Thesis for the degree of Licentiate of Engineering

On Power Control and Scheduling to Mitigate Adjacent Channel Interference in Vehicle-to-Vehicle Communication

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Abstract

Safety applications play an essential role in supporting traffic safety and efficiency in next generation vehicular networks. The efficiency of safety applications depends heavily on the establishment of reliable communication since these types of applications have strict requirements on latency and reliability. Recently, vehicle-to-vehicle (V2V) communication have captured great attention due to its potential to improve traffic safety, effective driving assistance, and intelligent transport systems. Typically cellular communication performance is limited by co-channel interference (CCI). However, in the case of V2V broadcast communication with sufficient amounts of dedicated spectrum, we can avoid CCI by allocating non-overlapping frequency resources to vehicular user equipments (VUEs). However, in this scenario, adjacent channel interference (ACI) becomes a deciding factor for the communication performance. This thesis investigates how to mitigate the impact of ACI on V2V broadcast communication by scheduling and power control.

In Paper A, we study the impact of ACI on V2V communications and conclude that the ACI indeed significantly affects the reliability of V2V links. Second, we formulate a power control optimization problem for vehicles to reduce the negative influence of ACI, which is shown to be NP-hard. Furthermore, we propose two power control schemes where the first one solves the formulated problem by a branch and bound method and the second one considers a heuristic algorithm with much reduced complexity. Numerical results show the necessity of power control when ACI exists and also show promising performance of the proposed algorithms.

In Paper B, we formulate the joint scheduling and power control problem, with the objective to maximize the number of connected vehicles, as a mixed integer programming problem with a linear objective and a quadratic constraint. From the joint formulation, we derive (a) the optimal scheduling problem for fixed transmit powers as a Boolean linear programming (BLP) problem and (b) the optimal power control problem for a fixed schedule as a mixed integer linear programming (MILP) problem. Near-optimal schedules and power values for smaller instances of the problem can be computed by solving first (a) and then (b). To handle larger instances of the problem, we propose heuristic scheduling and power control algorithms with reduced computational complexity. We provide exhaustive simulation results in Paper C appended in this thesis for various duplex scenarios and ACI models. As a baseline result, we also show the optimum performance that can be achieved by a block interleaver scheduler (BIS). We observe that significant performance improvement can be achieved using the proposed heuristic algorithms compared to BIS. Moreover, the heuristic algorithms perform close to the near-optimal scheme for small instances of the problem.

Keywords: V2V Communication, ACI, Power Control, Scheduling

List of Publications

Included Papers

This thesis is based on the following appended papers.

[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, "Scheduling and Power Control for V2V Broadcast Communications with Adjacent Channel Interference," *submitted to IEEE Transactions on Vehicular Technology, Connected Vehicle Series*, Aug. 2017.

[C] 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., Aug. 2017.

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Gothenburg, October 2017

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Acronyms

ACI	adjacent channel interference
ACIR	adjacent channel interference ratio
BIS	block interleaver scheduler
BLP	Boolean linear programming
CDF	cumulative distribution function
CSMA	carrier sense multiple access
D2D	device-to-device
DPD	digital predistortor
LOS	line-of-sight
LP	linear programming
LTE	long term evolution
MAC	medium access control
MILP	mixed integer linear programming
MIQCP	mixed integer quadratically constrained programming
NLOS	non line-of-sight
PA	power amplifier
PHY	physical
RB	resource block
RRM	radio resource management
V2V	vehicle-to-vehicle
VUE	vehicular user equipment

Contents

Part I

Overview

Chapter 1

Introduction

1.1 Background

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 helps to survey immediate neighborhoods and prevent possible collisions. However, radar and vision based systems are limited by small coverage distance and obstruction by other vehicles. But wireless communication can overcome these limitations by supporting non line-of-sight (NLOS) over long range.

Direct vehicle-to-vehicle (V2V) communication can help reduce accidents by providing up-to-date local information and emergency informations to the driver. To this end, both periodic and event-driven messages are conveyed. Periodic messages are sent by all vehicles to inform neighbors about their current status like position, speed, direction, and acceleration, whereas event-driven messages are sent when any emergency situation has been detected. Conveying such safety critical messages requires low latency and high reliability for V2V communication, therefore, efficiency of the safety applications heavily depends upon the establishment of reliable communication. For example, the US National Highway Traffic Safety Administration (NHTSA) Department of Transportation has issued a proposed rule, "The Federal Motor Vehicle Safety Standard (FMVSS); V2V Communications," that would require automakers to include V2V technologies in all new light-duty vehicles [1].

