CHALMERS

Resource Allocation and Power Control for Device-to-Device (D2D) Communication

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Thesis code: EX001/2014

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2013

Master's Thesis 2013

MASTER'S THESIS 2013

Resource Allocation and Power Control for Device-to-Device (D2D) Communication

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ACKNOWLEDGEMENT

Sincere thanks to our examiner Professor Erik Ström for his proficient guidance, his inspiring motivation, and his support from even before the thesis start, till the end. We would like to acknowledge the feedback and help by our supervisor Wanlu Sun for her informative discussions about the thesis. Our collective salutations would go to our parents for their prayers and financial support, and all those researchers whose transfer of knowledge helped us in our thesis work.

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NOTATIONS

Terminology:

3GPP	Third Generation Partnership Project
ALPF	Augmented Lagrangian Penalty Function
ARIB	Association of Radio Industries and Businesses (Japan)
ATIS	Alliance for Telecommunications Industry Solutions (USA)
BS	Base Station
CCSA	China Communications Standards Association (China)
D2D	Device-to-Device
DVB	Digital Video Broadcasting
ETSI	European Telecommunications Standards Institute (Europe)
FDM	Frequency Division Multiplexing
GSM	Global System for Mobile Communications
HD	High Definition
IMT	International Mobile Telecommunication
IMT-A	IMT Advanced
ITU-R	International Telecommunication Union- Radio communication Sector
IRC	Interference Rejection Combination
ISI	Inter-Symbol Interference
JRP	Joint RB Allocation and Power control
LOS	Line-of-Sight
LP	Linear Programming
LTE	Long Term Evolution
MCM	Multi-Carrier Modulation
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Squared Error
MRC	Maximum Ratio Combination
OFDM	Orthogonal Frequency Division Multiplexing
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service

RB	Resource Block
RLC	Radio-Link-Control
SIMO	Single Input Multiple Output
SINR	Signal to Interference and Noise Ratio
SRP	Separate RB allocation and Power control
TSG	Technical Specification Group
TTA	Telecommunications Technology Association (Korea)
TTC	Telecommunication Technology Committee (Japan)
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UTRA	UMTS Terrestrial Radio Access

ABSTRACT

Recently a tremendous increase has occurred in the number of mobile users as well as in their applications. Due to bandwidth limitation, it is vital to utilize the techniques which can achieve high spectral efficiency. Device-to-Device (D2D) communication, as an efficient way to improve the spectral efficiency, has been proposed to enable devices to communicate directly to each other without the help of Base Station (BS). D2D communication is an effective way to increase spectral efficiency in underlying Orthogonal Frequency Division Multiplexing (OFDM) based network.
Since the D2D link reuses the cellular resource blocks (RBs), the interference is one of the critical issues. In this thesis we focus on the interference management, and have proposed two schemes for resource allocation and power control. Our aim is to minimize total power consumption with certain rate targets on D2D links and cellular users, respectively. Firstly we derive a joint resource allocation and power control (JRP) scheme by using dual decomposition theory. Then we propose a separate resource allocation and power control (SRP) scheme. In summary, the JRP scheme is more power efficient and more likely to be feasible, but its complexity is much higher compared to the SRP scheme. Moreover, we derive a lower bound for the minimization problem and compare it with the proposed schemes.

Keywords: Wireless networks, Device-to-Device (D2D) communication, OFDM network, dual decomposition.

CHAPTER 01

INTRODUCTION

1.1 Introduction

There has been a very fast evolution in the mobile technologies from previous few decades, starting from analog mobile radio system implemented in 80s as the 1st Generation (1G) to current 4th generation (4G). The primary goal for evolution of mobile system is to improve the spectral efficiency, reduce the power consumption and make the system more cost effective. In modern research, a lot of work has been done on the development of Third-Generation Partnership Project (3GPP) Long term Evolution (LTE) for higher system capacity and higher data rate. LTE-Advance incorporates many dimensions of enhancement including multi radio channels, advanced antenna techniques (Multiple Input Multiple Output (MIMO) or Single Input Multiple Output (SIMO)) [1], and pre-coding etc. [2].

In cellular network, the communication between cellular users is relayed through the Base Station (BS), even if the source and destination are closer to each other than to the BS. The main advantage of this kind of operation is the relatively easy resource and interference control. But the drawback is inefficient resource utilization.

In the past decade, a tremendous increase has occurred in cellular users along with the applications of different kind of multimedia services like mobile television, video phone and online High Definition (HD) graphics games etc., hence there is an increasing requirement for higher data rate transmission. But due to congestion of spectrum below 5GHz, the spectrum which is allocated to mobile communication must be utilized efficiently in order to satisfy the demands for high spectral efficiency. 3GPP have been submitted to the International Telecommunications Union (ITU) to introduce new technology components for LTE to meet International Mobile Telecommunications Advanced (IMT-A) requirements. Among which Device-to-Device (D2D) communication is a highly fascinated technique for improving spectral efficiency [2], [3], [4], [5].

D2D Communication using cellular network spectrum is an efficient way to handle the local traffic in a cost efficient manner. A D2D link is a direct connection from D2D transmitter ($D2D_{Tx}$) to D2D receiver ($D2D_{Rx}$) in spectrum managed by cellular network. There are several gains related to D2D communication underlying a cellular infrastructure [2], namely proximity gain of user equipment that allows high bit rate, low delays and low power consumptions [6], [7], the reuse gain that concedes radio resources to be utilized by cellular and D2D links simultaneously [8], and finally hop gain that refers to applying an individual link in the D2D mode rather than using an uplink and a downlink resource when communicating via the BS in the cellular mode.

In Figure 1.1, a mixed cellular – D2D communication is shown, the round mobile shows cellular users that communicate with each other through the BS. The blue mobile pair shows the D2D link that directly communicates with each other. Since the D2D link is reusing the cellular spectrum (dedicated spectrum in some cases), it encounters some interference from the cellular users, on the other hand, it also induces interference to BS (in case of reusing uplink time-frequency slot) and cellular users (in case of reusing downlink time-frequency slot). The green line indicates the communication between one D2D link, whereas the red lines show the interference from cellular users to $D2D_{Rx}$. The interference is a damaging factor for both cellular and D2D communication and leads to low Quality of Service (QoS) and high packet loss rate. To solve this issue many possible remedies have been proposed on interference management, for instance power control [4, 9, 10], proper resource allocation [11], various interference avoidance MIMO techniques [1], proper mode selection and advanced coding schemes [6, 8].

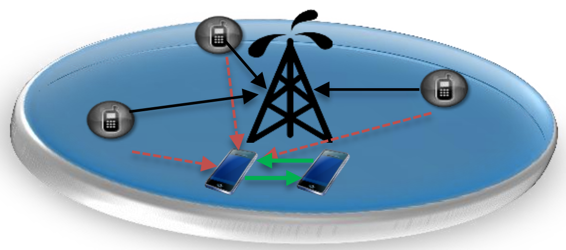

Figure 1.1: Mixed cellular-D2D environment

In our thesis we have focused on the interference management issue. We have considered cellular uplink in which the D2D link reuses the resource blocks (RBs) allocated to cellular users by taking into account both the inter-cell and intra-cell interference. Our novelty is to minimize total power under D2D and cellular rate constraints. We have proposed two schemes for RBs allocation and power control. JRP scheme jointly considers RB allocation and power control in dual domain by using a sub-gradient method, it not only gives good performance in power efficiency and infeasibility, but also most importantly offers a lower bound of optimal solution, however this scheme has high complexity. Alternative to the JRP scheme we have proposed the SRP scheme, which separately manages resource allocation and power control with low complexity, however, its performance is worse than the JRP scheme.

1.2 Previous work outline

Since interference is a critical issue of mixed cellular and D2D environment, there is a wide research going on interference management.

- Norbert Reider and Gabor Fodor have worked on a distributed power control algorithm for D2D communication. They have used distributed power control algorithm, which has two parts, first one is to minimize total power consumption with fixed Signal to Interference and Noise Ratio (SINR) target. The second is power allocation part that sets the power level and power loading matrices over MIMO streams subject to sum rate and single user peak power constraints [6].
- Runhua Chen and Robert W. Heath Jr. have worked on multi-dimensional power control problem for an uplink cellular MIMO spatial multiplexing system [7]. Since in MIMO there is co-ordinations between receiving antenna and also there

is a nonlinear dependence between interference and eigen spaces of channel matrices, they have proposed two schemes for the solution of the mentioned problem,

  - ✓ power to all transmitting antennas is allocated equally in the first scheme;
  - ✓ power to all transmitting antennas is allocated adaptively in the second scheme.

- Chia-Hao Yu, Klaus Doppler has also done a good degree of work on power optimization for D2D communication [10]. They have considered a single cell scenario in which the interference between the two links is coordinated in such a way that increase the sum rate without overwhelming the cellular service.
- Studies in [10] focus on several uplink cases reusing uplink resource with proportional fair scheme, the goal is to minimize inter/intra cell interference while maximizing the total cell rate with single power constraint and minimum SINR.
- [9] proposes an algorithm where the spectrum resources are grouped in several RBs, the D2D link keeps on scanning each RB and selects the one that satisfies its target rate constraint, moreover the proposed algorithm has also been compared with a reference RB allocation scheme [6, 11] in which each D2D link shares RB with one cellular user.
- In [10] power and RB allocation for D2D communication are jointly considered in order to optimize sum throughput of D2D links, guaranteeing QoS of cellular users with Radio-Link-Control (RLC) constraint [11].

CHAPTER 02
BACKGROUND

2.1 Background of LTE/LTE-Advanced

The technological development can be distinguished by the generation of mobile communication [14]. The first generation 1G was an analog mobile radio system introduced in 80s, followed by 2G which was the first digital mobile system. Then 3G came into being, which was the first mobile system capable of handling broadband data. The LTE started from first release called Release 8 being labled as 3.9G (pre-4G or beyond 3G). The work by 3GPP to define a 4G standard started in Release 9 with the study phase for LTE-Advanced.

2.2 Third Generation Partnership Project (3GPP)

3GPP was formed in 1998, it is a standardizing body that sets the standards for mobile communication like LTE/LTE-Advanced, 3G Universal Mobile Telecommunications System (UMTS), Universal Terrestrial Radio Access (UTRA) and 2G Global System for Mobile communications (GSM) [15].

