors propose a novel MAC protocol and transport layer in IEEE 802.11p in order to satisfy real-time V2V requirements. All of the above studies consider the impact of CCI alone, while this thesis takes into account of ACI as well.

4.1 System Model

We consider a network of N VUEs, denoted by the set $\mathcal{N} = \{0, 1, \cdots, N-1\}$, and assume that the total bandwidth for transmission is divided into F frequency slots and the total time duration into T timeslots. A frequency slot in a timeslot is denoted as resource block (RB), i.e., frequency slot f in timeslot t is called RB (f, t). For example, in long term evolution (LTE) an RB consists of 12 consecutive sub-carriers, or 180 kHz, for a duration of 1 ms [42].

We indicate a transmitting VUE as VUE i, receiving VUE as VUE j, and interfering VUE as VUE k, as illustrated in Fig. 3.2. Similarly the link (i, j) indicate the link from VUE i to VUE j. The parameter $H_{i,j}$ is the average channel power gain from VUE i to j. Hence, $H_{i,j}$ takes into account pathloss, penetration loss, and large-scale fading between VUE i and j. Our RRM scenario is generalized to multicast scenario, where broadcast scenario can be implemented as a special case. Assume VUE i wants to transmit its messages to VUEs in the set $\mathcal{R}_i \subset \mathcal{N}$. Note that $|\mathcal{R}_i| \leq 1, \forall i$, implies unicast communication, and $\mathcal{R}_i = \mathcal{N} \setminus \{i\}, \forall i$, implies broadcast communication. There are totally M messages to be multicasted using $F \times T$ RBs, and a VUEs transmit power is limited to $P^{\max}$. Furthermore, we assume that a VUE can transmit a message in an RB or a group of RBs with error probability ϵ, if the received average SINR is above a certain threshold γ^{T} [72, Lemma 1].

The parameter λ_r is the inverse adjacent channel interference ratio (ACIR) from a frequency slot f to frequency slot $f \pm r$ [73, section 17.9]. Therefore, $\lambda_{|f'-f|}$ is the inverse ACIR from frequency slot f' to f, see Fig. 3.3. In other words, $\lambda_{|f'-f|}$ is the ratio of the received ACI power in frequency slot f to the received signal power in frequency slot f', when the interfering VUE is transmitting in frequency slot f'. Note that when $f' = f$, then the interference is CCI instead of ACI. Therefore, to accommodate CCI and to make interference computations correct in the problem formulations, we set $\lambda_0 = 1$.

We consider both distributed and centralized RRM schemes. Although distributed RRM schemes are readily applicable in vehicular networks with a distributed topology, they usually have limited network throughput and experience severe data congestion when the traffic density is heavy. On the other hand, centralized RRM schemes require centralized controller but make more optimized scheduling decisions based on the collected information, leading to reduced data congestion and improved network throughput.

4.2 Joint Scheduling and Power Control in V2V Communication

Let us consider a link (i, j) in RB (f, t). The desired signal power $S_{i,j,f,t}$, the total received power $R_{j,f,t}$, and SINR $\gamma_{i,j,f,t}$ received by VUE j while decoding the message from VUE i in RB (f, t) can be computed as follows,

$$S_{i,j,f,t} = P_{i,f,t} H_{i,j}, \tag{4.1}$$

$$R_{j,f,t} = \sum_{f'=1}^{F} \sum_{k=1}^{N} \lambda_{|f'-f|} P_{k,f',t} H_{k,j}, \tag{4.2}$$

$$\gamma_{i,j,f,t} = \frac{S_{i,j,f,t}}{\sigma^2 + (R_{j,f,t} - S_{i,j,f,t})}, \tag{4.3}$$

$$Y_{i,j,f,t} = \mathbb{1}\{\gamma_{i,j,f,t} \geq \gamma^{\mathrm{T}}\} \tag{4.4}$$

where $Y_{i,j,f,t} \in \{0, 1\}$ indicate if the link (i, j) is successful or not with sufficiently low error probability ϵ, i.e., SINR of the link (i, j) is above a certain threshold γ^{T}. With the above constraints, we show the problem formulations for various objectives below.

