Power Control and Resource Allocation for Device-to-Device Communications in Cellular Networks

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Abstract

Device-to-device (D2D) communications in cellular networks will improve traditional cellular systems in many ways. By allowing user equipment (UE) in proximity to communicate through direct links, the transmitter would be able to transmit with lower power while the receiver could still receive better-quality signals. Both spectrum and energy efficiency can be significantly increased. Moreover, D2D communications in cellular networks will make an effective way for emerging proximity-based services.

The introduction of D2D links into a cellular network complicates the interference situation. Traditional macro-cellular links will experience high interference from D2D links, especially if D2D links are reusing the cellular radio resources. This amplifies the importance of power control and resource allocation techniques to mitigate interference. This thesis evaluates the performance of three power control algorithms, namely LTE power control, utility maximization, and hybrid power control. LTE power control plays the role of the most practical power control scheme as it has been standardized. Utility maximization power control is an optimal distributed power control designed to improve spectrum and energy efficiency in a balanced manner. Hybrid power control is a scheme proposed in this thesis, which combines LTE power control for the cellular UEs and utility maximization power control for the D2D UEs. It is designed to have compatibility with existing LTE system as well as to protect cellular links.

Four resource allocation algorithms are considered in this thesis, namely random resource allocation, balanced random allocation (BRA), cellular protection allocation (CPA), and minimum interference (MinInterf) allocation. They are all heuristic algorithms with different degrees of complexity. Numerical results are obtained with Monte Carlo simulations, modelling a cellular system with randomly dropped UEs in each iteration. System performance metrics resulted from different power control and resource allocation algorithms are evaluated and compared. The performance metrics of interest include both spectrum and energy efficiency, SINR, and transmit power. The results show that LTE power control performs well in terms of D2D UEs’ SINR if the path loss compensation factor is set to a sufficiently high value, e.g. 0.8.

Meanwhile, the performance of utility maximization power control depends heavily on its tuning parameter. If the parameter is low, high spectrum efficiency is achieved in the exchange of high transmit power, or vice versa.
Hybrid power control is proven to yield better cellular UEs’ SINR compared to other power control algorithms. This depends on an interference threshold parameter. If the threshold parameter is lower, the cellular links are better protected. Simulation results also show that the MinInterf allocation algorithm is superior than other resource allocation algorithms in terms of UEs’ SINR. However, MinInterf is a complex algorithm which requires the knowledge of all cellular and D2D link qualities. Therefore, it might be preferable to use either of three other algorithms. Simulation results show that BRA performs better than random resource allocation, although in many cases their performance metrics are almost identical. CPA algorithm performs slightly better than random resource allocation and BRA in the low-SINR region, but it performs badly in the high-SINR region.
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<tr>
<td>3GPP</td>
<td>Third Generation Partnership Project</td>
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<tr>
<td>BRA</td>
<td>Balanced Random Allocation</td>
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<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>CPA</td>
<td>Cellular Protection Allocation</td>
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<tr>
<td>D2D</td>
<td>Device-to-Device</td>
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<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
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<td>LTE</td>
<td>Long Term Evolution</td>
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<td>LTE-A</td>
<td>Long Term Evolution Advanced</td>
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<td>MinInterf</td>
<td>Minimum Interference</td>
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<tr>
<td>NSPS</td>
<td>National Security and Public Safety</td>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<td>PC</td>
<td>Power Control</td>
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<td>RA</td>
<td>Resource Allocation</td>
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<td>RB</td>
<td>Resource Block</td>
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<tr>
<td>RRM</td>
<td>Radio Resource Management</td>
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<tr>
<td>SINR</td>
<td>Signal to Interference-plus-Noise Ratio</td>
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<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<td>UE</td>
<td>User Equipment</td>
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Chapter 1

Introduction

1.1 Background and Motivation

The term device-to-device (D2D) generally refers to direct connections between two communicating devices. By this definition, direct communication links established in any kind of spectrum can be called D2D. Bluetooth and peer-to-peer Wi-Fi technologies, for example, would represent D2D communications operating on unlicensed spectrum bands. As indicated in the title, this thesis focuses on D2D links created on licensed cellular bands and integrated with cellular networks.

Third generation partnership project (3GPP) is currently investigating the concept of enabling D2D communications in the fourth generation cellular systems standard, the long term evolution-advanced (LTE-A) [2, 3]. D2D is planned to be an important feature introduced in Release 12 of LTE, which is scheduled to be completed by September 2014. The expected benefits of incorporating D2D communications in LTE systems are higher spectrum efficiency, higher energy efficiency, and the possibility of creating new peer-to-peer and proximity-aware services [4, 5]. Support of D2D communications in LTE is also intended for national security and public safety (NSPS) purposes—D2D will be the main communication protocol in case the base station (BS) fails to work.

The idea of D2D communications in cellular networks is that when two user equipments (UEs) want to communicate with each other, they can be allowed to exchange information through a direct link. Cellular links normally created between the UEs and the BS can be bypassed. The BS no longer acts as a relay in the information exchange. This concept is illustrated in Figure 1.1. UEs communicating through direct links are operating in the D2D mode, while UEs communicating via the BS are in the cellular mode.

Typically, communicating D2D devices are located close to each other. Low-power and energy-efficient transmission is achievable because of this physical proximity. Spectrum efficiency, on the other hand, can be improved because of two reasons. The first one is that when two UEs are communicating in D2D
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mode, only one communication link is required instead of two, as shown in Figure 1.1. The second reason is that it is possible to allocate the same radio resources for cellular as well as D2D links in a cell [5]. This concept is called resource reuse and is proposed to promote efficient radio resource utilization.

Severe interference is one of the main problems brought by the presence of D2D links in a cellular system. This is especially true when D2D links are sharing radio resources with the cellular links. Traditional LTE systems without D2D links allocate orthogonal resources to all cellular UEs in a cell, therefore intracell interference becomes negligible. When cellular UEs are forced to share their resources with D2D links, intracell orthogonality is lost and intracell interference must be taken into account [6]. In addition to the increase of intracell interference, allowing D2D communications in a cellular system also leads to higher intercell interference. D2D UEs at the cell edge can interfere with cellular UEs in neighbouring cells, provided that they use the same radio resource [7].

Interference situation of a cellular system allowing D2D communications makes the role of power control and resource allocation in the system becomes more vital. It is important to notice that the level of interference caused by D2D links depends on the allocated resource and transmit power of each UE. Therefore there is a great need of investigating how power control and resource allocation should be done in a cellular system when D2D links are present, as well as how they would affect the spectrum and energy efficiency of the system.

1.2 Related Work

An overview of the technical challenges in D2D communications underlying a cellular network is shown in Figure 1.2 [4, 8]. Power control and resource allocation discussed in this thesis are in the area of radio resource management (RRM).

Peer and service discovery techniques are not the focus of this thesis. However, due to the importance of this process, it is good to know some previous works in this subject. Peer discovery is the first step of D2D link establishment, in which the UEs and/or the BS detect the presence of D2D candidates.
A D2D candidate is a pair of UEs, a potential D2D transmitter and a potential D2D receiver, which are in the proximity of each other. A number of algorithms for peer and service discovery have been proposed, both the ones requiring network assistance [9] and the ones not requiring network assistance [10]. Performance measures that are often used to evaluate discovery algorithms are energy efficiency, resource utilization, discovery time, and discovery rate [11].

RRM techniques are essential to manage intracell and intercell interference in the system. RRM algorithms for D2D communications in cellular networks are developed with certain objectives such as increasing network capacity, improving reliability, minimizing total transmit power, or protecting cellular links from interference caused by D2D transmissions [8].