The organizational partners of 3GPP are ETSI, ARIB, TTA, TTC, ATIS and CCSA. (See Page V for the abbreviations). These organizational partners are from Europe, North-America and Asia. They discover the general policies and strategies for 3GPP. They are obliged to identify regional requirements. The organizational partners of 3GPP are responsible of

- ✓ approval and maintenance of 3GPP scope;
- ✓ maintenance of partnership project description;
- ✓ to take decision either to create or discontinue technical specification group (TSG) and commend their terms of reference and scope;
- ✓ allocating financial funds or man power to project co-ordination group;
- ✓ acting as a body of appeal on procedural matters referred to them;

3GPP takes care of the boundaries and limitations of ITU, and is obligated to submit its work being carried out to ITU. 3GPP documents are divided into releases, where each release is enhanced by some sets of features compared to the previous release. Moreover, the TSG is responsible to define the features in work items.

2.3 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is used to transmit information by using a large number of parallel narrow band subcarriers instead of single wide band carrier. OFDM is one of the most widespread digital modulation techniques used in various communication systems [16]. The ability to work with notable robustness to radio channel impairments and providing high data rate have made OFDM as one of the most used techniques. Some wireless standards like WiMaX, IEEE 802.11a, LTE, DVB have adopted OFDM as the modulation scheme [17]. OFDM is an efficient Multi-Carrier Modulation (MCM) technique which uses orthogonal subcarriers (as overall transmission bandwidth is

sliced into subcarriers) for modulation, thus it requires less bandwidth than conventional Frequency Division Multiplexing (FDM).
To analytically express the OFDM signal, assume the time interval $mT_u \leq t < (m+1)T_u$, we have

$$x(t) = \sum_{k=0}^{N_c-1} x_k(t) \tag{2.1}$$

$$= \sum_{k=0}^{N_c-1} a_k^{(m)} e^{j2\pi k\Delta f t}, \tag{2.2}$$

where $x_k(t)$ is the modulated subcarrier with frequency $f_k = k \cdot \Delta f$. Since each subcarrier is applied with the modulation symbol (e.g. QPSK, 16QAM or 64QAM) during a particular OFDM symbol interval, and this complex modulated symbol is expressed by $a_k^{(m)}$ [18]. The number of subcarriers can range from few to thousands, where each subcarrier is spaced by some value from the other. The space between the subcarriers depends on the type of environment in which the system is deployed. A typical OFDM modulation is depicted in Figure 2.1 [19].

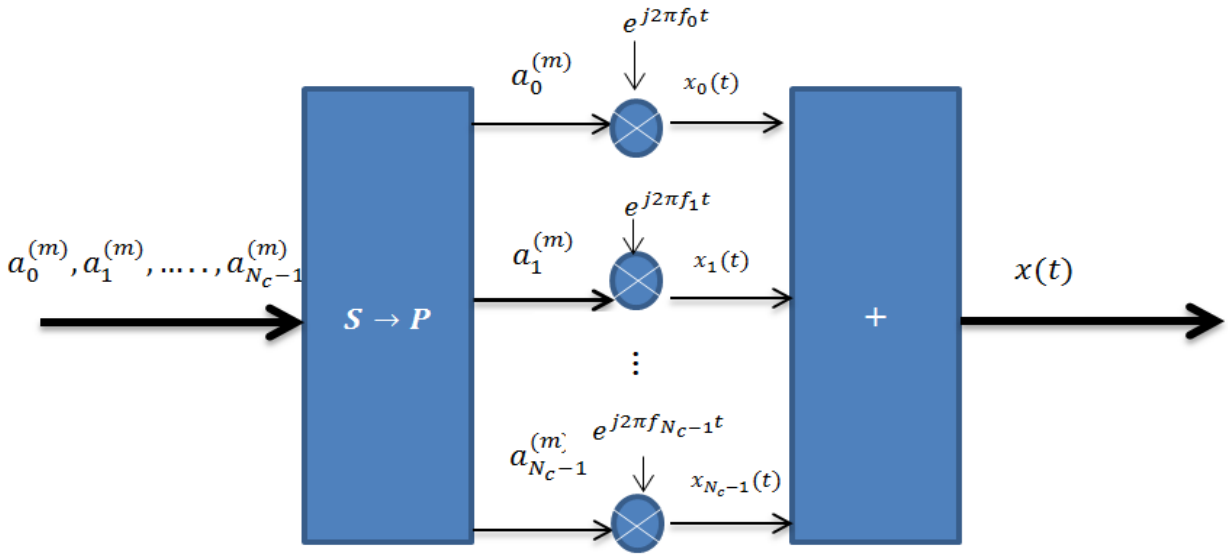

Figure 2.1: Typical OFDM modulation

2.4 Resource block (RB)

In OFDM the RB is a time-frequency grid, where each unit in row (frequency) represents one OFDM subcarrier whereas each unit in column (time) corresponds to one OFDM symbol, as shown in Figure 2.2.

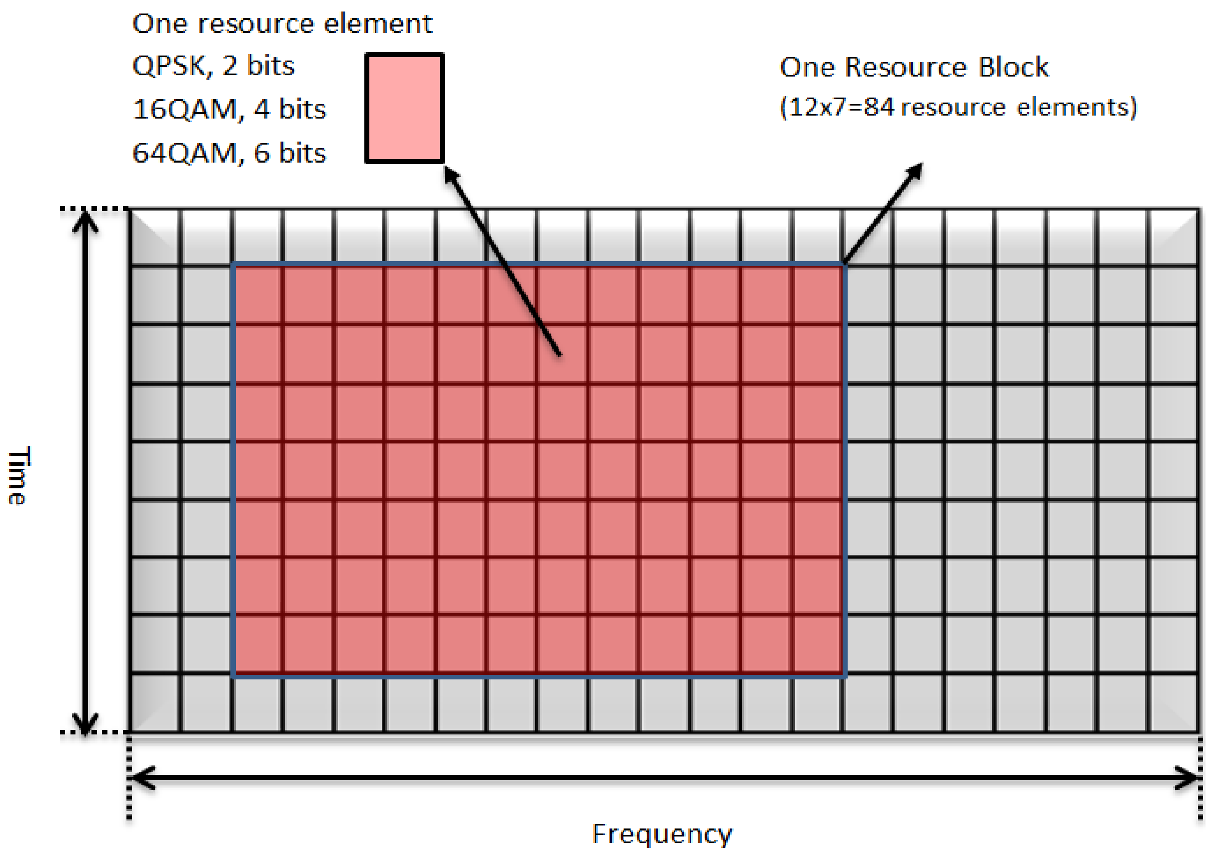

Figure 2.2: 12x7 RB [1]

As in Figure 2.2, one RB contains 12 consecutive subcarriers and 8 consecutive OFDM symbols according to the LTE standard from 3GPP Release 8.

2.5 Channel model

The wireless channels are time variant and therefore frequent and reliable channel estimation is necessary. In OFDM systems, pilot tones are generally used to estimate the channel [20]. In this process, some known pilot symbols are inserted at fixed positions of the OFDM signals and transmitted together with other data symbols. At the receiver, the channel information can be acquired by using the received pilot symbols. For the channel estimation, the channel should stay stationary for at least one OFDM symbol. However, since the pilot symbols are non-informative, they reduce the throughput of the system in terms of spectral efficiency and power utilization. In mobile communication, the factors that strongly influence the signal propagation are [21]

- reflection,
- diffraction,
- scattering.

[1] Inspired by the RB figure in http://shishireahmed.blogspot.it/2012/09/long-term-evolution-lte.html, we draw this figure.

When a smooth surface (having dimension larger than the wavelength of RF signal) is being struck by RF signal, reflection takes place.
When a radio path between the receiver and transmitter is hindered by a dense body (having dimension larger than the wavelength of RF signal), some secondary waves are formed behind the obstructed body, this phenomena is called diffraction.
When a large rough surface having a dimension equal to or less than the wavelength of RF signal, it causes the signal reflected randomly in all directions, this phenomena is called scattering.
In our thesis we have considered the following channel impairments

- path loss,
- large scale fading,
- small scale fading.