4.2.1 Maximizing Connectivity

Note that, VUE i and j are defined to be connected when VUE j is able to decode any of the messages from VUE i in any of the RBs. Let us define $Z_{i,j} \in \{0,1\}$ to indicate if VUE i is connected to j or not. Following the constraint (4.4), we can define $Z_{i,j}$ as,

$$Z_{i,j} \triangleq \begin{cases} 1, & \bar{\gamma}_{i,j,f,t} \geq \gamma^{\mathrm{T}} \quad \text{for any RB } (f,t) \\ 0, & \text{otherwise} \end{cases} \tag{4.5}$$

$$= \bigvee_{f} \bigvee_{t} Y_{i,j,f,t} \tag{4.6}$$

Correspondingly, the joint scheduling and power control problem formulation can be formulated as follows,

$$\max_{\mathbf{P}} \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{R}_i} Z_{i,j} \tag{4.7}$$

$$\text{subject to:}$$

$$\mathbf{P} \in [0, P^{\max}]^{N \times F \times T}$$

where $P_{i,f,t}$ indicate the transmit power of VUE i in RB (f,t), i.e., $P_{i,f,t} > 0$ indicates that VUE i is scheduled to transmit in RB (f,t). All constraint formulations are shown in [Paper A].

4.2.2 Maximizing Throughput

In order to accommodate any kind of traffic model for packet arrival, we define the parameter $\Omega_{i,m,t} \in \{0,1\}$ indicating if VUE i can transmit the message m, $0 \leq m \leq M-1$, at the earliest timeslot t or not.

We define a variable $W_{j,m,t}$ indicating the message reception status at VUE j as follows,

$$W_{j,m,t} \triangleq \begin{cases} 1, & \text{if VUE } j \text{ receives message } m \text{ during timeslot } t \text{ for the first time,} \\ 0, & \text{otherwise} \end{cases} \tag{4.8}$$

The Boolean matrix $\mathbf{X} \in \{0,1\}^{N \times M \times F \times T}$ indicate the scheduling for all VUEs, i.e., $X_{i,m,f,t}$ indicate if VUE i is scheduled to transmit message m in RB (f,t), or not. A VUE can transmit message m either upon generating message m, or receiving message m from some other VUE, where in the later case VUE relays the message. In other words, scheduling matrix is constrained as follows,

$$X_{i,m,f,t} \leq \left(\bigvee_{t'=0}^{t} \Omega_{i,m,t'}\right) \vee \left(\bigvee_{t'=0}^{t-t^{\mathrm{P}}} W_{i,m,t'}\right). \tag{4.9}$$

where t^{p} accounts for the processing delay for relaying. Note that all Boolean operators (such as AND, OR, ... etc) can be translated into linear operators as shown in [Paper C] Appendix A.

Correspondingly, throughput maximization problem can be formulated as follows,

$$\max_{\mathbf{X},\mathbf{P},\mathbf{W}} \sum_{j,m,t} W_{j,m,t} \tag{4.10}$$

$$\begin{aligned}&\text{subject to:}\\&\quad \mathbf{X} \in \{0,1\}^{N\times M\times F\times T}\\&\quad \mathbf{P} \in [0, P^{\max}]^{N\times F\times T}\end{aligned}$$

where constraints formulations are shown in [Paper C].

4.2.3 Minimizing Age of Information

The variable $A_{i,j,t} \in \mathbb{R}^{+}$ indicating the age of information of the messages from VUE i to VUE j at the end of timeslot t, which can be computed as follows,

$$A_{i,j,t} = \min_{m\in\mathcal{M}_i} (t + A^{\text{init}}_{i,j} + 1 - (t^{\text{gen}}_{m} + A^{\text{init}}_{i,j} + 1) \sum_{t'=0}^{t} W_{j,m,t'}) \tag{4.11}$$

where the parameter $A^{\text{init}}_{i,j}$ is the initial AOI for the link (i,j) before the start of the scheduling and t^{gen}_{m} is the message generation time of m.