Apart from power control and resource allocation, there are other key RRM techniques identified for D2D communications, e.g. mode selection and pairing. Mode selection is a process of determining whether a D2D candidate should communicate in cellular or D2D mode. A simple decision criterion for mode selection is the D2D link quality, but it is also possible to take cellular link quality and interference into account [12]. Pairing, a concept which only exists when D2D links are reusing cellular resources, refers to assigning one cellular UE and one or more D2D links for each resource block [13].

Power control has a direct impact to the system’s spectrum and energy efficiency. A number of power control algorithms have been developed for D2D communications in cellular networks. They can generally be categorized into centralized algorithms [14] and distributed algorithms [7, 8], depending on whether the power levels are decided by the BS as a central entity or by the UEs themselves. The power control algorithms are designed for different objectives, such as maximizing the rate [15], minimizing total sum power with respect to a target rate [7], or maximizing a utility function characterized by
CHAPTER 1. INTRODUCTION

the trade-off between spectrum and energy efficiency [8]. Additionally, there is also an option of applying the standard LTE power control for D2D links as well as the cellular links [14, 16].

Resource allocation, a process of selecting radio resources for each cellular and D2D link, can be done jointly with mode selection and pairing [13, 17]. Resource allocation can be done in many ways, the simplest one would be random resource allocation. Optimality of resource allocation algorithm can be achieved by taking the quality of cellular and D2D links into account [8].

An idea which has not been much addressed in literature is the performance of more practical, suboptimal schemes. For instance, in the topic of power control for D2D communications in cellular network, investigation on utility-optimal [8] and existing LTE uplink power control [14] algorithms have been performed. However, the results show that existing LTE power control is not an efficient solution by itself [14]. The utility-optimal scheme, despite being able to achieve satisfying performance, is not standardized and may still have a long way to make it to the LTE standard. Therefore, it is interesting to develop a power control scheme which is somewhere between the optimal and the standardized, e.g. by applying LTE power control to the cellular UEs and utility-optimal power control to the D2D UEs.

The same thing goes for resource allocation algorithms, that is, a suboptimal scheme is required. Random allocation will not be suitable for bigger systems with more radio resources and more D2D UEs. Meanwhile, the optimal resource allocation algorithm requires the knowledge of all cellular and D2D links [8]. In practice, while it is feasible to know the quality of cellular links, it is very difficult to obtain the channel quality between D2D devices. This poses a need of developing a resource allocation algorithm which only requires cellular link quality information.

1.3 Thesis Structure

The problem addressed in this thesis is performance evaluation of different power control and resource allocation algorithms for D2D communications in cellular networks. The objective is to provide insights on the behaviour of the algorithms and how it affects system performance. Numerical results for performance evaluation are obtained by simulation. Practicality and optimality of the algorithms are also analysed.

The thesis is organized into seven chapters. Chapter 2 explains the key terms: D2D communications in cellular networks, power control, and resource allocation. Chapter 3 is dedicated to the details of all power control algorithms studied in this thesis. Chapter 4 explains the resource allocation algorithms. Chapter 5 describes how the simulations are conducted, including how the system is modelled. Chapter 6 presents the numerical results and analysis. Finally, conclusions are drawn in Chapter 7.
Chapter 2

Theoretical Background

2.1 Cellular Networks

A cellular network provides wireless connectivity to users in a certain area by dividing the area into cells. Each cell is served by one antenna system at the base station. A base station is connected to all UEs located in the cell it serves by radio links. A radio link corresponding to transmission from the UE to the base station is called uplink, while a radio link corresponding to transmission from the base station to the UE is called downlink. UEs are generally mobile. When a UE moves to an area outside the coverage of its respective cell, a handover mechanism is carried out to assign a different serving base station to the UE.

Although shapeless in reality, cells are commonly modelled as hexagons. This geometrical model is chosen because it can cover the service area without overlaps. In addition to geographical considerations, cell planning also has a lot to do with radio resource management. More details on what resource management is about are given in section 2.4.

Ideally, all UEs in the same cell are allocated orthogonal radio resources so that they do not interfere with each other. However, this set of orthogonal resources may be reused in other cells. In order to reduce intercell interference, in many cases resources are not reused by adjacent cells and the cellular network can then be divided into clusters. A cluster is a group of cells which do not share radio resources. Figure 2.1 illustrates the concept.

This thesis considers an LTE system with OFDM transmission scheme, which implies reuse factor of 1. It means that the same set of orthogonal resources is used in all cells. The allocated radio resources are time-frequency block. This would increase system capacity and resource utilization efficiency.

Traditional cellular systems do not allow UEs to communicate directly with each other. All communications must be relayed by the base station, even if the UEs are in the same cell. Communication between UEs in different cells is made possible because base stations are connected by a backhaul network. The transmitting UE sends the information to its serving base station through the
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6

Figure 2.1: A cellular system model with 2 clusters and cluster size 7

uplink channel, and then the base station forwards it to the receiver UE’s base station through the backhaul network. The receiving base station transmits the information to the receiving UE through the downlink channel.

2.2 D2D in Cellular Networks

The basic principles of D2D communications in cellular networks have been mentioned in Chapter 1. Taking advantage of the UEs’ proximity, D2D eliminates the need of relaying information through the base station. UEs are allowed to communicate through a direct link instead of cellular uplink or downlink. This can lower transmission power and/or increase signal to interference-plus-noise ratio (SINR). Consequently, spectrum and energy efficiency can be improved.

2.2.1 Radio Resource Considerations

The presence of D2D UEs in a cellular network requires allocation of some of the cellular radio resource to the D2D pairs. This brings up a question of which links to choose—should we allocate uplink or downlink resources for the D2D links? This thesis assumes that only uplink resources are allocated for D2D communications. There is a reason for this assumption, which is related to the interference situation between the D2D UEs in a certain cell with cellular UEs in adjacent cells.

Let us consider a case when a D2D pair is located at the cell edge, and that there is a cellular UE at the edge of the neighbouring cell. Firstly let us evaluate the downlink case, that is, the cellular UE is receiving signal from its base station. If the D2D UEs use downlink resource, the D2D transmitter might cause strong interference to the cellular UE. Because they are located in different cells, D2D transmitter cannot know how close the cellular UE is.

Now let us evaluate the uplink case, which means the cellular UE is trans-
mitting signal to its base station. The cellular UE might generate strong interference to the D2D receiver. In short, choosing between allocating uplink or downlink resource for D2D links is equivalent to choosing between sacrificing the received signal quality of D2D receiver or cellular UE. Since cellular operators will most likely prefer to protect the cellular users, it would be better to allocate uplink resources for D2D links.

2.2.2 Procedure

The procedure of carrying out D2D communication can be divided into two phases: discovery phase and communication phase. Discovery phase is the prerequisite for communication phase.

Discovery Phase

Before D2D communication between two UEs can happen, the network and/or the UEs must detect the D2D candidates. D2D candidates are pairs of transmitting and receiving UEs which are close enough to each other and can potentially communicate in D2D mode. Discovering the presence of D2D candidates is typically done by beacon signal transmission. LTE’s synchronization sequences, for instance, could serve as beacon signal.

There are two alternatives of D2D discovery process, which are called a-priori discovery and a-posteriori discovery [4]. The difference between these two is the time at which D2D candidates are detected. In a-priori discovery, D2D candidates are detected before any communication session takes place. For example, a D2D server transmits a beacon signal that can be received in the cell’s coverage area, and then finds a D2D client that detects the beacon. In a-posteriori discovery, D2D candidates are detected by the base station or UEs when a normal cellular mode communication is already ongoing.

Although device discovery is a critical phase in D2D communications, it is not the focus of this thesis. The work done in this thesis assumes that discovery phase is already done.

Communication Phase

The communication phase covers all processes that occur after the D2D candidate is detected. This includes channel estimation, mode selection, resource allocation, power control, and the actual transmission of the information. Resource allocation and power control will be discussed in details later on.