2.5.1 Path loss

When signal is propagating through space, its power is attenuated due to path loss impairment. Path loss is mainly influenced by distance from transmitter to receiver and environment that signal propagates in, the environment includes propagation medium (moist or dry air) and location of antennas. Therefore, path loss (PL) can be statistically estimated as a function of distance (dis), shown below

$$PL(dis)\ \alpha\ \left(\frac{dis}{dis_0}\right)^n,$$

where dis_0 is a reference distance ($dis_0 \leq dis$) and n is environment factor. This expression can be alternatively manifested in term of decibels as follow

$$PL(dis)_{dB} = PL(dis_0)_{dB} + 10n\log\left(\frac{dis}{dis_0}\right). \qquad (2.3)$$

2.5.2 Large scale fading

Large scale fading is also referred as shadow fading, which is an attenuation of signal power. When an obstacle appears between the wireless transmitter and receiver, the signal wave might be shadowed or blocked by the obstacle. The main cause of shadow fading is terrain contours like hills, buildings or forests etc. between the receiver and transmitter. As this fading severely influences signal, it is very important to take into account the losses, which can be described in term of a log-normal distribution [22].

2.5.3 Small scale fading

Small scale fading is a property of radio propagation due to the presence of scattering and reflection phenomena, which cause multiple versions of transmitted signal reaching the receiver with distorted phase, angle and amplitude. Rayleigh fading is an effect of small scale fading, if there are a large number of reflective propagating paths and no propagation path for the line-of-sight (LOS), the envelope of the received signal would be described statistically in term of Rayleigh PDF. However when the LOS or nonfading propagating path is dominant, small scale fading is described by Ricean PDF [23]. The nonfading or LOS propagating path is called specular component and Rayleigh faded components is sometimes referred to scattered, diffuse or random component. As the amplitude of specular component approaches to zero, the Ricean PDF approaches to Rayleigh PDF [24]. If r is the received signal's envelope amplitude and the pre-detected average power of the multipath signal is denoted by $2\sigma^2$, the PDF of receiving signal can be expressed as

$$P(r)=\begin{cases} \frac{r}{\sigma^2}e^{-\frac{r^2}{2\sigma^2}} & \text{for } r \geq 0 \\ 0 & \text{otherwise.} \end{cases}$$

CHAPTER 03
OPTIMIZATION PROBLEM

3.1 Optimization

Optimization is a problem of making the best choice among a set of candidate choices. An optimization problem can be written as

$$\begin{aligned} &\text{minimize} && f_{\text{obj}}(\boldsymbol{x}), && \\ &\text{subject to} && f_i(\boldsymbol{x}) \le 0, && i = 1, \dots\dots, k, \\ & && h_j(\boldsymbol{x}) = 0, && j = 1, \dots\dots, l, \end{aligned} \tag{3.1}$$

where the vector $\mathbf{x} = [x_1, \dots, x_n]$ $(\boldsymbol{x} \in R^n)$ is the variable of the optimization problem, $f_{\text{obj}}(\boldsymbol{x}) \colon R^n \to R$ is the objective function, whose value represents the cost of choosing variable $\boldsymbol{x}$. $f_i(\boldsymbol{x}) \le 0$ $(f_i \colon R^n \to R, \text{for } i = 1, 2, \dots, k)$ is an inequality constraint while $h_j(\boldsymbol{x}) = 0$ $(h_j \colon R^n \to R, \text{for } i = 1, 2, \dots, l)$ is an equality constraint, they represent limits on variable $\boldsymbol{x}$. The variable $\boldsymbol{x}$ needs to be determined in order to minimize the given objective function subject to the constraints.

The variable set in the optimization problem is denoted by D, which is called the domain of the optimization problem. For the given optimization problem (3.1), the set D is expressed as

$$D = \left(\cap_{i=1}^{k} \operatorname{dom} f_i\right) \cap \left(\cap_{j=1}^{l} \operatorname{dom} h_j\right).$$

$\boldsymbol{x} \in D$ is a feasible point if it satisfies all the constraints. The optimization problem (3.1) is feasible when there is at least one feasible point, otherwise infeasible [25]. We define the optimal value P_{opt} of the objective function equals $+\infty$, if the problem is infeasible. If the problem is unbounded below, such as there are feasible points x_p with $f_{\text{obj}}(x_p) \to -\infty$ as $p \to \infty$, we have $P_{\text{opt}} = -\infty$ [26].

3.2 Duality theory

In optimization theory, the solution of the dual problem provides a lower bound of the optimal solution of the primal problem (3.1). In convex optimization problems, the gap between the optimal solutions of dual and primal problem is zero, thus the optimal solution of primal problem can be given by the dual problem. However, in non-convex cases, the optimal solutions of the primal and dual problems are usually not equal, and their difference is called the duality gap.

3.2.1 The Lagrange dual function

Consider the problem (3.1) is non-convex and its domain D is non-empty. In Lagrangian duality, the objective function of (3.1) is augmented while taking into account a weighted sum of its constraint functions. The Lagrangian function $L \colon R^n \times R^k \times R^l \to R$ corresponds to the primal problem (3.1) can be defined as

$$L(\boldsymbol{x},\boldsymbol{\lambda},\boldsymbol{\beta}) = f_{\text{obj}}(\boldsymbol{x}) + \sum_{i=1}^{k} \lambda_i\, f_i(\boldsymbol{x}) + \sum_{j=1}^{l} \beta_j\, h_j(\boldsymbol{x}), \qquad (3.2)$$

where domain of L is $D \times R^k \times R^l$. λ_i and β_j are the associated Lagrangian multipliers with the ith inequality constraint $f_i(x) \le 0$, and the jth equality constraint $h_j(x) = 0$, respectively. The vectors $\boldsymbol{\lambda} = [\lambda_1, \dots, \lambda_k]$ and $\boldsymbol{\beta} = [\beta_1, \dots, \beta_l]$ associated with the problem (3.1) are known as Lagrangian multiplier vectors or dual variables.
The Lagrange dual function $g: R^k \times R^l \to R$ can be defined as the minimum value of Lagrangian function (3.2) over all $\boldsymbol{x}$ values from set D, i.e.

$$g(\boldsymbol{\lambda},\boldsymbol{\beta}) = \inf_{x\in D} L(\boldsymbol{x},\boldsymbol{\lambda},\boldsymbol{\beta}) = \inf_{x\in D} \left(f_{\text{obj}}(\boldsymbol{x}) + \sum_{i=1}^{k} \lambda_i\, f_i(\boldsymbol{x}) + \sum_{j=1}^{l} \beta_j\, h_j(\boldsymbol{x}) \right). \qquad (3.3)$$

This dual function value goes to $-\infty$, when the Lagrangian problem is unbounded in set D. Finally, the Lagrange dual problem is formulated as

$$\begin{aligned} &\text{maximize} \quad g(\boldsymbol{\lambda},\boldsymbol{\beta}), \\ &\text{subject to} \quad \boldsymbol{\lambda} \ge 0,\ \boldsymbol{\beta} \ge 0, \end{aligned} \qquad (3.4)$$

where $g(\boldsymbol{\lambda},\boldsymbol{\beta})$ is a concave function respect to $\boldsymbol{\lambda}$ and $\boldsymbol{\beta}$. Therefore, the dual problem is always a convex optimization problem. Dual problem can be solved by using the agreement constraint that constitutes Lagrange multipliers and an iterative algorithm like subgradient algorithm.

3.2.3 Lower bound of optimal solution

Suppose a point $\tilde{\boldsymbol{x}}$ is feasible for the problem (3.1), then, for $\boldsymbol{\lambda} \succeq 0$, we have

$$\sum_{i=1}^{k} \lambda_i\, f_i(\tilde{\boldsymbol{x}}) + \sum_{j=1}^{l} \beta_j\, h_j(\tilde{\boldsymbol{x}}) \le 0, \qquad (3.5)$$

Since we have $f_i(\tilde{\boldsymbol{x}}) \le 0$ and $h_j(\tilde{\boldsymbol{x}}) = 0$, $\sum_{i=1}^{k} \lambda_i\, f_i(\tilde{\boldsymbol{x}})$ is negative and $\sum_{j=1}^{l} \beta_j\, h_j(\tilde{\boldsymbol{x}})$ is zero. Therefore

$$L(\tilde{\boldsymbol{x}},\boldsymbol{\lambda},\boldsymbol{\beta}) = f_{\text{obj}}(\tilde{\boldsymbol{x}}) + \sum_{i=1}^{k} \lambda_i\, f_i(\tilde{\boldsymbol{x}}) + \sum_{j=1}^{l} \beta_j\, h_j(\tilde{\boldsymbol{x}}) \le f_{\text{obj}}(\tilde{\boldsymbol{x}}).$$

As a result,

$$g(\boldsymbol{\lambda},\boldsymbol{\beta}) = \inf_{x\in D} L(\boldsymbol{x},\boldsymbol{\lambda},\boldsymbol{\beta}) \le L(\tilde{\boldsymbol{x}},\boldsymbol{\lambda},\boldsymbol{\beta}) \le f_{\text{obj}}(\tilde{\boldsymbol{x}}). \qquad (3.6)$$

As cleared from (3.6), for each feasible point $\tilde{\boldsymbol{x}}$ we have $g(\boldsymbol{\lambda},\boldsymbol{\beta}) \le f_{\text{obj}}(\tilde{\boldsymbol{x}})$, which means that the optimum of (3.4) is a lower bound of the primal problem (3.1). When $g(\boldsymbol{\lambda},\boldsymbol{\beta}) = -\infty$, problem (3.1) is unbounded. When $g(\boldsymbol{\lambda},\boldsymbol{\beta}) = \infty$, problem (3.1) is infeasible.

3.3 Dual decomposition method

Generally, by dividing an optimization problem into subproblems we can efficiently solve these subproblems in parallel with low complexity. Dual decomposition is a method to divide the original optimization problem into two or more subproblems, together with linear constraints that enforce some conceivings of agreement between solutions to different problems. Moreover, this method is typically efficient for the problem with coupling constraints [27].

A standard problem with a coupling constraint is formulated as

$$\begin{aligned} &\text{minimize} \quad f_1(\boldsymbol{x_1}) + f_2(\boldsymbol{x_2}), \\ &\text{subject to} \quad \boldsymbol{x_1} \in C_1,\ \boldsymbol{x_2} \in C_2, \\ &\qquad\qquad\quad h_1(\boldsymbol{x_1}) + h_2(\boldsymbol{x_2}) \leq 0, \end{aligned} \tag{3.7}$$

where the coupling constraint $h_1(\boldsymbol{x_1}) + h_2(\boldsymbol{x_2}) \leq 0$ can be interpreted as a limit on resource shared between two subproblems, $\boldsymbol{x_1}$ and $\boldsymbol{x_2}$ are local variable vectors.