Current conventional solution for V2V is based on IEEE 802.11p standard which has physical (PHY) layer as regular 802.11 OFDM with 10 MHz channel, medium access control (MAC) layer as carrier sense multiple access (CSMA), and backend-based communication over long term evolution (LTE) cellular standard. The main problem with the legacy 802.11p system is that these are mainly optimized for WLAN-type of environment for adhoc communication with very low mobility, hence not optimized for vehicles. Additionally, CSMA techniques used in these systems may lead to packet collision resulting in low reliability and high latency. Moreover, the typical handshaking protocol involving request-to-send (RTS)/clear-to-send (CTS) in IEEE 802.11p increases the latency, therefore, these conventional CSMA approaches are inefficient for broadcast transmission in high density traffics scenarios [2]. More sophisticated techniques are required for scheduling and allocating power values to vehicular user equipment (VUE) to meet the requirements.

V2V communication based on device-to-device (D2D) in LTE has been proposed as a potential solution for vehicular communication [3, 4]. 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. The key challenge in both cases is the mitigation of the generated interferences. In [5], Huang et al. compared these two approaches based on transmission capacity, and Yu et al. have done a similar comparison based on throughput in [6]. 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. In this thesis, we consider spectrum overlay where V2V communication uses dedicated spectrum separate from the cellular spectrum.

In a typical cellular communication systems, the communication performance is majorly limited by co-channel interference (CCI), which is cross talk between two different transmitters when using the same time-frequency slot. However, in V2V communication with dedicated spectrum, we can remove CCI by allocating non-overlapping time-frequency resources to different VUEs for their transmission. However, in this scenario, communication performance is limited by adjacent channel interference (ACI). ACI is the spill over power from one frequency band to adjacent frequency bands, which affects communication links when two transmitters are simultaneously transmitting on close by non-overlapping frequency bands. In an ACI-limited communication network, a link's performance is heavily dependent on the scheduling of nearby frequency slots too.

1.2 Objectives

The objectives of the thesis are as follows,

1. Analyze the impact of ACI in vehicular broadcast communication, and check if it is possible to satisfy the stringent requirement for latency and reliability for V2V communication when ACI is present.

2. Analyze if it is possible to reduce the impact of ACI using scheduling and power control techniques.

3. Quantify the maximum impact reduction of ACI that is possible by using optimal scheduling and power control.

4. Formulating heuristic scheduling and power control algorithms to provide reasonably good performance with low computational complexity.

1.3 Outline

We start by discussing the characteristics of ACI and quantify the impact of ACI using simulations in Chapter 2. In this chapter, we also explain adjacent channel interference ratio (ACIR) and ACI models. In Chapter 3, we explain channel model and topology of vehicular networks, which are vital for efficient design of algorithms. In the same chapter, we provide a brief introduction upon the problem formulation for joint scheduling and power control [Paper B]. We also explains heuristic algorithms which improves the performance with less computational complexity. Finally, the contributions of this thesis and future directions are summarized in Chapter 4.

Chapter 2

Adjacent Channel Interference

A thorough understanding of ACI is important to design algorithms to mitigate its impact. In this chapter, we make an analysis of ACI and its impact on vehicular communications.

2.1 Cause of ACI

The power amplifier (PA) is an important component in a transmitter, which is responsible for the increase in power to the level suitable for transmission. A typical PA output response is nonlinear as shown as the red curve in Fig. 2.1. However, linearity is an important requirement for PAs since nonlinear behavior leads to more bit error rate and distortion. This distortion causes transmit power leaking into neighboring channels resulting in ACI [7]. 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.

To avoid excessive leakage, the PA needs to 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 saturation point leads to low power efficiency in PAs. Power efficiency of PAs is of paramount importance since it is the major contributing factor for the large energy consumption in wireless networks [8]. Due to PA's inefficiency in converting direct current (DC) power into radio frequency (RF) power, PAs produce a large amount of heat which requires an air conditioning unit to cool down, further increasing the energy consumption [8]. Unfortunately, power efficiency and linearity are conflicting requirement of PAs, hence there is a tradeoff in it.