The problem formulation to minimize average AOI of all VUEs in the network is as follows,

$$\min_{\mathbf{X},\mathbf{W},\mathbf{P}} \sum_{i,j,t} A_{i,j,t} \tag{4.12}$$

$$\begin{aligned}&\text{subject to:}\\&\quad \mathbf{X} \in \{0,1\}^{N\times M\times F\times T}\\&\quad \mathbf{P} \in [0, P^{\max}]^{N\times F\times T}\end{aligned}$$

For the constraint formulations, refer to [Paper C].

4.3 Scheduling

The scheduling algorithms can be broadly classified as non-overlapping and overlapping scheduling. In non-overlapping scheduling, each RB is scheduled to at most one VUE, thereby avoiding CCI. However, ACI would become a limiting factor for the communication in this scenario and sufficient number of resources are required to allocate to all VUEs. The overlapping scheduling allows scheduling multiple VUEs in an RB, however, in this scenario CCI also has to be handled.

In the case of non-overlapping scheduling, $\mathbf{U} \in \{0, 1, \ldots, N\}^{F\times T}$ represent the scheduled VUEs in an $F \times T$ RBs, where $U_{f,t}$ is the VUE index scheduled in RB (f,t) and

(a) BIS ($w = 1$) (b) BIS ($w = 2$)

Fig. 4.1: Scheduling of VUEs in RBs (i.e., matrix $\mathbf{U}$) when $N = 8$, $F = 6$, and $T = 3$

$U_{f,t} = 0$ implies no VUE scheduled in (f, t). Fundamentally, scheduling is the process of allocating VUEs in the available RBs, which is equivalent to populating the matrix $\mathbf{U}$ with appropriate VUE indices, as illustrated in Fig. 4.1.

4.3.1 Optimal Scheduling

Note that the scheduling alone problem is a special case of joint scheduling and power control problem formulation when the power values are fixed. That is, the scheduling problem formulation can be derived from the joint problem formulation by fixing the power values. The derived problem formulation is a Boolean linear programming (BLP) problem as shown in [Paper B]. The problem formulation is solved using Gurobi solver [74], which internally uses the branch and bound method. However, due to the high computational complexity of the problem, the branch and bound method involves a number of linear optimizations which, in the worst case, is believed to be exponential in the number of binary variables. Therefore, we propose various scheduling algorithms with less complexity, which are broadly categorized as non-overlapping and overlapping schedulers as follows.

4.3.2 Block Interleaver Scheduler (BIS)

The block interleaver scheduler (BIS) is a simple non-overlapping distributed scheduler proposed in [Paper A], where each VUE requires only its position index to schedule. BIS is a very low complexity algorithm that can be used as a baseline while trying to find a better scheduling algorithms. The approach here is to schedule all VUEs exactly once in the available frequency-timeslots. If there are more VUEs than the available RBs, i.e., $N > FT$, then we choose maximum FT VUEs out of N VUEs which are maximally far apart, then schedule them.

If $N \leq T$, the scheduling problem is trivial; each VUE can be scheduled in each timeslot. However, if $N > T$, then we need to multiplex VUEs in frequency, which results in ACI. To reduce the ACI problem, we strive to use as few frequency slots as possible and space the frequency slots as far apart as possible. Since we can schedule T

VUEs per frequency slot, the smallest required number of frequency slots is $\tilde{F} = \lceil N/T \rceil$, that is, we need to schedule $\tilde{F}$ frequency slots in a timeslot. We choose $\tilde{F}$ frequency slots that are maximally spread among F frequency slots, i.e., the minimum gap between any two scheduled frequency slots is maximized. Besides, we permute the chosen frequency slots using a block interleaver with width w [42, section 5.1.4.2.1], and the value of w is chosen which would maximize the performance as explained in [Paper A]. Examples of BIS scheduling for various values of w are shown in Fig. 4.1.

4.3.3 Heuristic Scheduler

Heuristic scheduler is an overlapping greedy scheduling algorithm, where each RB is scheduled with the best possible VUE under the assumption that the schedule for all other RBs are fixed. The order of looping through the RBs for scheduling is important. The resulting schedule can lead scheduling a VUE in zero or multiple RBs, as opposed to BIS, which schedules a VUEs at most once.