Problem (3.7) associated Lagrangian expression is

$$\begin{aligned} L(\boldsymbol{x_1}, \boldsymbol{x_2}, \lambda) &= f_1(\boldsymbol{x_1}) + f_2(\boldsymbol{x_2}) + \lambda\big(h_1(\boldsymbol{x_1}) + h_2(\boldsymbol{x_2})\big) \\ &= \big(f_1(\boldsymbol{x_1}) + \lambda h_1(\boldsymbol{x_1})\big) + \big(f_2(\boldsymbol{x_2}) + \lambda h_2(\boldsymbol{x_2})\big), \end{aligned} \tag{3.8}$$

where λ is Lagrangian multiplier. Since (3.8) is separable, we divide it into two subproblems

$$\begin{aligned} &\text{minimize} \quad f_1(\boldsymbol{x_1}) + \lambda h_1(\boldsymbol{x_1})\,, \\ &\text{subject to} \quad \boldsymbol{x_1} \in C_1, \end{aligned} \tag{3.9}$$

and

$$\begin{aligned} &\text{minimize} \quad f_2(\boldsymbol{x_2}) + \lambda h_2(\boldsymbol{x_2})\,, \\ &\text{subject to} \quad \boldsymbol{x_2} \in C_2. \end{aligned} \tag{3.10}$$

Hence, the subproblem (3.9) and (3.10) associated Lagrangian dual functions are

$$g_1(\lambda) = \inf_{\boldsymbol{x_1} \in C_1} \big(f_1(\boldsymbol{x_1}) + \lambda h_1(\boldsymbol{x_1})\big), \tag{3.11}$$

$$g_2(\lambda) = \inf_{\boldsymbol{x_2} \in C_2} \big(f_2(\boldsymbol{x_2}) + \lambda h_2(\boldsymbol{x_2})\big). \tag{3.12}$$

Finally we determine the dual function of problem (3.7)

$$g(\lambda) = g_1(\lambda) + g_2(\lambda). \tag{3.13}$$

The dual problem with variable λ and can now be solved by any appropriate optimization technique. One possible way to update λ is using sub-gradient method, which can be shown as

$$\lambda^{q+1} = \max\big(0, \lambda^q + \alpha\big(h_1(\boldsymbol{x_1}) + h_2(\boldsymbol{x_2})\big)\big), \tag{3.14}$$

where λ^{q+1} is the updated value while λ^q is the previous value, and α is the step size.

CHAPTER 04

SYSTEM MODEL AND PROBLEM FORMULATION

In our model, we consider an uplink OFDM system with two cells (as shown in Figure 4.1). Each cell has a BS serving N cellular users. One cell contains M D2D links, which reuse the resource spectrum allocated to the N cellular users of the corresponding cell ($M \leq N$). Besides, the N cellular users from the neighbouring cell also reuse the same resource spectrum. Therefore, D2D links are effected by both intra-cell interference (red dotted line in Figure 4.1) from cellular users in its own cell and inter-cell interference (black dotted line in Figure 4.1) caused by cellular users from the neighbouring cell.

The entire resource is divided into N RBs, and this number is equal to the number of cellular users belonging to each cell. We assume that each RB is occupied by one cellular user from each cell and at most one D2D link. Besides, N RBs have been pre-allocated to $2N$ cellular users before D2D link appears.

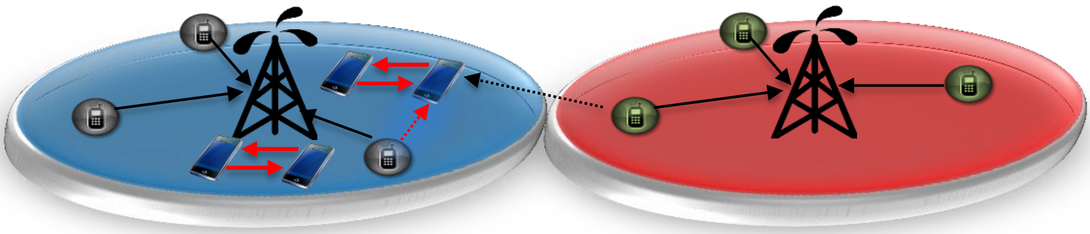

Figure 4.1: System model

We express the ith D2D user rate on the kth RB as

$$R_k^{d_i} = log_2\left(1 + \frac{P_k^{d_i} g_{d_i,k}^{\mathcal{w}(d_i)}}{\sigma^2 + P_k^{c_1} g_{c_1(k),k}^{\mathcal{w}(d_i)} + P_k^{c_2} g_{c_2(k),k}^{\mathcal{w}(d_i)}}\right), \tag{4.1}$$

where $k \in \{1,2, \dots . N\}, i \in \{1,2, \dots , M\}$, d_i denotes the ith D2D link, $c_1(k)$ and $c_2(k)$ represent the cellular users on the kth RB in the first cell and second cell, respectively, σ^2 is the noise power, $\mathcal{w}(x)$ is the desired receiver of the transmitter x. $g_{u,k}^{v}$ denotes the channel gain from the transmitter u to the receiver v on the kth RB, $P_k^{c_m}$ shows the transmitter power of the cellular user in the cell m ($m \in \{1,2\}$) using the kth RB and $P_k^{d_i}$ denotes the transmitter power of the ith D2D link on the kth RB.

Therefore, the sum rate of the ith D2D link is expressed as

$$R^{d_i} = \sum_{k=1}^{N} R_k^{d_i} . \tag{4.2}$$

Moreover, the rate for cellular user belonging to the *m*th cell on *k*th RB is given as

$$R_k^{c_m} = log_2\left(1 + \frac{P_k^{c_m} g_{c_m(k),k}^{w(c_m(k))}}{\sigma^2 + P_k^{c_n} g_{c_n(k),k}^{w(c_m(k))} + P_k^{d_i} g_{d_i,k}^{w(c_m(k))}}\right), \qquad (4.3)$$

for all $k; m, n \in \{1,2\}$ denotes the particular cell such that $n \neq m$, where we assume that the *k*th RB is reused by the *i*th D2D link.

Our goal is to minimize the total power consumption with rate constraints and maximum transmit power constraints on both the cellular users and D2D links. Therefore we formulate the given problem as below

$$\begin{aligned}
\text{minimize} \quad & \textstyle\sum_{k=1}^{N}\left(P_k^{c_1} + P_k^{c_2} + \sum_{l=1}^{M} P_k^{d_i}\right), & (4.4)\\
\text{subject to} \quad & C_1: \quad 0 \leq P_k^{c_m} < P_{max} \quad \text{for all } m \text{ and } k, &\\
& C_2: \quad 0 < \textstyle\sum_{k=1}^{N} P_k^{d_i} < P_{max} \quad \text{for all } i, &\\
& C_3: \quad R_k^{c_1} > R_T^{C} \quad \text{for all } k, &\\
& C_4: \quad R_k^{c_2} > R_T^{C} \quad \text{for all } k, &\\
& C_5: \quad R^{d_i} > R_T^{D} \quad \text{for all } i, &\\
& C_6: \quad P_k^{d_i} \cdot P_k^{d_j} = 0, \quad \text{for all } k, i, j \text{ with } i \neq j, &
\end{aligned}$$

where P_{max} is the upper bound of transmit power for cellular users and D2D links. R_T^C is the target rate constraint for cellular users and R_T^D is the target rate constraint for D2D links. In this formulation, C_1 is the maximum transmit power constraint of each cellular user, likewise C_2 on each $D2D_{Tx}$. C_3 and C_4 are the rate constraints for cellular users in two cells respectively. C_5 is the rate constraints for D2D links. C_6 imposes orthogonality constraint, i.e. one RB cannot be occupied by multiple D2D links simultaneously.

Due to the cellular rate constraints C_5, as well as the orthogonality constraint C_6, the problem (4.4) is non-convex. Hence, the global optimal solution cannot be guaranteed except for grid searching over all the possible values of all the variables. Since there are multiple optimization variables in the problem (4.4), we have to implement high dimensional grid search, however the grid search method for this problem is basically infeasible. That is the reason that we have dropped out the optimal solution in our thesis.

CHAPTER 05

PROPOSED SCHEMES AND ALGORITHMS

The objective function of formulated optimization problem (4.4) consists of a number of individual functions, where each function is associated to one RB. In this way, the problem (4.4) can be considered as a multi-RBs problem. Since the problem (4.4) has a standard form as dual decomposition problem (3.6), it can be solved in dual domain with decomposition method. As the problem (4.4) is non-convex, the duality gap is not necessarily zero. However, based on the Time-Sharing condition in [28], if the number of RBs goes to infinity, the duality gap approaches to zero [29].

In this section, we have proposed two schemes. The first one is the JRP scheme, where the power control and resource allocation are jointly considered, whose complexity exponentially increases with the number of RBs or D2D links. Nevertheless, it can derive the lower bound of the problem (4.4) based on the duality theory. The second scheme is the SRP scheme, where the power control and resource allocation are separately considered with low complexity. Its main principle is that a D2D link chooses the RBs that offer largest rate contribution with fairness among all the D2D links.

5.1 Joint Resource allocation and Power control (JRP) scheme

We define $\Omega = \{1,2,\dots,N\}$ as the set of all the RBs, and Ω_i , $i \in \{1,2,\dots,M\}$ as the set of RBs allocated to the ith D2D link. For all $i,j \in \{1,2,\dots,M\}$ and $i \neq j$, $\Omega_i \neq \emptyset$, $\Omega_i \cap \Omega_j = \emptyset$, $\Omega_1 \cup \Omega_2 \cup \dots \cup \Omega_M = \Omega$. Since the combination of RBs assigned to D2D links has been given, each RB has a dedicated D2D link. Therefore, C_6 of (4.4) can be eliminated.