In order to improve efficiency-linearity tradeoff, system designers prefer to operate PAs at high-efficiency levels and later remove the distortions caused [9]. Over the past years, many techniques have been investigated for improving the linearity of PAs [10]. However, in recent years, advanced methods such as digital predistortor (DPD) has been proposed [9–11]. The idea of DPD is to distort the input signal to PAs so that the

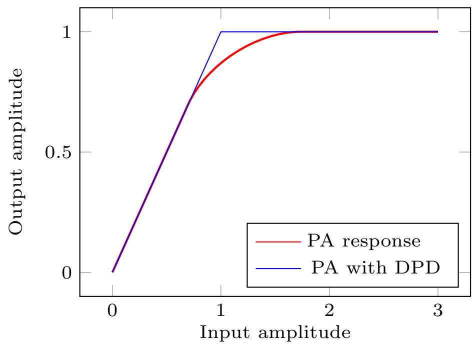


Fig. 2.1: Illustration of PA response with and without DPD

combined response of DPD and PA would be linear as shown as the blue curve in Fig. 2.1. However, irrespective of DPD, the clipping behavior of PAs causes ACI, and an example of resulting ACI is presented in Section 2.3 .

2.2 ACIR Definition

In this section we explain ACIR using an example. As illustrated in Fig. 2.2, VUE i is transmitting a packet to VUE j while VUE k is also transmitting in a nearby frequency slot. The received SINR of the packet from VUE i to VUE j is worsened by ACI from VUE k. A parameter named ACIR is widely used to measure the ACI [12, section 17.9]. As illustrated in Fig. 2.3, ACIR is defined as 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.

More specifically, ACIR from frequency slot f to frequency slot f' when a transmitter transmit on frequency slot f is computed as $S_f/I_{f'}$, where S_f is the average received power in frequency slot f, and $I_{f'}$ is the average received leakage power in frequency slot f'.

2.3 ACI Models

ACI caused by a transmitter depends on the power amplifier and the transmission scheme used in the communication. For simulation purposes, we used two ACI models. The first one is the ACI mask specified by 3GPP [13], and the second one is the ACI of a typical single carrier frequency division multiple access (SCFDMA) signal with a power amplifier with 1% clipping threshold. The corresponding inverse ACIR values are shown in the black and blue curves respectively in Fig. 2.4. The red-colored step curve in Fig. 2.4 shows the SCFDMA ACI averaged over each frequency slot.

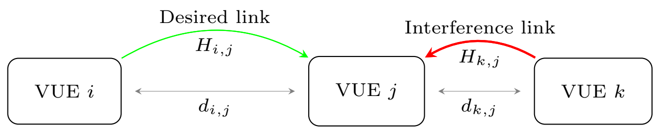


Fig. 2.2: System model

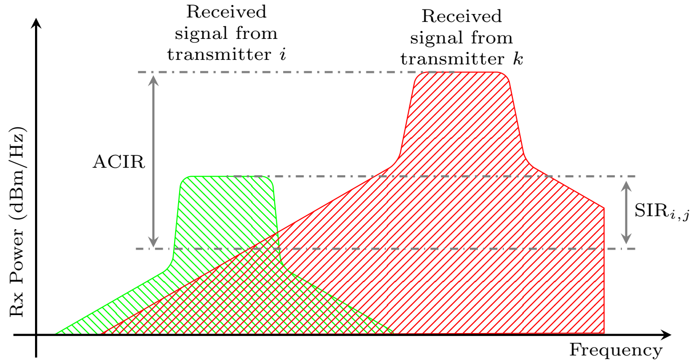


Fig. 2.3: Received power spectral density at receiving VUE j.

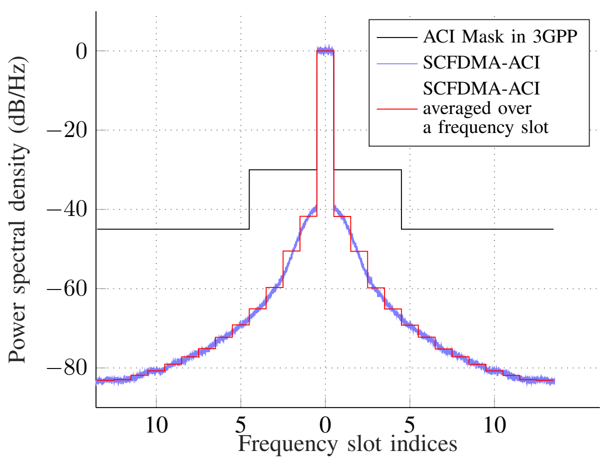


Fig. 2.4: Inverse ACIR model

2.4 ACI Impact on V2V Communication

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 transmitting a packet to VUE j while VUE k is interfering the reception as illustrated in Fig. 2.2. For this study, we assume VUE i and k are transmitting in adjacent frequency slots, i.e., in frequency slots f and $(f+1)$ respectively. Let α denote the inverse ACIR for single frequency slot gap, i.e., α is the ratio of received power by VUE j from VUE k on frequency slot f to received power on frequency slot $(f+1)$. Here, we assume SCFDMA ACIR, hence $\alpha = -43\,\text{dB}$ from Fig. 2.4.