The algorithm is executed in two steps: 1) determine the RB scheduling order, 2) use this order to sequentially schedule an RB. The scheduling order is computed in such a way that the consecutive scheduling is done in far away frequency slots. This is done in order to minimize the total received ACI among VUEs. Once we find out the RB scheduling order, we schedule the VUE that maximizes the systems objective, under the assumption that scheduling of all other RBs remain unchanged. More details of the scheduler can be found in [Paper A].

4.4 Power Control

Power control in V2V multicast communication is done with two goals in mind: 1) improve the primary objective 2) reduce the total power consumption. The primary objective can be maximizing connectivity/throughput or minimizing AOI as discussed in Section 4.2. Improving the primary objective 1) is more important than the secondary goal 2), hence, power reduction is generally preferred only when it does not affect our primary objective.

4.4.1 Optimal Power Control

Observe that in order to get the problem formulation for optimal scheduling in Section 4.3.1, we fixed the power values of all VUEs in the joint problem. Similarly, we can convert the joint scheduling and power control problem into a power-control alone problem by fixing the schedule, i.e., by fixing $\mathbf{X}$ in the problem formulations in Section 4.2, and optimize over power values $\mathbf{P}$. The resulting problem is a mixed Boolean linear programming (MBLP) problem with the VUEs power values as optimization variables. However, the above problem is NP-hard as proved in [75, Lemma 1]. Therefore, for larger networks, heuristic algorithms with reduced complexity are preferable.

4.4.2 Heuristic Power Control Algorithm

The heuristic power control algorithm proposed in [Paper A] strives to find the transmit power values for all VUEs in all timeslots which would maximize the connectivity among VUEs. Given a set of candidate links $\mathcal{L} \subseteq \{(i,j) : i \in \mathcal{N}, j \in \mathcal{R}_i\}$, it is easy to verify if there exists any set of power values to make all links in $\mathcal{L}$ to be successful or not. This is done by checking if a feasible solution for power values exists for the resulting linear programming (LP) problem [75]. So our task is to find the set of links $\mathcal{L}$ with maximum cardinality which can be made to be successful links with appropriate power values. We compute $\mathcal{L}$ in an iterative way and each iteration may involve addition/removal of links from the set $\mathcal{L}$.

The algorithm is an iterative algorithm involving two steps in each iteration. Since it may not be possible to ensure success for all links, our first step is to find the set of candidate links $\mathcal{L}$. The second step is to compute the power values $P_{i,t}$ for all VUEs in all timeslots in order to maximize the number of successful links in $\mathcal{L}$. Therefore, we update both $\mathcal{L}$ and $P_{i,t}\ \forall\, i,t$ in each iteration. We terminate the algorithm, when we observe that all the links in $\mathcal{L}$ are achieving the SINR target γ^{T}.

We initialize $\mathcal{L}$ to the set of all intended links, i.e., $\mathcal{L} \subseteq \{(i,j) : j \in \mathcal{R}_i, i \in \mathcal{N}\}$, and initialize the transmit power of all VUEs as P^{init} in the first iteration. In the subsequent iterations, the transmit power is increased/decreased in order to maximize the connectivity among links in $\mathcal{L}$. Assume that the variable $\tilde{P}_{i,j,t}$ is the required transmit power of VUE i during the timeslot t in an iteration in order to make link (i,j) to be successful under the assumption that the interference remains the same. If $\tilde{P}_{i,j,t} > P^{\max}\ \forall\, t$, then the link (i,j) is a failed link. We remove repeatedly failed links over many iterations from the set $\mathcal{L}$.

The results of all considered scheduling and power control algorithms are given in the report [76] for many possible values of F, T, and N, and for half-duplex/full-duplex, SCFDMA-ACI/3GPP-ACI-mask scenarios.