For each combination of RB allocation, the Lagrangian associated with the problem (4.4) is

$$L(\boldsymbol{p}^{c_1}, \boldsymbol{p}^{c_2}, [\boldsymbol{p}^{d_i}]_{i=1}^{M}, \boldsymbol{\lambda}, \boldsymbol{\beta}) = \sum_{k=1}^{N}\left[P_k^{c_1} + P_k^{c_2} + \sum_{i=1}^{M}\left(P_k^{d_i} + \lambda_i h_{i,k} + \beta_i h'_{i,k}\right)\right], \tag{5.1}$$

where $[\,]_p^q$ denotes the vector from the pth element to the qth, $\boldsymbol{P}^{c_m} = [P_1^{c_m}, \dots, P_N^{c_m}]$ is the power vector of corresponding cellular users, $\boldsymbol{P}^{d_i} = [P_1^{d_i}, \dots, P_N^{d_i}]$ is the power vector of corresponding D2D links, $\boldsymbol{\lambda} = [\lambda_1, \lambda_2, \dots, \lambda_M]$ and $\boldsymbol{\beta} = [\beta_1, \beta_2, \dots, \beta_M]$ are vectors of Lagrangian multiplier associated with C_5 and C_2, $h_{i,k}$ and $h'_{i,k}$ represent rate and power constraints respectively and can be expressed as

$$h_{i,k} = \frac{R_T^D}{N} - R_k^{d_i}, \tag{5.2}$$

$$h'_{i,k} = P_k^{d_i} - \frac{P_{max}}{N}. \tag{5.3}$$

Then, the Lagrangian dual function is

$$g(\boldsymbol{\lambda},\boldsymbol{\beta}) = \min_{\{P_k^{c_1}, P_k^{c_2}, P_k^{d_i}\} \in \{C_1, C_3, C_4\}} L(\boldsymbol{p}^{c_1}, \boldsymbol{p}^{c_2}, [\boldsymbol{p}^{d_i}]_{i=1}^{M}, \boldsymbol{\lambda}, \boldsymbol{\beta}),$$
$$= \min_{\{P_k^{c_1}, P_k^{c_2}, P_k^{d_i}\} \in \{C_1, C_3, C_4\}} \sum_{k=1}^{N} f_k(P_k^{c_1}, P_k^{c_2}, P_k^{d_i}, \boldsymbol{\lambda}, \boldsymbol{\beta}), \quad (5.4)$$

where

$$f_k(P_k^{c_1}, P_k^{c_2}, P_k^{d_i}, \boldsymbol{\lambda}, \boldsymbol{\beta}) = P_k^{c_1} + P_k^{c_2} + \sum_{i=1}^{M}\left(P_k^{d_i} + \lambda_i h_{i,k} + \beta_i h'_{i,k}\right). \quad (5.5)$$

Due to the independence between different RBs, the dual problem can be divided into N subproblems, where each subproblem is intended for one RB and all the subproblems can be solved in parallel. The individual kth subproblem in (5.4) can be solved independently as

$$\begin{array}{lll} \text{minimize} & f_k(P_k^{c_1}, P_k^{c_2}, P_k^{d_i}, \boldsymbol{\lambda}, \boldsymbol{\beta}), & \\ \text{subject to} & C_1: \quad 0 \le P_k^{c_m} < P_{max} & \text{for all } m \text{ and } k, \\ & C_3: \quad R_k^{c_1} > R_T^{C} & \text{for all } k, \\ & C_4: \quad R_k^{c_2} > R_T^{C} & \text{for all } k. \end{array} \quad (5.6)$$

In order to solve problem (5.6), we have proposed Algorithm 1. In this algorithm, we transform (5.5) into a concave function regarding $P_k^{c_1}$ and $P_k^{c_2}$ by grid searching $P_k^{d_i}$ at the first step, which means in the following steps $P_k^{d_i}$ is fixed. Since (5.5) is a concave function now, the minimum function value of (5.5) is located at the set edge of variable $P_k^{c_1}$ and $P_k^{c_2}$, therefore, we search all the edge points to find the one with the smallest function (5.5) value. Eventually, the final solution is found among all $P_k^{d_i}$ grid searching values.

Algorithm 1: Algorithm for subproblem (5.6)

1: Assume the ith D2D link uses the kth RB.

2: Clear $\boldsymbol{P}$, where $\boldsymbol{P}$ is the set of $\{P_k^{c_1}, P_k^{c_2}, P_k^{d_i}\}$.

3: **for** $P_k^{d_i} = 0 : \frac{P_{max}}{10000} : P_{max}$, **do**

4: $\left(P_k^{c_1}, P_k^{c_2}\right) = argmin_{(P_k^{c_1}, P_k^{c_2}) \in D}\ f_k$. (All constraints are linear regarding $P_k^{c_1}$and $P_k^{c_2}$. D is the set of all edge points of constraint set $\left(P_k^{c_1}, P_k^{c_2}\right)$.)

5: $\boldsymbol{P} = \boldsymbol{P} \cup [P_k^{c_1}, P_k^{c_2}, P_k^{d_i}]$. (Store all the alternative powers.)

6: **end for**

7: $(P_k^{c_1^*}, P_k^{c_2^*}, P_k^{d_i^*}) = argmin_{\{P_k^{c_1}, P_k^{c_2}, P_k^{d_i}\} \in \boldsymbol{P}}\ f_k$.

8: $h_{i,k} = \frac{R_T^D}{N} - R_k^{d_i^*}$. ($R_k^{d_i^*}$ is the D2D rate corresponding to $(P_k^{c_1^*}, P_k^{c_2^*}, P_k^{d_i^*})$).

9: $h'_{i,k} = P_k^{d_i^*} - \frac{P_{max}}{N}$.

After achieving the optimum of (5.4), which is a function of $\boldsymbol{\lambda}$ and $\boldsymbol{\beta}$, the Lagrangian dual problem of the primal problem (4.4) is formulated as

$$\begin{aligned} &\text{maximize} \quad && g(\boldsymbol{\lambda}, \boldsymbol{\beta}), \\ &\text{subject to} \quad && \boldsymbol{\lambda} \geq 0,\ \boldsymbol{\beta} \geq 0. \end{aligned} \tag{5.7}$$

To solve problem (5.7) the $\boldsymbol{\lambda}$ and $\boldsymbol{\beta}$ are updated by using subgradient method (3.11) shown in following Algorithm 2.

Algorithm 2: Subgradient algorithm

$h_{\lambda,i} = \sum_{k=1}^{N} h_{i,k}$, for all i,

$h_{\beta,i} = \sum_{k=1}^{N} h'_{i,k}$, for all i,

$\lambda_i = \max(0, \lambda_i + \alpha\, h_{\lambda,i})$, for all i, (α is step size).

$\beta_i = \max(0, \beta_i + \alpha\, h_{\beta,i})$, for all i,

After solving problem (5.7), we get lower bound from the dual problem and the corresponding solution of the primal problem (4.4) for each combination of RBs and D2D links. Finally, we try all these combinations to find the minimal solution among them. If any constraint is violated, for example, the set of $P_k^{c_1}$ and $P_k^{c_2}$ is empty, or the primal and dual problems have very slow convergence, we count this realization infeasible.

The JRP scheme can be expressed as follow

Algorithm 3: JRP algorithm

Try all combinations of RBs and D2D links, for one combination we assume on the *i*th D2D link we have the set Ω_i.

Initialize $[h_{\lambda,i}]_{i=1}^{M}$=1, $[h_{\beta,i}]_{i=1}^{M}$=1, $[\lambda_i]_{i=1}^{M} = 1$, $[\beta_i]_{i=1}^{M} = 1$.

while $[h_{\lambda,i}]_{i=1}^{M} > 0.01$ || $[h_{\beta,i}]_{i=1}^{M} > 0.01$, **do**

  for $k = 1{:}N$, **do**

    Use Algorithm for subproblem (5.6) (Algorithm 1).

  end for

  Use Subgrandient algorithm (Algorithm 2) to update $\boldsymbol{\lambda}$ and $\boldsymbol{\beta}$.

end while

$P_{LB}^{*} = \sum_k^N [P_k^{c_1} + P_k^{c_2} + \sum_i^M (P_k^{d_i} + \lambda_i h_{i,k} + \beta_i h'_{i,k})]$.

$P_{JRP}^{*} = \sum_k^N [P_k^{c_1} + P_k^{c_2} + \sum_i^M P_k^{d_i}]$.

if $P_k^{c_m} > P_{max}$ (for any k and m.) && $\sum_{k=1}^{M} P_k^{d_i} > P_{max}$ (for any i.) || the iteration time exceeds 1000, **then**

  It is infeasible in this combination.

end if

Pick the minimal power P_{JRP}[1] and P_{LB}[1] from all the combinations of RBs and D2D links. When all the combinations are infeasible, it is infeasible in this realization.

---

1 P_{JRP} : The power of JRP algorithm
P_{LB} : Power of the lower bound on the JRP algorithm.

5.2 Separate Resource allocation and Power control (SRP) scheme

In practice, when the network system has deficient amount of RBs, the duality gap cannot be ignored. Additionally, as the number of D2D links or RBs increases, the complexity of the proposed JRP scheme grows exponentially. Therefore, we have proposed an alternative SRP scheme which works well with less complexity. This scheme includes two components, one is power control algorithm and the other one is resource allocation algorithm.

First we use power control algorithm to figure out rate contribution on each RB for all D2D links independently, then based on these contributions we use resource allocation algorithm to assign RBs to each D2D link. Finally we use power control algorithm again to allocate power on the assigned RBs for each D2D link.

5.2.1 Power control algorithm

As the cellular users' RBs and power have been well-allocated before D2D links appear in the network, this Power control algorithm (Algorithm 4) aims to achieve the minimal increased power consumption over all RBs for newly coming D2D link with a specific rate target.

In this algorithm, we use greedy method to scan all the RBs for an individual D2D link, and determine its power consumption on each RB. First we use very small rate ΔC on D2D link to scan all the RBs, and assign ΔC to the RB with minimal increased power consumption, meanwhile the assigned rate on the RBs and the corresponding power are updated. These steps are repeated for all individual D2D links $\frac{R_T^D}{\Delta C}$ times [6]. If there is a case in which the power constraints (C_1, C_2) are violated, we count this realization infeasible. This power control algorithm is presented as follow.

Algorithm 4: Power control algorithm

Input: Ω_i, ΔC is a small rate increment. R_T^D is the rate target of D2D links.

Output: The ith D2D link's rate on each RB, and power consumption of both the ith D2D link and cellular users on each RB.