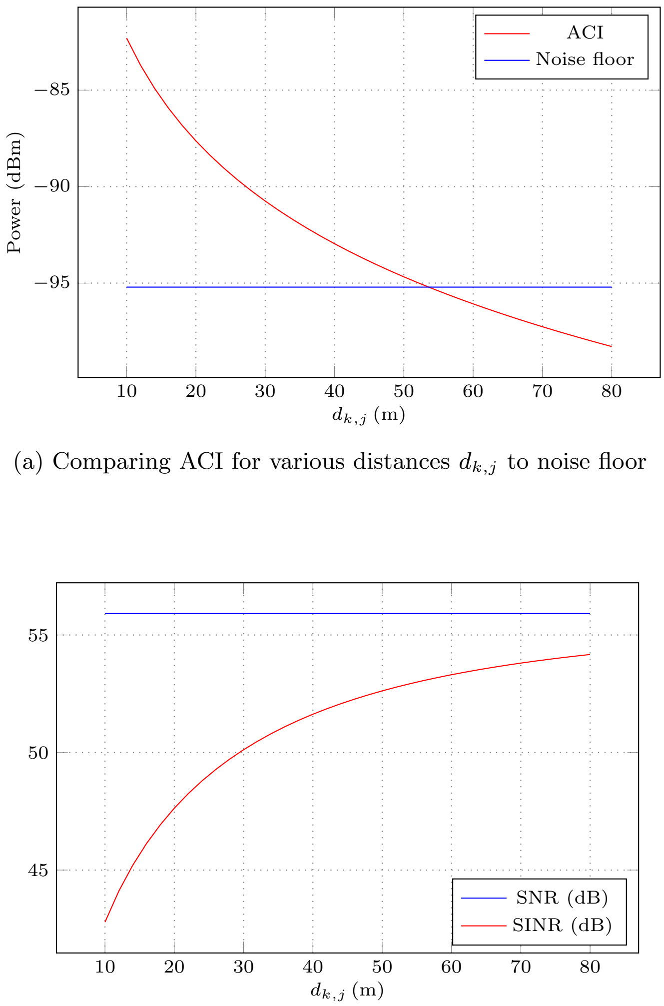
The variable $H_{\ell,\ell'}$ and $d_{\ell,\ell'}$ denote the channel power gain and distance between VUE ℓ and ℓ' respectively. The path loss in dB for a distance d is computed as,

$$\text{PL}(d) = \text{PL}_0 + 10n\log_{10}(d/d_0) \tag{2.1}$$

where n is the path loss exponent, PL_0 is the path loss at a reference distance d_0. The values of the channel parameters are taken from [14], and noise floor is as per 3GPP recommendation [13]. The variables P_i and P_k are transmit powers of VUE i and k respectively, and we assume that both the VUEs are transmitting at its max power, i.e., $P_i = P_k = P^{\max}$, where $P^{\max}$ is assumed to be $24\,\text{dBm}$ [13].

In Fig. 2.5(a), we compare the ACI (for a typical SCFDMA system) from VUE k with noise power for various values of distance from interferer $d_{k,j}$. We compute the ACI from VUE k to VUE j in the frequency slot f as $P_k H_{k,j}\alpha$. We observe that ACI is higher than noise power for lower distances from the interferer, i.e., whenever $d_{k,j} < 54\,\text{m}$. Obviously ACI would be more when there are multiple interferers.

In Fig. 2.5(b), we compare SINR with SNR for various distances from interferer $d_{k,j}$ when $d_{i,j} = 10\,\text{m}$. The SINR is computed as $P_i H_{i,j}/(P_k H_{k,j}\alpha + \sigma^2)$, and SNR is computed as $P_i H_{i,j}/\sigma^2$, where σ^2 is the noise power. Clearly, SINR is far less compared to SNR indicating the high influence of ACI. The impact of ACI is further justified by the performance gap among scheduling and power control schemes in the absence of CCI, as shown in the attached papers. With these results, we conclude that ACI indeed plays an important role in V2V communication with dedicated spectrum when CCI is absent.