4.5 Addressing Scalability Issues

4.5.1 Column Generation Method

The RRM based on column generation method is a novel method proposed in [Paper B] to reduce the computational complexity with respect to the number of timeslots T. The intuition behind this method is to choose the best T single-timeslot power value matrices out of a set of available power value matrices. Assume that we have an ordered set of Q distinct single-timeslot power matrices $\tilde{\mathcal{P}} = \{\tilde{\mathbf{P}}^1, \tilde{\mathbf{P}}^2, \ldots, \tilde{\mathbf{P}}^Q\}$, where $\tilde{\mathbf{P}}^q \in \mathbb{R}^{N \times F},\ \ 1 \leq q \leq Q$, can be thought of as the power allocation in a single timeslot. Let $\tilde{\mathbf{Z}}^q \in \{0,1\}^{N \times N}$ be the corresponding successful link matrix, i.e., $\tilde{\mathbf{Z}}^q_{i,j}$ indicating if VUE i and j are connected when $T = 1$ and $\mathbf{P}$ is fixed and equals to $\tilde{\mathbf{P}}^q$. Let $\tilde{\mathcal{Z}} = \{\tilde{\mathbf{Z}}^1, \tilde{\mathbf{Z}}^2, \ldots, \tilde{\mathbf{Z}}^Q\}$. Resource allocation can be thought of as choosing the best T power value matrices from $\tilde{\mathcal{P}}$ and higher values of Q generally results in improved performance. Therefore, the RRM problem can be split into two subproblems as follows,

1. Computing the appropriate set of power value matrices $\tilde{\mathcal{P}}$ and the corresponding $\tilde{\mathcal{Z}}$.

2. Choosing T power value matrices from $\tilde{\mathcal{P}}$.

The subproblem 1) above is solved using an iterative column generation method, where in each iteration we compute the best power value matrix $\tilde{\mathbf{P}}^q$ to augment the set $\tilde{\mathcal{P}}$ which would improve the performance. We utilize the concepts of dual variable and reduced costs to compute the best power value matrix $\tilde{\mathbf{P}}^q$ and decide when to terminate the iterations. The subproblem 2) is an NP-hard problem as proved in [Paper B], hence, we adopt a simple heuristic approach which would provide a reasonably good solution.

4.5.2 Clustering of Network

The problem formulations to compute optimal scheduling and power control in previous sections have high computational complexity for larger networks. Therefore, partitioning of the large network into smaller networks is recommended as proposed in [Paper C]. The network of N VUEs can be partitioned into C clusters, and each cluster is further partitioned into G groups, and a group g in cluster c is called group (c, g) as illustrated in Fig. 4.2. The idea of splitting is that, a group in a cluster is *low-interfering* to the corresponding groups in any other clusters, i.e., channel gain from any VUEs in group (c, g) to any VUEs in $(c', g), c \neq c'$, is less than a small threshold value δ. In order to avoid inter-group interference within a cluster, groups within a cluster are allocated with distinct timeslots. However, groups with same group index g in different clusters are allocated with the same timeslots, thereby ensuring low inter-cluster interference. As an example, it is possible to allocate timeslots $\{g, g + G, g + 2G, \cdots, \}$ to group g in all clusters, where G is the number of groups in a cluster. The value of G can be decided based on the maximum allowed inter-cluster interference, i.e., if the maximum allowed inter-cluster interference is low, then G has to be set high.

Assume that $\mathcal{T}^{(c,g)} \subseteq \mathcal{N}$ and $\mathcal{R}^{(c,g)} \subseteq \mathcal{N}$ are the set of Tx and Rx VUEs in the group (c, g). The transmitter groups form a partition of the network, hence non-overlapping, i.e., $\mathcal{T}^{(c,g)} \cap \mathcal{T}^{(c',g')} = \emptyset, \forall (c', g') \neq (c, g)$. However, receiver group $\mathcal{R}^{(c,g)} = \{j : i \in \mathcal{T}^{(c,g)}, j \in \mathcal{R}_i\}$ can be overlapping. A simple method to form group (c, g) is to group every adjacent n^{Tx} VUEs, i.e.,

$$\mathcal{T}^{(c,g)} = \{(cG + g)n^{\mathrm{Tx}}, (cG + g)n^{\mathrm{Tx}} + 1, \ldots, (cG + g + 1)n^{\mathrm{Tx}} - 1\} \tag{4.13}$$

$$\mathcal{R}^{(c,g)} = \{j : i \in \mathcal{T}^{(c,g)}, j \in \mathcal{R}_i\} \tag{4.14}$$

An example of clustering and grouping is shown in Fig. 4.2, where $n^{\mathrm{Tx}} = 3$.