1: **for** $k = 1{:}N$ && $k \in \Omega_i$, **do**

2: By changing C_3 and C_4 into equality, we obtain three equations $\{R_{k,\text{new}}^{d_i} = R_k^{d_i} + \Delta C, R_k^{c_1} = R_k^C,\ R_k^{c_2} = R_k^C\}$, from these thee equations we can get cellular and D2D power on this RB $\{P_{k,\text{new}}^{c_1},\ P_{k,\text{new}}^{c_2},\ P_{k,\text{new}}^{d_i}\}$.

3: $\Delta P_k = (P_{k,\text{new}}^{c_1} - P_k^{c_2}) + (P_{k,\text{new}}^{c_2} - P_k^{c_2}) + (P_{k,\text{new}}^{d_i} - P_k^{d_i})$. (Calculate increased power on each RB.)

4: **if** $P_{k,\text{new}}^{c_1} > P_{\max} \,||\, P_{k,\text{new}}^{c_2} > P_{\max} \,||\, P_{k,\text{new}}^{d_i} > P_{\max}$, **then**

5: $\Delta P_k \leftarrow +\infty$. (Make the kth RB unavailable and no longer allocate to it.)

6: **end if**

7: **end for**

8: **if** $\Delta P_k = +\infty$ for all k, **then**

9: It is infeasible in this realization , and break the algorithm.

10: **end if**

11: $I = argmin_k(\Delta P_k)$, $I \leftarrow \Delta C$. (Calculate on which RB the increased power is minimum, and then allocate ΔC to this RB.)

12: Update the power on the Ith RB $(P_I^{c_1}, P_I^{c_2}, P_I^{d_i}) \leftarrow (P_{I,\text{new}}^{c_1}, P_{I,\text{new}}^{c_2}, P_{I,\text{new}}^{d_i})$ and the D2D rate $R_I^{d_i} \leftarrow R_{I,\text{new}}^{d_i}$.

13: Repeat all the previous steps $\frac{R_T^D}{\Delta C}$ times.

5.2.2 Resource allocation algorithm

After the greedy method based power control algorithm is implemented for all D2D links, the rate contributions of each D2D link on all RBs is known. Then we proposed a heuristic Resource allocation algorithm (Algorithm 5), where the main principle is that the D2D link obtains the RBs that have largest rate contributions on this D2D link and also maintaining RBs distribution fairness among different D2D links.

Algorithm 5: Resource allocation algorithm

1: **for** $i = 1{:}M$, **do**

2: Implement Algorithm 4 with inputs: $\Omega_i = \Omega, \Delta C$ and R_T^D.

3: **end for**

4: Each D2D's rate on all RBs is known from the output of Algorithm 4.

5: Allocate the RB to the D2D link who has the highest rate on it.

6: If a D2D link has less than $\left\lfloor \frac{N}{M} \right\rfloor$ RBs, pick the RB with the largest rate contribution for itself from other D2D links who have RBs greater than $\left\lfloor \frac{N}{M} \right\rfloor$. Repeat this step until no D2D link has less than $\left\lfloor \frac{N}{M} \right\rfloor$ RBs.

7: If there is a D2D link still having more than $\left\lfloor \frac{N}{M} \right\rfloor + 1$ RBs, the D2D link lends one RB to another D2D link who has less than $\left\lfloor \frac{N}{M} \right\rfloor + 1$ RBs.

8: Finally we get allocated RBs on all D2D links $\{\Omega_1, \Omega_2, \ldots, \Omega_M\}$.

The SRP scheme is illustrated with the following example. Assume there are 3 cellular users and 2 D2D links, and these 3 cellular users are pre-allocated with 3 RBs. For each D2D link, the available number of RBs can be $\left\lfloor \frac{N}{M} \right\rfloor = 1$ or $\left\lfloor \frac{N}{M} \right\rfloor + 1 = 2$, Figure 5.1 shows stacks of RBs for D2D link1 and D2D link2 respectively.

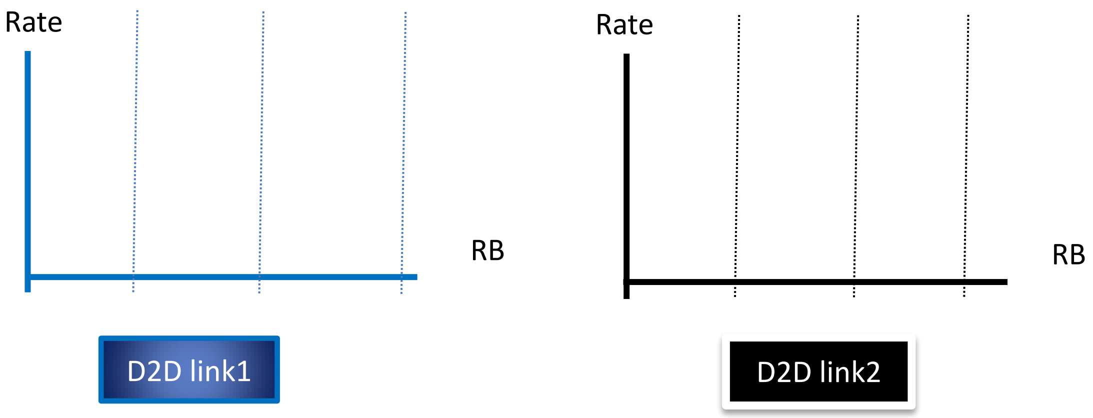

Figure 5.1: 2 D2D links and 3 RBs

After the first time greedy scanning, we suppose D2D link1 and D2D link2 find the first and the third RB respectively as more power efficient. Hence they will put their rate ΔC on these RBs respectively, shown in Figure 5.2.

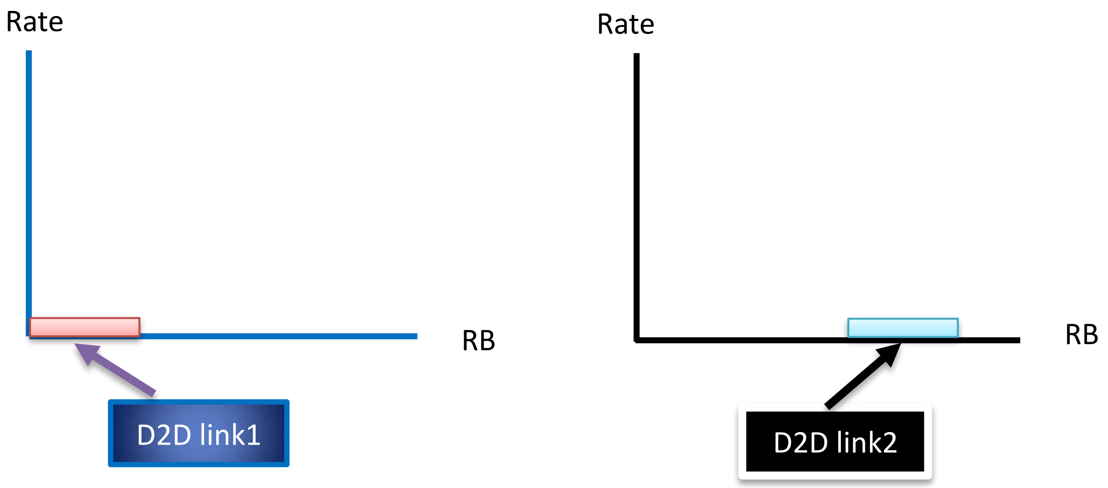

Figure 5.2: Example of rate assignment on power efficient RB

As long as the loop is running, each D2D link places its ΔC on RB which has less power consumption. These stacks of ΔC keep on accumulating on RBs until $\frac{R_T^D}{\Delta C}$ times ($\frac{R_T^D}{\Delta C}$ is an integer by properly choosing ΔC). The rate contributions from different RBs on D2D links are shown in Figure 5.3.

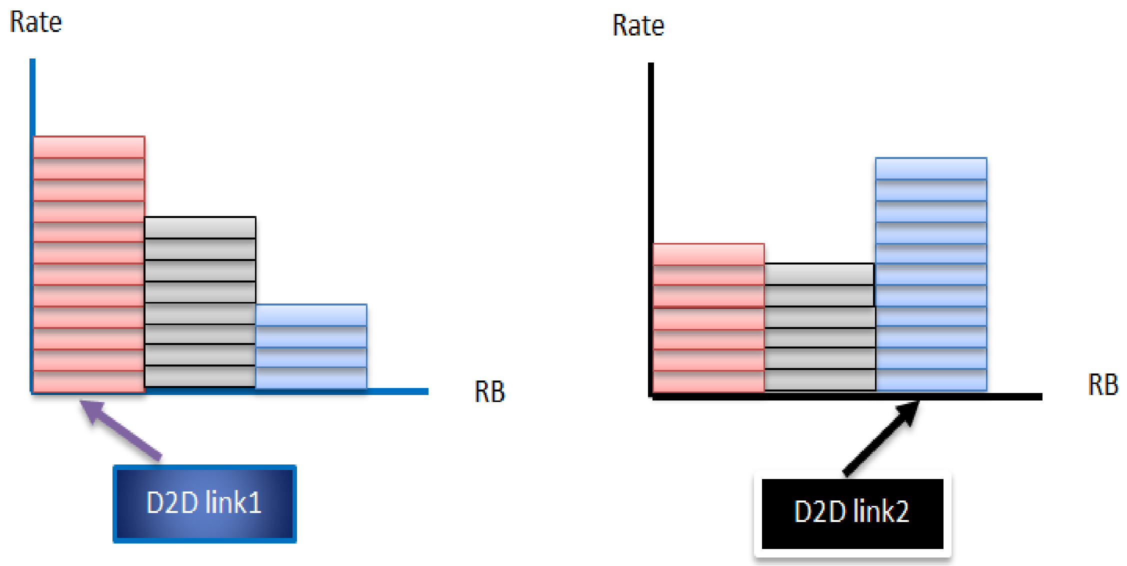

Figure 5.3: Rate contribution of each D2D link on RBs

As the D2D link1 in Figure 5.3, the highest rate contribution on the first RB implies that most of the time this RB is the most power efficient, likewise the third RB for the D2D link2. Hence the resource allocation algorithm will allot the first RB to the D2D link1 and the third RB to the D2D link2 as shown in Figure 5.4. Due to ΔC is much smaller than R_T^D, the iterative time $\frac{R_T^D}{\Delta C}$ is large, which induces large variety of rate distributions on the RBs, therefore, we barely have the scenario that the two D2D links have the same rate contribution on one RB. If happens, we randomly selete one.