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

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

Fig. 2.5: Effects of ACI

Chapter 3

Radio Resource Management

3.1 System Model

Assume that there are N VUEs in the network and the total bandwidth for transmission is divided into F frequency slots and total time duration into T timeslots. A time-frequency slot is also called a resource block (RB). A packet is to be transmitted within an RB and we assume that small-scale fading is constant over a single RB. A VUEs transmit power is limited by its maximum transmit power $P^{\max}$.

3.1.1 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. Similar to other wireless systems, it has been found that, the path loss coefficient in V2V links depends upon the type of environment. Path loss results have been derived for highway [5], [8], [11], rural [5], [8], urban [8], and suburban [3] environments. However, the number of measurements in those works are too low to allow general statements about the path loss behavior in these environments.

In [14], Karedal et al. presents parameterized path loss models for V2V communications based on extensive sets of measurement data collected mainly under line-of-sight conditions in four different propagation environments: highway, rural, urban, and suburban. The measurement setup is based on the setup proposed in [15] and close to the frequency 5.9 GHz. The spectrum around 5.9 GHz has been allocated for traffic safety applications in the US, Europe, and in other parts of the world by the Safety Spectrum Coalition (which represents a group of industries-high-way users, transportation technology, consumer, and safety advocates) [1]. The results show that the path loss exponent is low (i.e., $n = 1.77$), i.e., path loss 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 line-of-sight (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. In our study, we chose channel model for highway scenario and when vehicles are moving in the same direction as in a convoy.

3.1.2 Vehicular Topology

We consider a single-lane highway topology, where VUEs are enumerated from 1 (left-most) to N (right-most). However, vehicular topologies are different in different scenarios. For example, in a dense traffic scenario, VUEs 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 [16]. Moreover, adjacent VUEs maintain a minimum distance between them. Therefore, the distance between any two adjacent VUEs, d, is modeled 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. 3.1, which is given as,

$$f(d) = \begin{cases} (1/(d_{\text{avg}} - d_{\min})) \exp(-\frac{d-d_{\min}}{d_{\text{avg}}-d_{\min}}), & d \geq d_{\min} \\ 0, & \text{otherwise} \end{cases} \tag{3.1}$$

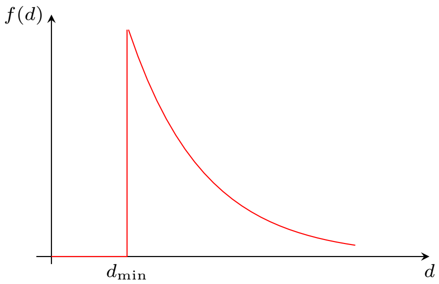


Fig. 3.1: Probability density function of distance

3.2 Requirement of V2V Broadcast Links

The radio resource management (RRM) strategies for conventional D2D systems have been extensively researched in [17–22], to name a few papers. Studied issues include how cellular users and D2D users share frequency resources and allocate its transmit power. Most of these studies have made the performance objective as the maximization of sum throughput. However, V2V safety-critical vehicular applications are not typically interested in high data rates, but have stringent requirement on latency and reliability [23]. Therefore, the power control problem formulation for conventional D2D networks might not be applicable here.

3.2.1 Latency, Reliability and SINR Requirements

This section describes how latency and reliability requirement of V2V links can be translated into achieving a certain SINR threshold.

Fig. 3.2 shows an illustration of a cumulative distribution function (CDF) of a packet delay τ. A communication system has latency requirement $\tau^{\max}$, i.e., a packet has to be successfully received within time period $\tau^{\max}$. In other words, the total number of timeslots T is limited by $\tau^{\max}$. 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^{out}. Similarly, $\Pr\{\tau = \infty\}$ is the probability of packet drop. Note that the outage probability is complementary of the reliability as shown in Fig. 3.2.