Upon forming clusters and groups, the available timeslots are allocated to all groups, and a group (c, g) can independently schedule and power control VUEs in $\mathcal{T}^{(c,g)}$ to transmit to VUEs in $\mathcal{R}^{(c,g)}$, either in a centralized or in a distributed way.

We note that the resource allocation can be done by any of the following entities:

1. A centralized controller for the whole network

2. Group-head with the assistance of network controller

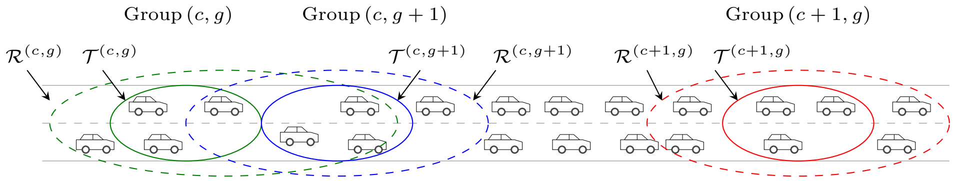


Fig. 4.2: Groups (c, g) and $(c+1, g)$ are *low-interfering* with each other, hence, can reuse the resources.

3. Group-head without the assistance of network controller
4. VUE with no assistance

The option 1) is for the sole purpose of reducing computational complexity, where the centralized controller can split the whole network into groups as per its convenience. In option 2) the grouping of the network is done with the network assistance, however, each group-head does resource allocation independently. In option 3), group-head may not communicate with the network controller or with each other. In this scenario inter-group relaying is not possible. In option 4), each VUE independently schedule itself without any assistance from other groups or network controller. We will see an example of such a scheduler in the next section. A centralized controller/group-head can be a VUE, ITS-S, or a BS.

4.5.3 Clustering Based Distributed Scheduling (CDS)

In the absence of a centralized scheduler or channel state information (CSI) for V2V communication, a VUE has to schedule itself in an adhoc manner. The proposed CDS algorithm in [Paper C] is for distributed scheduling by assuming that a VUE has the knowledge of its position index. A VUE can compute its cluster index and group index from its position index, as explained in [Paper C].

The CDS algorithm has two stages with each stage containing iterative steps. In the first stage, we schedule all VUEs exactly once, and in the second stage all unscheduled RBs are scheduled with the appropriate VUEs. In the first stage, in each iteration, a VUE and an RB triplet (i.e., (i, f, t)) is chosen and scheduled in a greedy way, such that VUE i receives the least interference in RB (f, t) compared to any other combinations of VUEs and RBs. In the second stage, we schedule each unscheduled RB iteratively with the VUE that receives the least interference in that RB.

However, finding the received interference for a VUE is impossible since a VUE does not have the channel knowledge $\mathbf{H}$. Therefore, a VUE has to estimate the received interference for all VUEs in the group using its available data. For this, we simplify the computation by assuming interference caused by VUE k scheduled in frequency slot f' to VUE j scheduled in f' as $\lambda_{|f'-f|}\alpha^{|k-i|-1}$, where α is a discount factor accounting for the pathloss and penetration loss of an intermediate VUE. The value of α can be approximated as $\mu^{1/l}$, where μ is the penetration loss of a blocking VUE, and l is the number of lanes in the road.

4.6 Other Practical Considerations

4.6.1 Addressing Sensitivity of the Problem

One issue while solving RRM problem formulations (to compute optimal solutions) is the sensitivity of the problem. Both ACIR and V2V channel values have got high dynamic rage, which leads to both small and large coefficients in SINR constraints (see (4.4)). This makes the problem more sensitive and numerically harder to solve. Moreover, high numerical sensitivity of the problem makes the solver to claim some failed links as successful, making solver to return a suboptimal solution instead of the optimal one. To overcome this sensitivity issue, a novel scheduling scheme based on cutting plane approach [77] is proposed in [Paper B].