Channel estimation is especially challenging for D2D communication in cellular networks because the base station now has the need to know the quality of the direct links. It might not be practical due to the amount of additional signaling required. In relation to channel estimation, some channel models have been proposed for D2D communications as seen in [14].
Mode selection, as mentioned in Chapter 1, is a process of deciding whether the D2D candidate should communicate in D2D mode or should just stick to cellular mode. This is important because in some cases, the direct link may have worse quality than the cellular links, making it unnecessary to operate in D2D mode. The design of mode selection mechanism must consider at least the decision criteria and the timing of mode selection. There are a lot of possibilities of decision criteria. Mode selection can be based on distance, interference, path gains, or the combinations of them. In regards to timing, mode selection can either be periodic or event-triggered [4].

2.2.3 Network Role

Up to this point, the discussion has been mostly about the benefits D2D links could bring to the cellular network, e.g. increasing system capacity or lowering the transmit power. We should now consider the other point of view—what is the advantage that the cellular network brings to the D2D communication? It is interesting to answer this question because a D2D-type communication can actually be carried out without a centralized network assistance. For instance, Bluetooth can provide free connectivity between proximate devices through a direct link.

There are several advantages of having network assistance for D2D communications. First of all, the cellular network can provide node synchronization and security. The cellular network also has the knowledge of system load, which is useful to enable faster and more energy-efficient device discovery [11]. Additionally, if D2D links are established on cellular spectrum, it is possible to communicate under high spectrum utilization with relatively controllable interference [4, 18].

An important design consideration of D2D communications in cellular networks is deciding how much control the network should have. Naturally, there are pros and cons which need to be evaluated. An extreme case of network control is having the base station do everything: collecting channel state information, deciding the communication mode (cellular or D2D), assigning resources and transmit powers, etc. This approach is better for interference coordination, but increases signaling and processing overhead [4]. As an alternative approach, it is also possible to delegate some important functionalities to the UEs themselves. For example, by exchanging information about channel state and transmit power level with each other, UEs can calculate how much power they should transmit in order to minimize interference. Such distributed approach is applicable for power control, resource allocation, mode selection, and other D2D functionalities.

For power control and resource allocation, which are the main topics of this thesis, the role of the network in each evaluated algorithm will be analysed. Based on the network control, the power control and resource allocation algorithms can generally be categorized into two: centralized and distributed
algorithms. In centralized algorithms, power control and resource allocation are performed by the base station. LTE power control is an example of a centralized algorithm. In distributed algorithms, power control and resource allocation are performed by the UEs.

2.2.4 Business Aspects

Cellular operators would certainly hope to make profits out of D2D communications. The business model that they can implement will be closely related to the network design, especially regarding the level of operator control.

There are two broad categories of operator-controlled D2D communications, namely fully controlled and loosely controlled D2D [18]. All data plane and user plane functions in a fully controlled D2D design is controlled by the cellular network. In a loosely controlled D2D design, the cellular network is only responsible for access authentication.

Consequently, in a fully controlled D2D system, the operator is able to charge users according to the time or bandwidth used for D2D communications. Meanwhile, in the loosely controlled case, operator can only apply a fixed fee for a certain amount of time, without taking the actual data usage into account.

In either case, operators must be careful when determining the fees. They should be aware that they cannot charge too much for D2D services. They must realize that although D2D communications in cellular networks could be technically superior, they still face a competition from free D2D technologies. In order to triumph in this competition, cellular operators can highlight the features that are the strength of D2D communications in cellular networks, such as quality of service, security, and context information.

D2D communications in cellular networks are expected to open up new business opportunities. Some examples are augmented reality, social networking, and mobile commerce and advertising [19]. All of them take advantage of proximity of the devices for quick content delivery and localized services, assisted by the cellular operator’s exact knowledge of the traffic.

2.3 Power Control Problem

Power control is a process of setting transmit power levels of base stations in the downlink or mobile stations in the uplink [20]. When we look at a single communication link, higher transmit power is desirable because it will lead to higher received power and consequently higher link capacity.

However, when a transmitter uses high transmit power, high interference will be generated to other links sharing the same resource, and system capacity can potentially decrease. In this sense, power control is a matter of finding the right trade-off between maximizing transmit power and limiting the generated interference.
As an example, consider a cellular system with \( n_{Tx} \) transmitters. Let \( i \) be the index of transmitters. Transmitter \( i \) transmits with power \( P_i \). The main idea of power control is to calculate the values of \( P_i \) that meet a certain objective.

Suppose that in this particular system, the objective of power control is to make sure that all links are able to achieve a fixed SINR target \( \gamma_0 \). The SINR of each link is denoted by \( \Gamma_i \). Hence, the power control objective can be expressed as:

\[
\Gamma_i \geq \gamma_0 \tag{2.1}
\]

Meanwhile, the SINR of each link can be calculated as follows.

\[
\Gamma_i = \frac{G_{ii} P_i}{\sum_{j=1, j\neq i}^{n_{Tx}} G_{ij} P_j + n_i} \tag{2.2}
\]

\( G_{ii} \) is the path gain of the desired communication links, while \( G_{ij} \) are path gains of interference links. \( P_j \) is thus the transmit power of interfering transmitters. \( n_i \) is the additive noise in link \( i \). Based on expressions 2.1 and 2.2, the power control solution becomes

\[
P_i \geq \gamma_0 \left( \sum_{j=1, j\neq i}^{n_{Tx}} \frac{G_{ij} P_j + n_i}{G_{ii}} \right) \tag{2.3}
\]

The above description is an example in which the aim is simply to meet a certain SINR target. In practice, many different objectives can be defined, e.g. achieving minimum total transmit power or maximum system throughput.

Three power control algorithms are considered in this thesis. These algorithms are designed specifically for cellular networks having D2D communication links.

1. Standard LTE uplink power control for both cellular and D2D UEs.
2. Utility-maximization power control \([8]\) for both cellular and D2D UEs.
3. A hybrid power control scheme, in which all UEs in cellular mode use LTE uplink power control and D2D UEs use the utility-maximization power control.

As explained in the previous section, power control algorithms can be based on either a centralized or distributed approach. The LTE power control falls into the centralized power control category, while the utility-maximization power control is a distributed approach. The hybrid power control is a mixture of centralized and distributed approaches.

The algorithms are evaluated in terms of spectral and energy efficiency. The utility-maximization power control scheme, which calculates transmit powers that correspond to the best trade-off between power and system capacity, is chosen as a benchmark for optimality.
CHAPTER 2. THEORETICAL BACKGROUND

2.4 Resource Allocation Problem

Radio resource allocation problem can be formally defined as figuring out how radio resources should be allocated to meet the instantaneous capacity and QoS demand of the users [21]. The term "resources" here depends on the channel access scheme. For instance, "resources" would mean time-slots in time division multiple access (TDMA) systems or frequency bands in frequency division multiple access (FDMA) systems. The concept of radio resources in TDMA and FDMA systems is best explained by Figure 2.2.

This thesis focuses on D2D communications in cellular networks with LTE technology, thus the physical transmission resources in question are OFDM time-frequency resource blocks, as illustrated in Figure 2.3. A resource block consists of 72 or 84 resource elements and is equivalent to 0.5 ms slot in the time domain and 12 subcarriers in frequency domain [1].

For each communication link, either cellular or D2D, sufficient resource blocks must be allocated. The number of required resource blocks can vary according to the application. Video streaming applications, for instance, would require more resources than email applications.