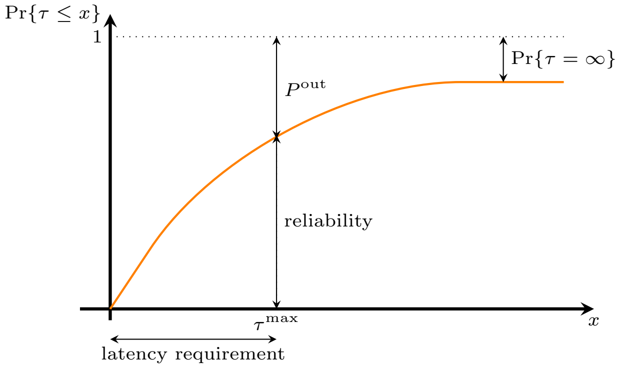


Fig. 3.2: Association between latency and reliability requirements

Let $H_{\ell,\ell'}$ be the average channel power gain from VUE ℓ to VUE ℓ'. Hence, $H_{\ell,\ell'}$ takes into account the pathloss and large-scale fading. Similarly, $h_{\ell,\ell'}$ is the variation in the instantaneous channel power gain, which takes into account the small scale fading between VUE ℓ to VUE ℓ'. In other words, $H_{\ell,\ell'}h_{\ell,\ell'}$ is the instantaneous channel power gain from VUE ℓ to VUE ℓ'. Let $f(k)$ and $f(j)$ be the frequency slots scheduled for VUE k and j respectively, and $\Lambda_{f(k),f(j)}$ is the ACIR between frequency slots $f(k)$ and $f(j)$. The instantaneous SINR $\gamma_{i,j}$ of the link from VUE i to VUE j is computed as

$$\gamma_{i,j} = \frac{P_i H_{i,j} h_{i,j}}{\sigma^2 + \sum_{\substack{k=1,\\ k\neq i}}^{N} \Lambda_{f(k),f(j)} P_k H_{k,j} h_{k,j}} \ , \tag{3.2}$$

where P_ℓ is the transmit power of VUE ℓ and σ^2 denotes the noise power.

Assume that VUE i is transmitting a packet of a certain size using ρ complex symbols to VUE j (that is, an RB consisting of ρ complex symbols). For the purpose of computing outage probability, the large scale fading and pathloss (i.e., $H_{\ell,\ell'}$ for any ℓ, ℓ') are assumed to be deterministic. However, $\gamma_{i,j}$ is a random variable due to small scale fading. We can compute the outage probability while VUE j receives the packet as

$$p_{i,j}^{\text{out}} = \Pr\left\{\rho \log_2(1+\gamma_{i,j}) < P^{\text{size}}\right\} \ , \tag{3.3}$$

where P^{size} is the packet size in bits. The reliability requirement can be interpreted from the perspective of outage probability as follows,

$$p_{i,j}^{\text{out}} \leq p_0 \tag{3.4}$$

where p_0 is the maximum tolerable outage probability.

We define average SINR $\bar{\gamma}_{i,j}$ upon ignoring small scale fading as follows,

$$\bar{\gamma}_{i,j} = \frac{P_i H_{i,j}}{\sigma^2 + \sum_{\substack{k=1,\\k\neq i}}^{N} \Lambda_{f(k),f(j)} P_k H_{k,j}} \ , \tag{3.5}$$

In [24, Lemma 1], Sun et al. proved that achieving $\bar{\gamma}_{i,j}$ above a certain threshold γ^{T} ensures that the outage probability is less than the required outage probability. In other words, outage probability constraint (3.4) can be translated into a constraint upon average SINR $\bar{\gamma}_{i,j}$ as follows,

$$\bar{\gamma}_{i,j} \geq \gamma^{\text{T}} \ , \tag{3.6}$$

where the SINR threshold γ^{T}, is assumed to be known. In general, γ^{T} depends upon several factors, including the packet size, the reliability requirement [24], and also the statistics of the random quantities in (3.3). However, specifying a value for γ^{T} is out of scope of this thesis.

3.3 Joint Scheduling and Power Control in V2V communication

In order to avoid CCI, we schedule an RB to at most one VUE. This way, we make sure that the performance is limited only by ACI and noise, not by CCI. Additionally a VUE is scheduled to at most one RB in a timeslot, since scheduling in multiple RBs in a timeslot reduces a VUEs maximum transmit power in an RB. However, a VUE can be scheduled in multiple timeslots.

Let us define the matrix $\mathbf{U} \in \{0, 1, \ldots, N\}^{F\times T}$ to represent the scheduled VUEs in an $F \times T$ RBs matrix. The value of $U_{f,t}$ (i.e., the element (f, t) of $\mathbf{U}$) is the VUE index scheduled in RB (f, t), i.e., in frequency slot f and in timeslot t. If $U_{f,t} = 0$, then no VUE is scheduled in the RB (f, t). Fundamentally, scheduling is the process of allocating VUEs in available RBs, which is equivalent to populating the matrix $\mathbf{U}$ with appropriate VUE indices, as illustrated in Fig. 3.3. Similarly, we define $\mathbf{P} \in [0, P^{\max}]^{N\times T}$ as the matrix containing power values of all VUEs in all timeslots. That is, $P_{i,t}$ is the power value of VUE i during timeslot t, if scheduled in timeslot t.