The main idea is to augment the set of sensitive SINR constraints with more robust Boolean cover inequalities. We first solve the RRM problem formulation, then find the SINR constraints which are violated by the solution returned by the solver. Next appropriate robust cover inequalities are generated and added to the problem formulation, which would avoid such SINR violations in the future iterations. The updated problem is solved, which results in new SINR violations that are used to construct additional robust cover inequalities. The process of iteratively adding robust cover inequalities (i.e., SINR constraints) is repeated until there are no more SINR constraint violations. At this point, we have arrived to a feasible solution for the scheduling problem which is also optimal since the added cover inequalities are not stronger than the original SINR constraints.

Next we show an example of constructing a cover inequality. Since we are only considering the scheduling problem, assume that the transmit power of VUE i during timeslot t as $\bar{P}_{i,t}$. Assume that $I_{i,j}^{\max}$ is the maximum tolerable interference to the link (i, j) such that the link error rate is sufficiently low. Following the SINR constraint for making link (i, j) to be successful, we can constrain $I_{i,j}^{\max}$ also as follows,

$$\frac{\bar{P}_{i,t} H_{i,j}}{I_{i,j}^{\max} + \sigma^2} = \gamma^{\mathrm{T}} \tag{4.15}$$

$$\Rightarrow \qquad I_{i,j}^{\max} = \frac{\bar{P}_{i,t} H_{i,j}}{\gamma^{\mathrm{T}}} - \sigma^2 \tag{4.16}$$

Any interfering VUE (or combination of VUEs) which causes more interference to the link (i, j) than $I_{i,j}^{\max}$ would make the link failure. So, one way to form cover inequality is to limit $Y_{i,j,f,t} = 0$ when such interfering VUEs are scheduled in frequency slots near to f in timeslot t. For example, suppose $\lambda_{|f'-f|} \bar{P}_{k,t} H_{k,j} > I_{i,j}^{\max}$, then scheduling VUE k in frequency slot f' would limit the performance of the link (i, j) in frequency slot f, which can be formulated as the following cover inequality,

$$Y_{i,j,f,t} \leq 1 - X_{k,m,f',t} \qquad \forall\, m \tag{4.17}$$

4.6.2 Supporting Large Message Payload

If a message payload is too big to fit into an RB, then either of the following approaches has to be adopted,

1. The message must be scheduled on multiple RBs. For this purpose, a set of contiguos RBs can be used as a scheduling unit, instead of a single RB. This would benefit scheduling by reducing the computational complexity and overhead.

2. The message can be fragmented into smaller packets and each packet has to be transmitted in separate RBs. The problem formulation for scheduling all message fragments is shown in [Paper C].

4.6.3 Supporting Very Low Error Rate

Assume that ϵ is the message error probability for a link if SINR of the link equals to γ^{T}, and ϵ^{req} is the required message error probability for end-to-end V2V communication. If $\epsilon > \epsilon^{\mathrm{req}}/N$, then we need to either increase SINR threshold γ^{T} or support repeated transmissions to achieve the required error probability, where the total number of transmissions required for a message is $\rho = \lceil \log \epsilon / \log(\epsilon^{\mathrm{req}}/N) \rceil$. If the receiver supports HARQ processing, then the number of repeated transmissions can be further reduced [78].

Chapter 5

Contributions and Conclusions

5.1 Contributions

This thesis studies the impact of ACI on V2V multicast communication systems, and ways to mitigate it by using scheduling and power control techniques. In typical V2V communications, each VUE wants to multicast a safety critical message to neighbouring VUEs, with a latency and reliability constraints. However, the reliability can be ensured by achieving an average SINR above a certain threshold which limits the outage probability within the required outage probability. With this result in mind, the scheduling and power control problem is formulated for various objectives. The contributions made by the author is presented in Part II of the thesis in the form of three papers summarized below.