If possible, orthogonal resources should be allocated to all links so that no intracell interference will be generated. However, this cannot happen if there are not enough orthogonal resources. In this situation, resource reuse is neces-
sary. This is a problem because UEs sharing the same radio resource generate interference to each other. Due to the random positions of the UEs, selection of resource for each link becomes critical as it will affect the interference generated to other links sharing the same resource. This is where resource allocation algorithms come into play. In this thesis, four resource allocation algorithms are considered:

1. Random resource allocation;
2. Balanced random allocation (BRA);
3. Cellular protection allocation (CPA);
4. Minimum interference allocation (MinInterf);

An important thing that needs to be considered is the kind of input required by each algorithm. Resource allocation algorithms typically need link quality information. For D2D communications, path gains of D2D links could be hard to obtain. MinInterf algorithm, which assumes that all cellular and D2D path gains are known, will then be used as a benchmark for optimality. Random resource allocation which does not require any knowledge of the channels will be considered as the most practical one.
Chapter 3

Power Control Algorithms

This thesis considers three power control algorithms: LTE power control, utility maximization power control, and hybrid power control. In this chapter, we give a brief explanation on each power control algorithm.

3.1 LTE Power Control

Uplink power control in LTE is a combination of open-loop and closed-loop power control mechanisms [1]. In the open-loop mechanism, UEs set their transmit power based on path loss measurements of the downlink. The closed-loop allows the base stations to make adjustments on the UEs’ transmit power by sending power-control commands to the UEs.

Open-loop power control in LTE uplink can be expressed in Equation 3.1 [14].

\[
P = \min\{P_{\text{max}}, P_0 + 10\log_{10} M + \alpha L\} \tag{3.1}
\]

where \(P_{\text{max}}\) is the maximum UE transmit power, \(P_0\) is a device-specific UE transmit power parameter, \(M\) is the number of assigned resource blocks, \(L\) is the measured downlink path loss, and \(\alpha\) is the path loss compensation factor.

Path loss compensation factor, a parameter whose value is in the range of 0 and 1, is intended to handle intercell interference. LTE uplink is designed to have no intracell interference in an ideal situation. In conventional LTE uplink, all UEs are allocated orthogonal resources. However, intercell interference can still be generated by UEs at the cell edge to UEs in neighbouring cells which are using the same resource. In other words, UEs at the cell edge generate greater interference than UEs close to the base station. Path loss compensation factor can then be set in such a way that UEs at the cell edge transmit with lower power. Typically, the farther away the UEs from the base station, the higher path loss compensation factor is assigned.

Closed-loop power control in LTE uplink is expressed in Equation 3.2 [14].

\[
P = \min\{P_{\text{max}}, P_0 + 10\log_{10} M + \alpha L + \Delta\} \tag{3.2}
\]
\( \Delta \) represents the tuning step, which can be fixed or dynamic. A dynamic tuning step based on the gap between targeted SINR and feedback SINR can be given as follows.

\[
\Delta = \begin{cases} 
\frac{|SINR_{\text{targeted}} - SINR_{\text{feedback}}|}{2}, & \text{if } > 1 \\
1, & \text{if } < 1
\end{cases}
\] (3.3)

### 3.2 Utility-Maximization Power Control

The utility-maximization power control is derived from an optimization problem which aims at maximizing the utility of all UEs while taking the transmit powers into account [8]. The utility itself is a function of SINR target, which can be mapped into transmission rate. The formal problem formulation is expressed in Equation 3.4.

\[
\begin{align*}
\text{maximize} & \quad \sum_l u_l(s_l) - \omega \sum_l P_l \\
\text{subject to} & \quad s_l \leq c_l(p), \quad \forall l, \\
& \quad p, s \geq 0
\end{align*}
\] (3.4)

In Equation 3.4, \( l \) is the link index; all cellular and D2D links are considered. Vectors \( p \) and \( s \) represent UE transmit powers and transmission rates respectively. \( u_l(\cdot) \) is the utility function, which is defined as \( u_l(x) \triangleq \ln(x), \forall l \). \( c_l(p) \) is the channel capacity associated with transmit power vector \( p \) and is expressed as follows. \( W \) is the system bandwidth and \( K \) is the SINR gap which depends on modulation and coding. \( \gamma_l(p) \) is the SINR at receiver-\( l \).

\[
c_l(p) = W \log_2(1 + K \gamma_l(p))
\] (3.5)

\( \omega \) is a parameter which tunes the rate-power trade-off. The value of \( \omega \) is positive, \( \omega \in (0, +\infty) \). If low power is desired at the expense of lower rate, \( \omega \) should be set to a high value. If high rate is the priority, \( \omega \) should be low.

An important property of utility-maximization algorithm is that it assumes adaptive SINR target. Since the aim is to maximize the utility of the whole system, instead of just one UE, it is advantageous to have higher SINR targets for links with good path gains. For the poor links, making the SINR targets adaptive ensures that the SINR targets can always be achieved.

Problem formulation in Equation 3.4 is not convex, therefore the optimization problem is redefined in its equivalent form given by Equation 3.6. Equation 3.6 assumes one-to-one correspondence between \( s_l \) and \( e^{\tilde{s}_l} \) as well as between \( P_l \) and \( e^{\tilde{P}_l} \).

\[
\begin{align*}
\text{maximize} & \quad \sum_l u_l(e^{\tilde{s}_l}) - \omega \sum_l e^{\tilde{P}_l} \\
\text{subject to} & \quad \log(e^{\tilde{s}_l}) \leq \log(c_l(e^{\tilde{P}})), \quad \forall l
\end{align*}
\] (3.6)
Problem defined in Equation 3.6 is convex and can be solved by using decomposition approach and iterative method. Utility-maximization algorithm is based on the decomposition of Equation 3.6 into two problems, namely Problem I and Problem II, which are about the user rate (SINR target) and transmit power respectively. Problem I is expressed in Equation 3.7.

\[
\begin{align*}
\text{maximize} & \quad v(\hat{s}) \\
\text{subject to} & \quad \hat{s} \in \hat{S} (3.7)
\end{align*}
\]

where the objective function \( v(\hat{s}) \) is defined as

\[
v(\hat{s}) \triangleq \sum_l u_l(e^{\hat{s}_l}) - \varphi(\hat{p})
\]

\[
\varphi(\hat{p}) \triangleq \omega \sum_l e^{\hat{p}_l} (3.8)
\]

As seen on Equations 3.7 and 3.8, Problem I is about finding the optimal SINR targets (thus are optimum user rates) for a given set of UE transmit powers. \( \hat{S} \) represents the set of feasible rate vectors that fulfills the constraints in Equation 3.6 for a given power vector \( \hat{p} \), that is \( \hat{S} = \{\hat{s}|\text{log}(e^{\hat{s}_l}) \leq \text{log}(c_l(e^\hat{p})), \forall l\} \). Problem I can be solved using Langrangian decomposition approach. Using iterative method to solve this optimization problem, a Lagrange multiplier is required in each iteration to update the SINR target.

Problem II, for a given \( \hat{s} \) vector, is expressed in Equation 3.9. Equation 3.9 shows that Problem II is about finding the optimal transmit power for a given set of SINR targets.

\[
\begin{align*}
\text{minimize} & \quad \omega \sum_l e^{\hat{p}_l} \\
\text{subject to} & \quad \text{log}(e^{\hat{s}_l}) \leq \text{log}(c_l(e^\hat{p})), \forall l
\end{align*} (3.9)
\]

This decomposition approach yields two problems that are intertwined. The utility-maximization power control algorithm employs a dual loop iterative solution to solve these optimization problems. Using an iterative method, Problem I is solved by outer loops which set the SINR targets in each iteration until the SINR targets are optimal.

Problem II is solved by inner loops which set UE transmit powers in each iteration until the transmit powers are optimal. When optimal transmit powers are reached, the inner loops also provide Lagrange multipliers (\( \lambda \)) required for SINR target update.