Following the constraint (3.6), let us define binary variables $X_{i,j}$ $\forall\, i,j = 1,...,N$, to indicate if the link from VUE i to VUE j is successful during any of the timeslots, i.e.,

$$X_{i,j} \triangleq \begin{cases} 1, & \bar{\gamma}_{i,j} \geq \gamma^{\mathrm{T}} \quad \text{for any timeslot } t,\ i \neq j \\ 0, & \text{otherwise} \end{cases} \tag{3.7}$$

In a typical safety critical vehicular communication scenario, each VUE want to broadcast a packet to all other VUEs. Since we would like to ensure that the SINR of every link is sufficiently large to deliver the packet with required outage probability, our goal is to maximize the total number of links achieving this SINR constraint. Therefore, we can state the joint scheduling and power control problem as follows,

$$\max_{\mathbf{U},\mathbf{P}} \sum_{i=1}^{N} \sum_{\substack{i=1 \\ i \neq j}}^{N} X_{i,j} \tag{3.8}$$

$$\text{subject to:} \quad \mathbf{U} \in \{0,1,\ldots,N\}^{F\times T}, \quad \mathbf{P} \in [0, P^{\max}]^{N\times T}$$

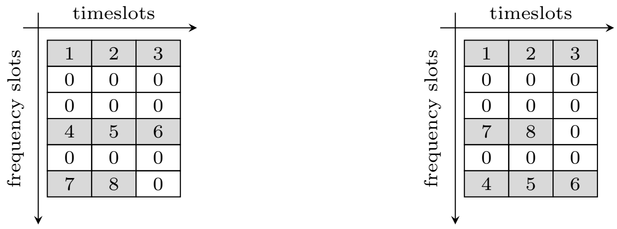
However, the above problem is a non-convex mixed integer quadratically constrained programming (MIQCP) problem, which is NP-hard as shown in [Paper B]. Therefore, as described in the following sections, we go for splitting the above problem into two subproblems 1) schedule VUEs with a fixed power, 2) allocate power to VUEs for a fixed schedule.

3.4 Scheduling in V2V Communication

In this section we solve the scheduling problem without considering any power control, and in the next section we solve the power control problem. For the scheduling problem, we set the transmit power of all VUEs to the maximum power $P^{\max}$, i.e., $P_{i,t} = P^{\max}$ $\forall\, i,t$. In an ACI limited network, a link performance also depends upon the scheduling of the other VUEs too.

3.4.1 Optimal Scheduling

Note that the scheduling alone problem is a subproblem of joint scheduling and power control problem formulation discussed in Section 3.3. Therefore, we can derive the problem formulation for scheduling from joint problem formulation by fixing the power values. The derived problem formulation is a Boolean linear programming (BLP) problem as shown in [Paper B]. A near optimal solution can be found by using Gurobi solver [25], which internally uses the branch and bound method. However, due to the high computational complexity of the problem, 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.



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

Fig. 3.3: Scheduling of VUE indices in RBs when $N = 8$, $F = 6$, and $T = 3$

3.4.2 Block Interleaver Scheduler

Block interleaver scheduler (BIS) is a simple naive scheduler which requires only the position indices of the VUEs. 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; we can schedule each VUE 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 the frequency slots as maximally spread among the available frequency slots, i.e., the minimum gap between any two scheduled frequency slots is maximized. Besides that, we permute the chosen frequency slots using a block interleaver with width w [26, section 5.1.4.2.1]. An example of scheduling for various values of w, is shown in Fig. 3.3. BIS can be used as a baseline scheduler when trying to find better scheduling algorithms.

3.4.3 Heuristic Scheduler

The approach taken here is to loop through all RBs and schedule either a real or dummy VUE to each RB. The scheduling decision is taken in a greedy fashion. That is, we strive to schedule the best possible VUE to the RB under the assumption that the schedule for all other RBs are fixed. The resulting schedule can schedule a VUE, zero, one, or multiple times, as opposed to BIS, which schedules all real VUEs at most once.

The heuristic algorithm is executed in two steps. In the first step, we determine the RB scheduling order, and in the second step, we use this computed order to visit the RBs and schedule VUEs sequentially. We compute scheduling order 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 total number of successful links, under the assumption that scheduling of all other RBs remains unchanged. More details can be found in [Paper A, B].

3.5 Power Control in V2V Broadcast Communication

Power control in V2V broadcast communication is done with two major goals in mind; 1) increase the total number of successful links 2) reduce the total power consumption. However our primary goal 1) is more important than the secondary goal 2), hence power reduction is generally preferred only when it does not affect the total number of successful links.