Paper A: "Scheduling and Power Control for V2V Broadcast Communications with Co-Channel and Adjacent Channel Interference"

In paper A, an overview of ACI model is presented with the simulated ACI for a typical V2V communication using SCFDM transmission scheme. From this, ACI is found to be larger than noise when vehicles are not very far apart. Moreover, the aggregate ACI becomes high when there are more number of vehicles in the network. Through extensive simulations, we observe that the communication performance is majorly limited by ACI in the absence of CCI, i.e., when VUEs are scheduled in non-overlapping RBs. The scheduling and power control problem in order to maximize the total number of successful links is formulated as a mixed integer quadratically constrained programming (MIQCP) problem (with less computational complexity compared to MBLP problem formulation accommodating CCI proposed in [Paper B]). From this, we derive the scheduling problem (for fixed transmit powers) as a BLP problem and the power control problem (for a fixed schedule) as an MBLP problem. For small instances of the problem, we compute a near-optimal solution for scheduling by solving the BLP problem and then compute a near-optimal power values by solving the MBLP problem. In order to reduce the computational complexity, heuristic RRM algorithms with polynomial time complexity are proposed. Additionally, a simple distributed BIS scheduler is designed to get baseline results.

Paper B: "Adjacent Channel Interference Aware Joint Scheduling and Power Control for V2V Broadcast Communication"

The joint scheduling and power control problem to maximize the VUE connectivity, in the presence of ACI, is formulated as an MBLP problem. From this problem formulation, the scheduling-alone problem formulation is derived as a BLP problem and the power-control-alone problem formulation as an MBLP problem. A column generation approximation method is proposed to reduce the computational complexity of the joint scheduling and power control problem with a minor compromise on performance. Due to the high dynamic range of channel and ACI values, the scheduling problem is numerically sensitive, resulting in the optimization solver returning near-optimal solutions instead of optimal solutions. Therefore, a novel method based on cover inequalities is proposed to avoid the sensitivity of the problem formulation and the optimal scheduling is computed at the price of increased computational complexity.

Paper C: "Radio Resource Management for V2V Multihop Communication Considering Adjacent Channel Interference"

In Paper C, we extend all problem formulations to allow multihop communication, i.e., relaying through VUEs, without losing the linearity nature of the problem formulations. The joint scheduling and power control problem formulation to minimize the average/worst-case AoI is also formulated as an MBLP problem. Furthermore, the error probability of a link failure is considered in all the problem formulations and the probability requirements for satisfying a certain throughput/connectivity/latency/AoI are accommodated. In order to address scalability of the network, a clustering algorithm is proposed which would partition the network into small groups, and RRM schemes can be applied to each group independently. A low-complexity distributed scheduling based on clustering is also proposed which can utilize multihop communication between far-away VUEs.

5.2 Conclusions

The conclusions from this thesis can be summarized as follows,

- The near-far situations are common in V2V communication scenario, hence V2V communication performance can be limited by ACI.
- Effective RRM techniques can be used to mitigate the impact of ACI and improve the performance. In general scheduling strategies are more effective than power control strategies.
- A joint schedule and power allocation to maximize connectivity/throughput or minimize AoI among VUEs in a multicast scenario can be stated as an MBLP

problem. The scheduling for a fixed power values, can be stated as a BLP problem, and power control for a fixed schedule can be stated as an MBLP problem.

- The computational complexity is high for computing the optimal schedule and power values. Moreover, the power control problem is proved to be NP-hard. However, the computational complexity can be reduced with respect to the number of timeslots using a column generation approximation method with a minor compromise on the performance.
- The scalability of the network is an issue due to the high computational complexity involved in computing optimal RRM solutions. But scalability issues can be addressed with a compromise on performance by applying heuristic algorithms and clustering based RRM as proposed in [Paper A] and [Paper C] respectively.
- Both ACIR values and channel values have high dynamic range in V2V communication, therefore, RRM problems can be numerically sensitive resulting in an optimality gap for the solutions returned by the solver. However, the sensitivity can be avoided by applying the proposed method in [Paper B] and the optimality gap due to the sensitivity issue is found to be marginal.
- Effective RRM schemes can reduce interference, but the performance can be limited by noise power due the high penetration loss by blocking vehicles. However, this limitation can be overcome by using the multihop communication scheme proposed in [Paper C]. The problem to compute the optimal multihop RRM can be stated as an MBLP problem.

5.3 Future Works

Some possible future directions are summarized as follows,

- Develop RRM schemes to support V2V broadcast communication in the case of no control information exchange among VUEs.
- Utilize the contextual information, such as location, speed, moving direction of the vehicles to improve the clustering method and RRM schemes.
- Derive a closed form mathematical expression for maximum and average number of connectivity possible in a V2V network.

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