Inner loop mechanism involves SINR measurement at both the transmitter and receiver. Transmitter’s transmit power is denoted as \( P \) while receiver’s transmit power is denoted as \( \mu \). The same power update mechanism is done by the transmitter and receiver until the optimal values \( P^* \) and \( \mu^* \) are reached. Updating of receiver’s power is needed because \( \mu^* \) is a necessary input for calculating the Lagrange multiplier. For a given SINR target, power update is done according to the measured SINR.

SINR target for each link is defined as follows.
CHAPTER 3. POWER CONTROL ALGORITHMS

\[ \gamma_{lt}^{tg}(\tilde{s}_l) \triangleq 2^{\tilde{s}_l/W} - 1 \quad (3.10) \]

For each inner loop iteration \( t \), transmitter power update is done as described in Equation 3.11 while receiver power update is done as in Equation 3.12. In these equations, \( \gamma_l(p(t)) \) and \( \gamma_l^{FC}(\mu(t)) \) are the SINR measured at the receiver and transmitter respectively, in the preceding loop.

\[ P_{lt}^{(t+1)} = \frac{\gamma_{lt}^{tg}(\tilde{s}_l)}{\gamma_l(p(t))} P_{lt}^{(t)} \quad (3.11) \]

\[ \mu_{lt}^{(t+1)} = \frac{\gamma_{lt}^{tg}(\tilde{s}_l)}{\gamma_l^{FC}(\mu(t))} \mu_{lt}^{(t)} \quad (3.12) \]

At the end of the inner loop mechanism, optimal transmit power for each link, \( P_l^* \), can be calculated as given in Equation 3.13. Afterwards, Lagrange multiplier \( \lambda_l^* \) is calculated as given in Equation 3.14.

\[ P_l^* = e^{\tilde{P}_l^*}, \forall l \quad (3.13) \]

\[ \lambda_l^* = \log \left( 1 + \frac{1 + \lambda_{lt}^{tg}}{\lambda_{lt}^{tg}} P_l^* \log(2) \omega \mu_l^* \frac{G_{ll}}{\sigma_l \lambda_{lt}^{tg}} \right), \forall l \quad (3.14) \]

For the outer loop mechanism, initially the SINR target should be set to a low value. Then, at each outer loop iteration \( k \), the updating process expressed in Equation 3.15 is done. Lagrange multiplier \( \lambda_l^* \) is obtained from the inner loop. \( \epsilon \) is a predefined parameter characterizing the updating step.

\[ s_l^{(k+1)} = s_l^{(k)} \exp \left( \epsilon s_l^{(k)} \left[ u_l' \left( s_l^{(k)} \right) - \frac{\lambda_l^* \left( s_l^{(k)} \right)}{s_l^{(k)}} \right] \right) \quad (3.15) \]

A pseudo-code of utility-maximization power control algorithm is given in Algorithm 1. At the start of the algorithm, it is assumed that mode selection and resource allocation have been done.

Transmit power calculated at the last iteration of the inner loop is assumed to be optimal. Likewise, SINR target calculated at the last outer loop iteration is assumed to be optimal. In that sense, the number of outer loop and inner loop iterations greatly affects the output of the algorithm. Currently there is no exact way to determine the number of outer and inner loop iterations. However, the number of inner and outer loop iterations must be large enough so that the power and SINR target values converge.

There are two parameters which affect the convergence: the number of outer loop iterations and the SINR step size, \( \epsilon \). If we want to minimize signaling and reduce processing time, less outer loop iterations and high \( \epsilon \) are desirable. However, these parameters must be treated carefully. If \( \epsilon \) is too low or there are not enough outer loop iterations, the algorithm might not converge.
Algorithm 1 Utility-maximization power control algorithm

1: Define $\omega$ and $\epsilon$
2: Initialize SINR target $s_i^{(0)}$ with a low value
3: Initialize UE transmit power $P_i^{(0)}$ with a low value
4: for each outer loop iteration $k$ do
5:   Calculate SINR target $\gamma_i^{\text{tot}} \left( s_i^{(k)} \right)$ (Equation 3.10)
6:   for each inner loop iteration $t$ do
7:      Measure SINR at the receiver
8:      Calculate Tx transmit power update $P_i^{(t+1)}$ (Equation 3.11)
9:      Measure SINR at the transmitter
10:     Calculate Rx transmit power update $\mu_i^{(t+1)}$ (Equation 3.12)
11:   end for
12:  Calculate optimal transmit power $P_i^*$ (Equation 3.13)
13:  Calculate Lagrange multiplier $\lambda_i^*$ (Equation 3.14)
14:  Calculate SINR target update $s_i^{(k+1)}$ (Equation 3.15)
15: end for

3.3 Hybrid Power Control

Hybrid power control implements LTE open loop power control for the cellular UEs and utility-maximization power control for the D2D UEs. The objective is to take advantage of the practicality of LTE power control scheme and the performance improvement of utility-maximization scheme. This hybrid scheme is designed to address the drawbacks of the two power control algorithms, making it have some preferable properties in comparison.

- Compared to utility-maximization algorithm, the hybrid power control:
  - has better compatibility with existing LTE systems
  - has less signaling and faster processing time

- Compared to LTE power control, the hybrid power control:
  - has better spectrum and energy efficiency
  - has better protection of cellular UEs

Hybrid power control is divided into two steps. The first step is power allocation for cellular UEs using LTE open loop power control. Transmit power for these cellular UEs will be kept at the values assigned by Equation 3.1. The second step is utility-maximization power control for the D2D UEs. The process is similar to normal utility-maximization power control, except that in hybrid scheme there is no transmit power update and there is an extra cellular protection mechanism.

A cellular protection mechanism is proposed for hybrid power control. Since cellular UEs’ transmit power levels are fixed, maximization of D2D UEs’ utility may result in D2D transmit power levels that are high enough to cause severe
interference to cellular UEs. In order to overcome this problem, an interference control parameter, \( I^* \), is introduced.

The parameter \( I^* \) is basically a maximum allowed value of the multiplication of \( P_l \) and \( G_l \). \( P_l \) is the D2D transmit power and \( G_l \) is the path gain between the D2D transmitter to the base station. Because it only considers interference from one D2D link, \( I^* \) does not represent the actual uplink interference received by cellular UEs. Instead, \( I^* \) can be seen as a practical approximation to such interference.

In terms of power allocation for D2D links, the problem of hybrid power control can be expressed in Equation 3.16. The index \( l \) of hybrid power control only represents the D2D links—this is different than the index \( l \) in the utility-maximization power control. The pseudocode of hybrid power control is given in Algorithm 2.

Maximize

\[
\sum_l u_l(s_l) - \omega \sum_l P_l
\]

subject to

\[
s_l \leq c_l(p), \quad \forall l,
\]

\[
p, s \geq 0, \\
P_l G_l \leq I^*
\]

Algorithm 2

1. Define \( \omega, I^* \), and \( \epsilon \)
2. Initialize SINR target \( s_l(0) \) with a low value
3. Initialize D2D UE transmit power \( P_l(0) \) with a low value
4. Assign transmit power for cellular UEs using LTE open loop power control (Equation 3.1)
5. for each outer loop iteration \( k \) do
6. Calculate D2D SINR target \( \gamma_l^{tgt}(s_l(k)) \) (Equation 3.10)
7. for each inner loop iteration \( t \) do
8. Measure D2D SINR at the receiver
9. Calculate D2D Tx transmit power update \( P_l^{(t+1)} \) (Equation 3.11)
10. Measure D2D SINR at the transmitter
11. Calculate D2D Rx transmit power update \( \mu_l^{(t+1)} \) (Equation 3.12)
12. if \( P_l G_l > I^* \) then
13. Assign \( P_l = I^*/G_l \)
14. Break inner loop
15. end if
16. end for
17. Calculate D2D optimal transmit power \( P_l^* \) (Equation 3.13)
18. Calculate Lagrange multiplier \( \lambda_l^* \) (Equation 3.14)
19. Calculate D2D SINR target update \( s_l^{(k+1)} \) (Equation 3.15)
20. end for


Chapter 4

Resource Allocation Algorithms

Four resource allocation algorithms are considered: random resource allocation, balanced random allocation, cellular protection allocation, and minimum interference allocation. All of the resource allocation algorithms include a mode selection mechanism.