3.5.1 Optimal Power Control

Observe that in order to get the problem formulation for optimal scheduling in Section 3.4.1, we fixed power values of all VUEs to $P^{\max}$, thereby converting the nonconvex MIQCP problem into a BLP 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 $\mathbf{U}$ in (3.8). The resulting problem is a mixed integer linear programming (MILP) problem with VUEs power values as optimization variables. However, the above problem is NP hard as proved in [Paper A, Lemma 1]. For large problems it might therefore be necessary to use a heuristic algorithm with reduced complexity.

3.5.2 Heuristic Power Control Algorithm

For notational convenience, we define the set of all the intended links as

$$\mathcal{A} = \{(i, j) : 1 \leq i, j \leq N, i \neq j\}. \tag{3.9}$$

Given a set of candidate links $\mathcal{C} \subseteq \mathcal{A}$, it is easy to verify if there exists any set of power values to make all links in $\mathcal{C}$ to be successful. This is done by checking if a feasible solution for power values exists for the resulting linear programming (LP) problem [Paper A]. So our task is to find the set of links $\mathcal{C} \subseteq \mathcal{A}$ with maximum cardinality which can be made to be successful links with appropriate power values. We compute $\mathcal{C}$ in an iterative way, in which each iteration involves addition/removal of links from the set $\mathcal{C}$. That is, when all the links in $\mathcal{C}$ can achieve SINR threshold, then $\mathcal{C}$ is augmented by adding a strong link from $\mathcal{A} \setminus \mathcal{C}$. Similarly, when at least one link in $\mathcal{C}$ cannot achieve SINR threshold, a weak link is removed from $\mathcal{C}$. Some links may not be feasible at all irrespective of power control, hence we remove those links from the set $\mathcal{A}$ over subsequent iterations. Finding strong and weak links is a tricky problem, for which the algorithms are described in [Paper A].

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

Chapter 4

Contributions and Conclusions

4.1 Contributions

This thesis studies the impact of ACI on V2V broadcast communication systems, and way to mitigate it by using scheduling and power control techniques. First the ACI model for a typical V2V communication using SCFDMA is generated by simulations. 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 [Paper A].

In a typical V2V communication, each VUE wants to broadcast a safety critical message to all other VUEs, therefore, our objective is to maximize the total number of successful links. In [24, Lemma 1], Sun et al. proved that achieving an average SINR above a certain threshold ensures that the outage probability is less than the required outage probability. With this result in mind, the scheduling and power control problem is formulated in order to maximize the total number of successful links as an MIQCP 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 MILP 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 MILP problem.

However, due to the NP hardness of the above problem formulation, a heuristic scheduling algorithm with polynomial time complexity is proposed. Additionally, a simple BIS scheduler is designed to get baseline results. The simulation results in [Paper B,C] show promising performance of the heuristic algorithm, compared to the BIS and near-optimal scheduler.

We also propose a heuristic power control algorithm with less computational complexity [Paper B]. We then applied the power control algorithms, on top of the above mentioned scheduling algorithms. The simulation results show that the proposed power control algorithm further improves the performance compared to equal power.

4.2 Conclusions

The conclusions from this thesis can be summarized as follows,

- Although ACI is negligible compared to CCI, the performance is mainly limited by ACI in the absence of CCI, i.e., when VUEs are multiplexed in frequency. However, we can improve the performance with effective scheduling and power control techniques.
- To find a joint schedule and power allocation to maximize the performance can be stated as a nonconvex MIQCP problem. Scheduling for a fixed power values, can be stated as a BLP, and power control for a fixed schedule can be stated as an MILP. However, all the above problem formulations are NP-hard.
- The proposed scheduling and power control algorithms in [Paper A, B] provide significant performance improvement compared to naive scheduling and power control at a low computational complexity. Additionally, the proposed algorithms perform close to the near-optimum solution for smaller instances of the problem.
- In general, scheduling with fixed and equal transmit powers is more effective in improving performance than subsequent power control.

4.3 Future Works

Future work is summarized as follows,

- Formulate an RB allocation and power control scheme that achieve better tradeoffs between performance and complexity than the present algorithms.
- Formulate a more general optimization problem statement which allows sharing of RBs among multiple VUEs, i.e., relax the constraint that VUEs are scheduled in non-overlapping RBs
- Do a thorough mathematical analysis in order to find out a closed form expression for maximum and average number of achievable successful links.

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