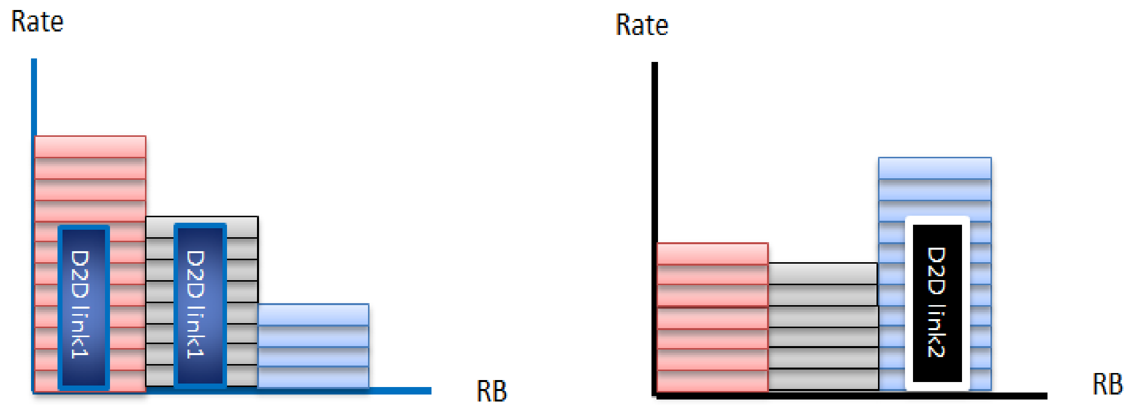

Figure 5.4: Resource allocation scheme

Since the second RB has more rate contribution on the D2D link1 compared to the D2D link2, it is allocated to the D2D link1 as shown in Figure 5.4. Hence the D2D link1 obtains two RBs whereas the D2D link2 gets one RB only. Once the RBs are assigned, we then implement Power control algorithm (Algorithm 4) to allocate power.

CHAPTER 06
SIMULATION RESULTS

To summarize, we have proposed two approaches to solve the problem (4.4), i.e. JRP scheme and SRP scheme, where the JRP scheme uses dual decomposition technique, where the contribution is not only to give a solution, but also to provide the lower bound of the optimal solution. On the other hand, the SRP scheme separately considers resource allocation and power control, which is much simpler compared to the JRP scheme.

In this section, we present the power consumption and infeasibility performances of the two proposed schemes under different system parameters. All parameters are inspired from [30], shown in Table 6.1.

Table 6.1 Parameters for numerical analysis

Parameters	Value
Max power for each user (Pmax)	1w
Inter-site distance	500 m
Path loss exponent	3.07
Shadow fading: Lognormal	st. dev: 5 dB
Fast fading model	Rayleigh flat
Number of cells	2
Number of cellular users in each cell	3
Number of D2D link in cell1, cell2	2, 0
D2D distance	30 m, 50 m
Cell radius	250 m
Bandwidth per RB	180 KHz
Noise figure	9dB

In the simulation, BS is located in the center of area. The channel includes path loss fading, shadow fading, and Rayleigh fading. According to the properties of D2D communication, uplink time-frequency slot is usually chosen for the scenario that D2D links that are far away from BS [31], and thus we randomly locate D2D links from 180m of radius to cell edge. Meanwhile, all cellular users are randomly placed in cells.

The simulation results under each measuring parameter are obtained by averaging over 500 realizations.

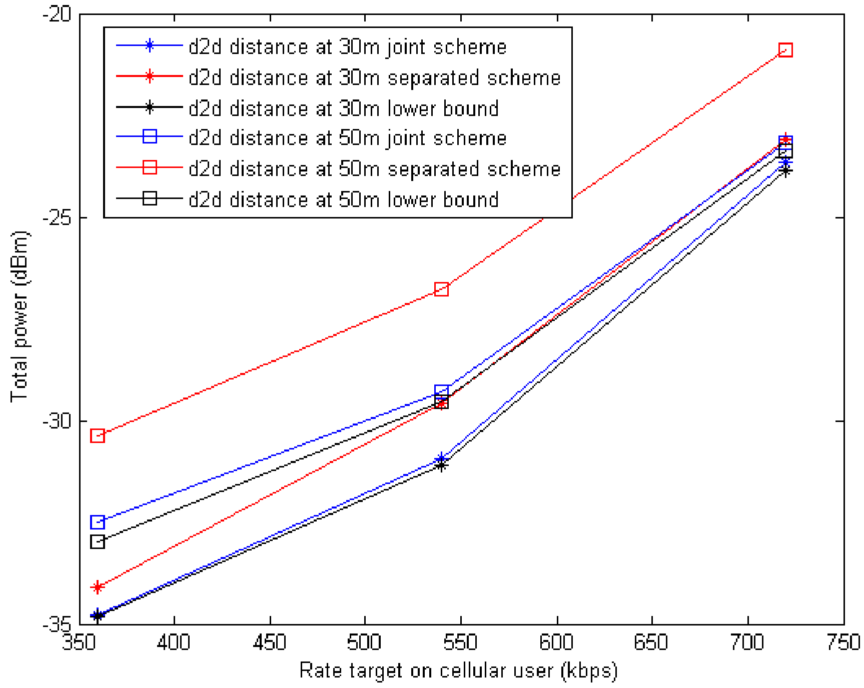

Figure 6.1: Power versus cellular rate target under 1080 kbps of D2D rate target

Figure 6.1 shows the total power consumption versus different cellular rate targets under 1080 kbps D2D rate. It is shown that the total transmit power increases as the cellular rate target or the distance between $D2D_{Tx}$ and $D2D_{Rx}$ increases.

Figure 6.2 plots the infeasibility under the same parameter settings as in Figure 6.1. Obviously, the JRP scheme has a lower infeasibility than the SRP scheme. Furthermore, when the distance between $D2D_{Tx}$ and $D2D_{Rx}$ or the cellular rate target increases, the infeasible probability increases significantly. Although the complexity of the SRP scheme is lower compared to the JRP scheme, it has higher infeasibility than the JRP scheme. Hence, there is a trade off between the infeasibility and the complexity.

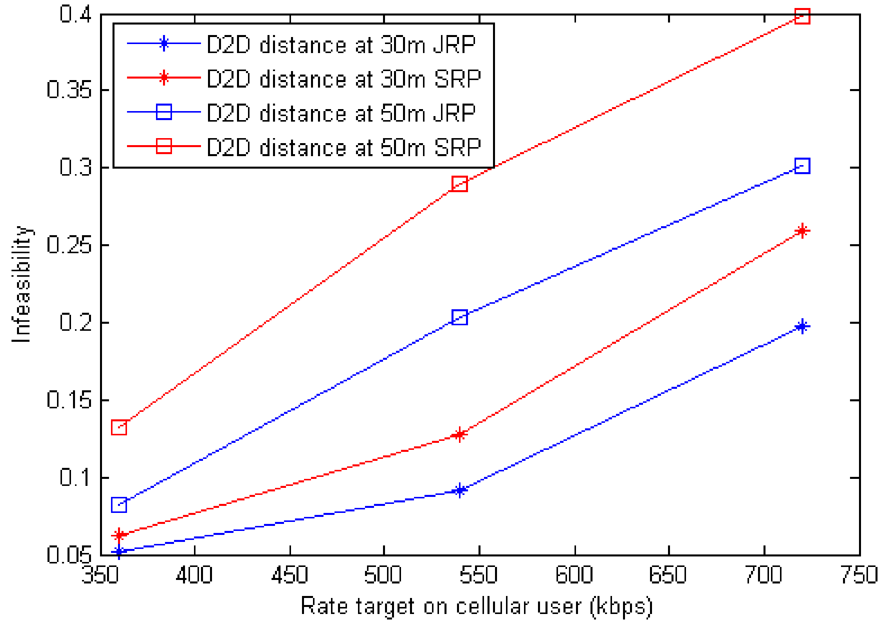

Figure 6.2: Infeasibility versus cellular rate target under 1080 kbps of D2D rate target

Similar result can be found in Figure 6.3, where we vary the D2D rate target with cellular rate target fixed. Due to the fact that the distance between $D2D_{Tx}$ and $D2D_{Rx}$ is short and the D2D link is far away from BS, the D2D link uses low power. Correspondingly, its interference to the cellular user is small. Therefore, increasing the D2D rate target has less impact on the total power consumption compared to the previous cases.