Before going into the details of the resource allocation algorithms, it is important to mention a fundamental assumption. Resource allocation in this thesis assumes that each communication link, whether it is cellular or D2D, only requires one radio resource. Consequently, all resource allocation algorithms described in this chapter only work under such assumption.

The general flow of resource allocation implemented in this thesis is illustrated in Figure 4.1.

![Figure 4.1: Resource allocation overview](image)

Figure 4.1 shows that the first step of resource allocation is to provide orthogonal resources for all macro-cellular UEs. Then, for a given D2D candidate, the availability of orthogonal resource is checked. If it is possible to allocate an orthogonal resource to a D2D candidate link, then mode selection is performed. Up to this point, all resource allocation algorithms considered in this thesis behave in the same way.
If there is no orthogonal radio resource available for the D2D candidate, resource reuse is necessary. Each resource allocation algorithm has different resource reuse criterion. In other words, the difference between resource allocation algorithms can only be observed when there is a reuse of resources.

### 4.1 Mode Selection

Mode selection is done after a D2D candidate is given an orthogonal resource. However, the fact that there is an orthogonal resource for the D2D link does not necessarily mean that the D2D candidate should operate in D2D mode. If it is more advantageous to use cellular mode on that particular resource, the D2D candidate should work in cellular mode instead.

This thesis applies a mode selection which is based on path gains. If the path gain between the D2D transmitter and D2D receiver (D2D mode path gain, denoted as $G_{D2DMode}$) is higher than path gain between the D2D transmitter and the base station (cellular mode path gain, denoted as $G_{CellularMode}$), then communication should be carried out in D2D mode. Otherwise, normal cellular mode is selected.

### 4.2 Random Resource Allocation

In the case where there are no orthogonal resources left, random resource allocation does not consider path gains when allocating resources to D2D links. When resource reuse is needed, random allocation algorithm simply picks one resource randomly. This is the reason why random resource allocation is the easiest algorithm to implement. A pseudo-code of random resource allocation is given in Algorithm 3.

---

**Algorithm 3** Random resource allocation algorithm

1: Randomly allocate orthogonal resources to cellular UEs
2: for each D2D candidate do
3: if there is an orthogonal resource-$l$ left then
4: if $G_{CellularMode} \leq G_{D2DMode}$ then
5: D2D candidate transmits in D2D-Mode on resource-$l$
6: else
7: D2D candidate transmits in Cellular-Mode on resource-$l$
8: end if
9: else
10: Select a resource-$j$ randomly among all resources that have been used by other links
11: D2D candidate transmits in D2D-Mode on resource-$j$
12: end if
13: end for
4.3 Balanced Random Allocation

BRA algorithm is an improvement of random resource allocation algorithm. It still does not consider path gains when deciding which resource to reuse, but it considers the number of times a resource has been used. BRA algorithm introduces a counting variable $\rho_j$ which indicates the number of times a resource-$j$ has been used. A pseudo-code of BRA algorithm is given in Algorithm 4.

Algorithm 4 Balanced random allocation (BRA) algorithm

1: $\rho_j = 0 \forall j$
2: if there are cellular UEs in the cell then
3: Allocate orthogonal resources to cellular UEs
4: Set $\rho_j = 1$ for RBs assigned to UEs
5: end if
6: $\rho_{\text{min}} := \min_{j=1 \ldots R} \rho_j$ where $R$ is the total number of resource blocks
7: for each D2D candidate do
8: if $\rho_{\text{min}} == 0$ (there is an orthogonal resource-$l$ left) then
9: if $G_{\text{CellularMode}} \leq G_{\text{D2DMode}}$ then
10: D2D candidate transmits in D2D-Mode on resource-$l$
11: else
12: D2D candidate transmits in Cellular-Mode on resource-$l$
13: end if
14: else
15: $\rho_{\text{min}} := \min_{j=1 \ldots R} \rho_j$
16: Pick a resource-$j$ randomly out of the resources for which $\rho_j == \rho_{\text{min}}$
17: D2D candidate transmits in D2D-Mode on resource-$j$
18: Increment $\rho_j$
19: end if
20: end for

Figure 4.2 illustrates how resource reuse is done in BRA algorithm. D2D links are allocated a resource which has been used least.

Figure 4.2: Resource reuse in BRA algorithm
BRA tries not to allocate too many D2D links to the same resource—hence the term “balanced allocation”. The reasoning behind it is that using a resource too many times can cause severe interference. By prioritizing resources which are least-used to be allocated for D2D links, lower interference and higher SINR can be expected. If two or more resources have the same value of $\rho$, resource allocation is done randomly among them.

### 4.4 Cellular Protection Allocation

CPA algorithm further improves resource allocation in reuse mode by taking the cellular path gains into account. A pseudo-code is given in Algorithm 5.

**Algorithm 5** Cellular protection allocation (CPA) algorithm

1: $\rho_j = 0 \forall j$
2: if there are cellular UEs in the cell then
3: Allocate orthogonal resources to cellular UEs
4: Set $\rho_j = 1$ for RBs assigned to UEs
5: Store $g(j)$, which is the path gain between cellular UE using RB-$j$ and the base station
6: end if
7: $\rho_{\text{min}} := \min_{j=1}^{R} \rho_j$ where $R$ is the total number of resource blocks
8: for each D2D candidate do
9: if $\rho_{\text{min}} == 0$ (there is an orthogonal resource-$l$ left) then
10: if $G_{\text{CellularMode}} \leq G_{\text{D2DMoDe}}$ then
11: D2D candidate transmits in D2D-Mode on resource-$l$
12: else
13: D2D candidate transmits in Cellular-Mode on resource-$l$
14: Store $g(l)$, which is the path gain between the D2D transmitter in Cellular-Mode using RB-$l$ and the base station
15: end if
16: else
17: $\rho_{\text{min}} := \min_{j=1}^{R} \rho_j$
18: Pick a resource-$j$ randomly out of the resources for which $\rho_j == \rho_{\text{min}}$ and for which $j = (\text{argmax})g(j)$
19: D2D candidate transmits in D2D-Mode on resource-$j$
20: Increment $\rho_j$
21: end if
22: end for

The idea of CPA is to reuse resources for which the path gain between cellular transmitter already using that resource and the base station is the highest. High path gain between the cellular UE and the base station would mean that the cellular UE is “strong”, therefore it will not suffer much from
the resource reuse. In this sense, CPA algorithm protects the weaker cellular UEs. Figure 4.3 illustrates how resource reuse is done in CPA algorithm.

![Figure 4.3: Resource reuse in CPA algorithm](image)

**4.5 Minimum Interference Allocation**

MinInterf algorithm assumes that all path gains for cellular and D2D links are known. Using the path gains, interference generated to and received from other links sharing the resource can be estimated. Interference generated to other links is estimated as the sum of path gains between the D2D transmitter to all receivers sharing the same resource. Interference received from other links is estimated as the sum of path gains between the D2D receiver to all transmitters sharing the same resource.

Let $G_{t,r,j}$ be the path gains between transmitter-$t$ and receiver-$r$ using resource-$j$. For a given resource $j$, the following quantities are defined for each D2D link $l$.

\[
G_{\text{InterferenceGenerated},l,j} = \sum_r G_{l,r,j} \quad (4.1)
\]

\[
G_{\text{InterferenceReceived},l,j} = \sum_t G_{t,l,j} \quad (4.2)
\]

In order to clarify what $G_{\text{InterferenceGenerated}}$ and $G_{\text{InterferenceReceived}}$ mean, consider a cell having two resource blocks called RB1 and RB2. Initially, the cell has one cellular UE transmitting using RB1 and one D2D pair transmitting using RB2. A D2D candidate is detected in the system. The resource allocation algorithm must decide whether this D2D candidate should reuse RB1 or RB2.

Path gains in the system are $G_1, ..., G_6$ and are illustrated in Figure 4.4.

If the D2D candidate uses RB1, its transmitter will generate interference to the base station, and its receiver will receive interference from the cellular UE. Hence, $G_{\text{InterferenceGenerated},RB1} = G_6$ and $G_{\text{InterferenceReceived},RB1} = G_5$.

If the D2D candidate uses RB2, its transmitter will generate interference to the existing D2D pair’s receiver, and its receiver will receive interference from the existing D2D pair’s transmitter. Hence, $G_{\text{InterferenceGenerated},RB2} = G_4$ and $G_{\text{InterferenceReceived},RB2} = G_3$. 
A pseudo-code of MinInterf algorithm is given in Algorithm 6 [8].

\begin{algorithm}
\caption{Minimum interference (MinInterf) allocation algorithm}
\begin{algorithmic}[1]
\State Randomly allocate orthogonal resources to cellular UEs
\For{each D2D candidate} \State \textbf{if} there is an orthogonal resource-\textit{l} left \textbf{then} \State \textbf{if} $G_{\text{CellularMode}} \leq G_{\text{D2DMode}}$ \textbf{then} \State D2D candidate transmits in D2D-Mode on resource-\textit{l} \State \textbf{else} \State D2D candidate transmits in Cellular-Mode on resource-\textit{l} \State \textbf{end if} \State \textbf{else} \For{each available resource-\textit{j}} \State $S(\textit{j}) = [G_{\text{InterferenceGenerated,j}} + G_{\text{InterferenceReceived,j}}]$ \State \textbf{end for} \State D2D candidate transmits in D2D-Mode on resource-\textit{j} corresponding to the minimum value of $S$ \State \textbf{end if} \State \textbf{end for}
\end{algorithmic}
\end{algorithm}

Figure 4.4: Path gains considered in MinInterf algorithm
Chapter 5

Simulation Methods

5.1 Tools

Simulation is done using rudimentary network emulator (RUNE), a network simulator tool developed by Ericsson in MATLAB environment. RUNE is able to simulate an OFDMA system with a given set of parameters. Additional MATLAB scripts and functions are added to integrate D2D communication functions into the RUNE environment and to implement the power control and resource allocation algorithms.

5.2 System Model

5.2.1 Simulation Procedure

Because of many random components in the system model, Monte Carlo simulation is performed to obtain statistically reliable results. In each Monte Carlo iteration, hexagonal cells are created, then cellular UEs and D2D UEs are randomly placed within the cell. Path gains for all links are then calculated, and power control and resource allocation are executed. After the last Monte Carlo iteration is executed, parameters of interest (e.g. SINR, consumed power, throughput) can be evaluated.

5.2.2 Network Layout

The cellular network is modelled as a hexagonal grid. Each hexagon represents a cell with radius $R$. The number of cells assumed in this thesis is 7. The antenna system is assumed to be omnidirectional, which means one base station serves exactly one cell. In order to better evaluate intercell interference, wrap-around technique is used. This technique replicates the network around the simulated system several times, so that interference experienced by border cells is not underestimated.
5.2.3 Positioning of UEs

Cellular UEs are randomly dropped within the cell with uniform distribution. Since the focus is on uplink transmission, only cellular transmitters are generated. The same number of cellular UEs are dropped in all cells.

A slightly different positioning technique is applied for D2D candidates. Unlike cellular UEs, D2D candidates are pairs so that both transmitters and receivers must be generated. In addition, there is a distance constraint for D2D transmitter-receiver pairs.

Firstly, D2D transmitters are randomly dropped within the cell with uniform distribution. D2D receivers are generated randomly within the distance $r_{D2D} \pm \Delta r_{D2D}$ from their respective transmitters. $r_{D2D}$ is the average distance between D2D transmitter and its receiver, while $\Delta r_{D2D}$ is the degree of freedom. This distance constraint makes sure that D2D transmitter and receiver are in the proximity of each other, which is important because D2D communication loses its gains when the transmitter and receiver are located far away from each other.

In Figure 5.2, a snapshot of the cellular system and generated UEs is shown. Figure 5.2 shows seven hexagonal cells with one cellular UE and two D2D pairs in each cell. Blue dots represent cellular UEs, green dots represent D2D transmitters, while red dots are D2D receivers.
5.2.4 Channel Model

Radio propagation experienced by each communication link is modelled as follows (in dB).

\[ G_l = G_{\text{dist}_l} + G_{\text{shadow}_l} + N_l \]  

Equation 5.1 describes the path gain of each link. The first term, \( G_{\text{dist}_l} \), is the distance-dependent component. This component is controlled by distance attenuation coefficient \( \alpha \). \( G_{\text{dist}_l} \) is proportional to \( r_l^{-\alpha} \), where \( r_l \) is the distance between the transmitter and receiver in link \( l \).

The second term, \( G_{\text{shadow}_l} \), is lognormal shadow fading. There are two parameters controlling the shadow fading component: \( \sigma \) and \( \rho_{DL} \). \( \sigma \) is the standard deviation of lognormal distribution characterizing the shadowing, while \( \rho_{DL} \) is the downlink correlation coefficient. For this thesis, \( \rho_{DL} \) is not relevant since downlink propagation is not considered. The last term, \( N_l \), is the additive thermal noise.

This channel model is relatively simple but enough to reasonably model a static environment. However, it should be noted that this channel model does not consider fast fading.

5.2.5 Parameters

Some simulation parameters, e.g. the number of UEs and the number of resource blocks, are set differently according to the intended simulation scenario. However, some parameters are always kept at the same values. Simulation parameters that are universal for all simulations in the thesis are summarized in Table 5.1.
Table 5.1: General simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System bandwidth</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Number of cells</td>
<td>7</td>
</tr>
<tr>
<td>Cell radius</td>
<td>500 m</td>
</tr>
<tr>
<td>Gain at 1 meter distance</td>
<td>-37 dB</td>
</tr>
<tr>
<td>Thermal noise per MHz</td>
<td>-114 dBm</td>
</tr>
<tr>
<td>Path loss coefficient, $\alpha$</td>
<td>3.5</td>
</tr>
<tr>
<td>Lognormal shadow fading $\sigma$</td>
<td>6 dB</td>
</tr>
<tr>
<td>Number of resource blocks requested by each user</td>
<td>1</td>
</tr>
<tr>
<td>Number of Monte Carlo simulations</td>
<td>100</td>
</tr>
</tbody>
</table>

Some simulation parameters, e.g. the number of UEs and the number of resource blocks, are set differently according to the intended simulation scenario. However, some parameters are always kept at the same values. Simulation parameters that are universal for all simulations in the thesis are summarized in the table.
Chapter 6
Simulation Results and Performance Analysis

6.1 Power Control

This section provides simulation results related to each power control algorithm. Each algorithm has different issues that need to be evaluated. For LTE power control, the issue is comparison between open-loop and closed-loop schemes. For utility-maximization and hybrid power control, the effects of each parameter and convergence of the algorithms are analysed. Finally, the performance of all power control algorithms are compared.