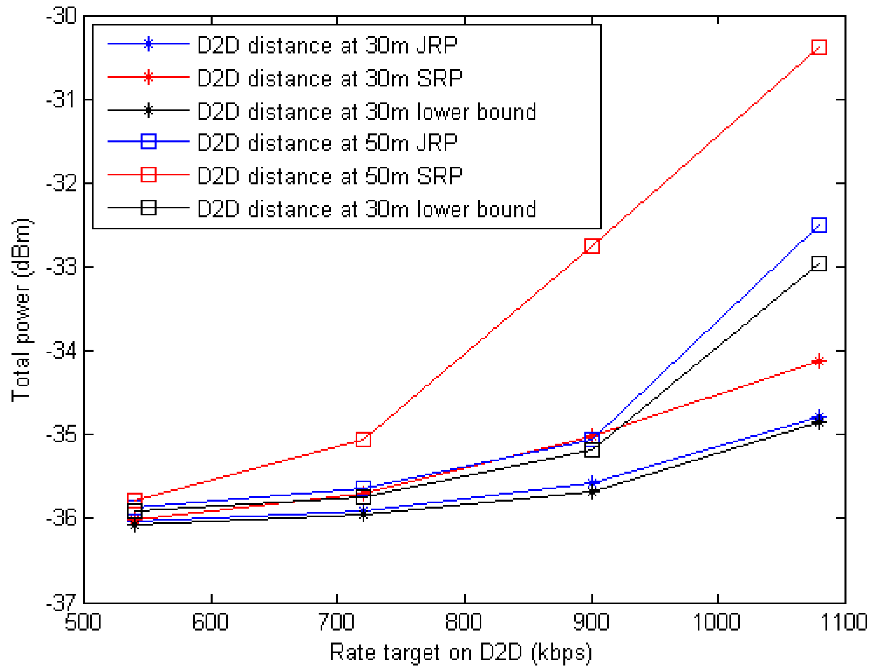

Figure 6.3: Power versus D2D rate target under 360 kbps of cellular rate target

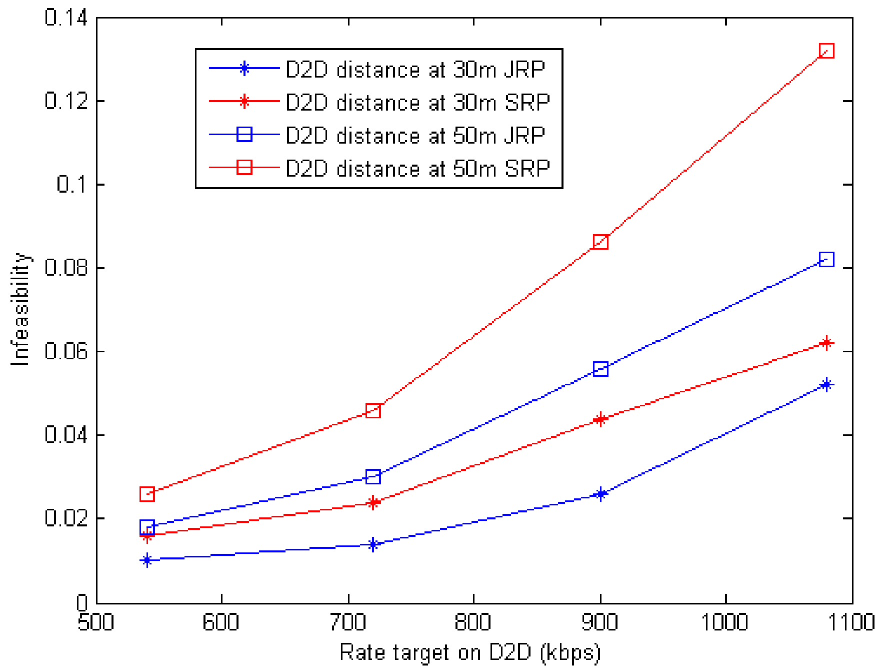

Figure 6.4: Infeasibility versus D2D rate target under 360 kbps of cellular rate target

Figure 6.4 shows the infeasibility versus different D2D rate targets under 360 kbps cellular rate. The infeasibility increases slowly with D2D rate target comparing to Figure 6.2. Moreover, we remark that the cellular rate target affects the infeasibilities of both schemes significantly. The reason is that the increment of the cellular rate target results in higher transmit power, which generates more interference to both the D2D link and the adjacent cellular user. Therefore, there is higher probability that infeasibility happens, which means that either the D2D rate target or the cellular rate target can not be reached, hence, no RBs can be allocated to the D2D link.

By comparing Figure 6.1 and Figure 6.3, although the performance of the JRP scheme is very close to the lower bound, the complexity of the JRP scheme is much higher than the SRP scheme, especially when the number of D2D links or RBs is large. Hence, it needs more research on improving the performance of the SRP scheme or simplifying the JRP scheme in the future.

CHAPTER 07

CONCLUSION

In this thesis, we first reviewed some basic communication aspects on LTE, OFDM, various channel models and some topics related to optimization. As nailed down on D2D aspect, we studied cutting-edge D2D techniques including D2D neighbor discovery; D2D and multi-hop communications; D2D channel measurements/modeling; energy efficiency analysis for D2D communications; resource allocation and power control for D2D communications and interference cancellation. And we concluded that these are the main topics of current D2D research. Finally, we have chosen to concentrate on resource allocation and power control as our topic.

After well understood on D2D properties and its research area, we proposed two schemes on the aspects of resource allocation and power control. Our novelties were aiming to minimize total power under D2D and cellular rate constraints. The JRP scheme jointly considered RB allocation and power control in the dual domain. It not only gives good performance in both power efficiency and infeasibility, but also offers the lower bound on the optimal solution. However, the proposed JRP scheme has very high complexity. Alternatively, we have proposed the SRP scheme with low complexity for resource allocation and power control, the performance of the SRP scheme is acceptably worse than the JRP scheme. Since these two proposed schemes provide a tradeoff between the complexity and the performance, our further work will focus on simplifying the JRP scheme and reducing power consumption of the SRP scheme.

8. BIBLIOGRAPHY

[1] E. Dahlman and S. Parkvall, "Multi-Antenna Techniques," in 4G LTE/LTE-Advanced for Mobile Broadband, Elsevier Ltd, 2011, pp. 59-77 (Ch.5).

[2] K. Doppler, K. Rinne, Wijting, Ribeiro and Hugl, "Device-to-Device Communication as an Underlay to LTE-Advanced Networks," in IEEE Communications Magazine, pp: 42 - 49 , Dec 2009.

[3] M. Zulhasnine, C. Huang and A. Srinivasan, "Efficient Resource Allocation for Device-to-Device Communication Underlaying LTE Network," in 6th IEEE International Conference on Digital Object Identifier: 10.1109/WIMOB.2010.5645039, 2010.

[4] K. Doppler and M. P. Rinne, "Device-to-Device Communications; Functional Prospects for LTE-Advanced Networks," in IEEE International Conference on Communications Workshops, 2009.

[5] C.H. Yu, O. Tirkkonen and K. Doppler, "On the Performance of Device-to-Device Underlay Communication with Simple Power Control," in IEEE 69th Vehicular Technology Conference, 2009.

[6] G. Fodor and N. Reider, "A Distributed Power Control and Mode Selection Algorithm for D2D Communications," EURASIP Journal on Wireless Communications and Networking 2012, Vols. 10.1186/1687-1499-2012-266 , 2012.

[7] Runhua Chen and J.G. Andrews, "Uplink Power Control in Multi-Cell Spatial Multiplexing Wireless Systems," IEEE Transactions on Wireless Communication, vol. 6, no. 7, pp. 2700 - 2711, 2007.

[8] C. Chien, Y. Chen and H. Hsieh, "Exploiting Spatial Reuse Gain Through Joint Mode Selection and Resource Allocation for Underlay Device-to-Device Communications," 15th International Symposium on Wireless Multimedia Communications (WPMC), 24-27 Sept. 2012

[9] X. Zhu, S. Wen, G. Cao, X. Zhang and D. Yang, "QoS-based Resource Allocation Scheme for Device-to-Device (D2D) Radio Underlaying Cellular Networks," in 19th International Conference on 2012 Telecommunications (ICT), Jounieh, 23-25 April 2012.

[10] C. Yu, Tirkkonen, K. Doppler and C. Ribeiro, "Power Optimization of Device-to-Device Communication Underlaying Cellular Communication," in IEEE International Conference on

Communications, June 2009.

[11] B. Wang, L. Chen, X. Chen, X. Zhang and D. Yang, "Resource Allocation Optimization for Device-to-Device Communication Underlaying Cellular Networks," in 73rd IEEE Vehicular Technology Conference (VTC Spring), Budapest, 15-18 May 2011.

[12] B. Peng, C. Hu, T. Peng and W. Wang, "Optimal Resource Allocation for Multi-D2D Links Underlying OFDMA-based Communications," in Wireless Communications, Networking and Mobile Computing (WiCOM), 21-23 Sept. 2012.

[13] W. Yu, G. Ginis and J. M. Cioffi, "Distributed Multiuser Power Control for Digital Subscriber Lines," in IEEE journal on selected areas in communiocation, vol. 20, no. 5, June 2002.

[14] "Cell Phone Generations 1G, 2G, 3G and now 4G – Tech Forums," Forums.techeblog.com, 16 October 2012.

[15] "3GPP statement on LTE-Advanced status," www.3gpp.org, April 8, 2013.

[16] Mark Elo, "Orthogonal Frequency Division Multiplexing," Keithley Instruments Inc, www.keithley.com, 2008.

[17] Debbah Mérouane, "Short introduction to OFDM," Alcatel-Lucent France, www.flexible-radio.org.

[18] J. York, Digital Communications, New York: McGraw-Hill, 2001.

[19] E. Dahlman and S. Parkvall, " Basic Principles of OFDM," in 4G LTE/LTE-Advanced for Mobile Broadband, Elsevier Ltd., 2011, pp. 27 - 44.

[20] J. V. de Beek and O. Edfors, "On Channel Estimation in OFDM Systems," Vehicular Technology Conference, vol. 2, pp. 815 - 819, 1995.

[21] Steele and Hanzo, "Characterisation of Mobile Radio Channels," in Mobile Radio Communications, Ch. 2, London, Pentech Press.

[22] Bernard Sklar, "Rayleigh Fading Channels in Mobile Digital Communication System Part 1: Characterization," in IEEE Communications Magazine, 1997.

[23] T. S. Rappaport, Wireless Communications, Chs. 3 and 4, Upper Saddle River, Prentice Hall.

[24] S. Mathur, "Small Scale Fading in Radio Propagation," Department of Electrical Engineering, Rutgers University, Piscataway, Spring 2005.

[25] Jon Dattorro, "Convex Optimization & Euclidean Distance Geometry", Palo Alto, California 94302: Meboo Publishing.

[26] S. Boyd, Convex Optimization, United Kingdom : University Press, Cambridge, Seventh printing with corrections 2009.

[27] S. Boyd, L. Xiao, A. Mutapcic and J. Mattingley, "Notes on Decomposition Methods," Notes for EE364B, pp. 3-31, 12 February 2007.

[28] P. Janis, C. Yu, K. Doppler, C. Ribeiro, C. Wijting, K. Hugl, O. Tirkkonen and V. Koivunen, "Power Optimization of Device-to Device Communication Underlaying Cellular Communication," in ICC' 2009, June 14 - 18, 2009.

[29] W. Yu, "Dual Methods for Nonconvex Spectrum Optimization of Multicarrier Systems," IEEE Transactions on Communications," vol. 54, no. 7, July 2006.

[30] R1-130599, "D2D Deployment and Performance Evaluation", Qualcomm Inc., January 28-February 1, 2013.

[31] C. Yu, O. Tirkkonen, K. Doppler and C. Ribeiro, "On the performance of Device-to-Device Underlay Communication with Simple Power Control," in 69th IEEE Vehicular Technology Conference (VTC Spring) , Barcelona, 1-5, 26-29 April 2009.