6.1.1 LTE Power Control

LTE power control is a heavily parameterised mechanism. For simplicity, $P_0$ and $P_{\text{max}}$ are always kept at the same values in this thesis, which are 24 dBm and -78 dBm respectively. A simulation is done to evaluate D2D performance when D2D UEs use LTE power control with different values of path-loss compensation factor $\alpha$ and two different types of LTE power control (open-loop and closed-loop). Cellular UEs, on the other hand, are always set to use open-loop LTE power control. Tuning parameter $\Delta$ in closed-loop LTE power control is set to 1 with 40 closed-loop iterations. Results are shown in Figure 6.1.

Figure 6.1 shows that D2D UEs perform better in terms of SINR when $\alpha$ is higher. This is simply caused by the fact that allocated transmit power is proportional to the path-loss compensation factor, as written in Equation 3.1. It can also be seen that closed-loop mechanism always allocates higher power than its open-loop counterpart, which is in line with Equation 3.2.

An interesting to note is that the difference between open-loop and closed-loop power control decreases when $\alpha$ is higher. In practice, it is common to set $\alpha$ to 0.8. For the rest of the discussion, unless specified otherwise, the term "LTE power control" would refer to open-loop LTE power control with $\alpha = 0.8$. 
Figure 6.1: Power and SINR performance with LTE power control
6.1.2 Utility-Maximization Power Control

Convergence Analysis

Utility-maximization power control is an iterative algorithm, hence we need to make sure that convergence is achievable. Figure 6.2 shows the evolution of transmit power for each UE in a utility-maximization algorithm.

![Figure 6.2: Power convergence in utility-maximization power control, $\epsilon = 0.05$](image)

$\epsilon = 0.08$

![Figure 6.3: Power convergence in utility-maximization power control, $\epsilon = 0.08$ and $\epsilon = 0.1$](image)

In order to assure convergence, it is crucial to choose the right value of $\epsilon$. It is desirable to have high value of $\epsilon$ in order to speed up the SINR convergence, but if $\epsilon$ is too high, the system will not be stable. Figure 6.2 shows that with $\epsilon = 0.05$, the system is stable and the transmit power of each UE converges. The red lines represent cellular UEs while the blue lines are D2D transmitters. Both cellular and D2D UEs start with a low transmit power level and gradually approach the optimum values. It can be seen that the assigned transmit power for each UE does, in fact, converge.
This simulation has been repeated with $0.05 < \epsilon < 0.1$ and considerable ripple appears in the steady state. If $\epsilon \geq 0.1$, power does not converge. Figure 6.3 shows the evolution of transmit power when $\epsilon = 0.08$ and $\epsilon = 0.1$ are chosen in the utility-maximization power control.

For the rest of the discussion, the simulation assumes a 7-cell system with 6 cellular UEs and 6 D2D pairs in each cell. Simulation is done with 100 outer loop and 10 inner loop iterations. SINR step size parameter $\epsilon$, unless specified otherwise, is set to 0.05. With $\epsilon = 0.05$, convergence of SINR and the corresponding rate can also be observed in Figure 6.4.

Compared to the outer loop mechanism, the inner loop mechanism converges much faster. For a given SINR target, the optimum transmit power can be achieved in about 10 inner loop iterations [8].

To minimize processing time and signaling, the number of outer loops must be decided carefully. The more outer loop iterations performed, the better the SINR would be, because outer loops essentially determine SINR target. However, sometimes it is not necessary to reach the actual point of optimality, because reducing the number of outer loops by 10 or 20 would still result in a good SINR performance. Such phenomenon is shown in Figure 6.5. For example, running the utility-maximization algorithm with 90 or 100 outer loop iterations would result in identical SINR for both cellular and D2D UEs. Figure 6.5 shows that 70 would be a reasonable number of outer loop iterations to achieve next-to-optimal performance.

Figure 6.6 shows how total utility converges. This figure compares two cases, one is an 8-PRB system (8 resource blocks, 6 cellular UEs, and 6 D2D pairs per cell) and the other is a 4-PRB system (4 resource blocks, 3 cellular UEs, and 3 D2D pairs per cell). Figure 6.6 also compares two different values of $\omega$ for each case. Looking at the results, we can observe that all four cases require at least 70 outer loop iterations to reach utility convergence. This suggests that neither $\omega$ nor the number of UEs affects the convergence speed, which is understandable because these two parameters merely scale the utility.
Based on the whole convergence analysis of utility-maximization power control algorithm, it is safe to say that convergence speed is only affected by the SINR step size parameter, $\epsilon$. Although essentially $\epsilon$ is the key of outer loop convergence, it also controls inner loop convergence because inner loop updating process is a function of SINR target (see Equation 3.11 and Equation 3.12). For $\epsilon = 0.05$, at least 70 outer loop iterations are needed to achieve optimality, regardless of $\omega$ and the number of users.

**Effects of $\omega$**

A positive number $\omega$ is a very important design parameter in the utility-maximization power control algorithm. It basically tunes the power-rate trade-off. According to Equation 3.4, if $\omega$ is set to a low value, utility-maximization
Figure 6.7: Utility-maximization power control with different $\omega$: Distribution of SINR and power

will result in high SINR target and high transmit power. On the contrary, if $\omega$ is set to a high value, the impact of increasing transmit power to the decrease of utility will be more severe. Consequently, the algorithm will assign low transmit power at the expense of low SINR target, i.e. low rate. This behaviour is clearly apparent in simulation results presented in Figure 6.7.

All plots in Figure 6.7 compare four different values of $\omega$ and evaluate the power and SINR for distribution cellular and D2D UEs. The performance is benchmarked against open-loop LTE power control (with $\alpha = 0.8$). Figure 6.7 demonstrates how utility-maximization power control can be very flexible. When $\omega = 1$, for instance, the distribution of cellular UEs’ transmit power is similar to that of open-loop LTE power control.

Utility-maximization power control is clearly superior in terms of SINR performance of D2D UEs. However, for the macro-cellular UEs, we can see
that there is a small performance degradation brought by utility-maximization power control in the low SINR region. This result motivates the introduction of parameter $I^*$ in the proposed hybrid power control design.

The choice of $\omega$ is, in principle, arbitrary. If the network design requires high spectrum efficiency more than it needs energy efficiency, a low $\omega$ should be chosen. If energy efficiency is prioritized instead, $\omega$ should be high. However, it should be noted that $\omega$ cannot be too high nor too low. If $\omega$ is too low, what would happen is that all UEs will be allocated the same power which is $P_{\text{max}}$ (the maximum allowed transmit power for the UEs). A similar behaviour can be observed in Figure 6.7; when $\omega = 0.01$, roughly half of the cellular UEs transmit in maximum power. Then, the system will be very interference-limited and system throughput will be low. If $\omega$ is too high, all UEs will transmit with power $P_{\text{min}}$, which basically means nobody is transmitting.

6.1.3 Hybrid Power Control

Convergence Analysis

The left plot of Figure 6.8 displays the evolution of UEs’ transmit power in a hybrid power control algorithm with 200 outer loop and 10 inner loop iterations. This figure assures that although the cellular UEs do not play by the rules of utility-maximization—cellular UEs’ transmit power is fixed by LTE power control—in hybrid power control, convergence can still be achieved.

![Figure 6.8: Power and SINR convergence of individual UEs in hybrid power control](image)

It can be seen in the figure, that macro-cellular UEs’ transmit power levels (drawn by red lines) are kept constant throughout the looping operations. Meanwhile, D2D UEs (blue lines) follow the utility-maximization algorithm to approach the optimum transmit power levels. In the simulation, the interference threshold is set at $I^* = 50N_0$, where $N_0$ is the thermal noise power. With this level of threshold, we can observe how D2D UEs are allocated considerably
Figure 6.9: Hybrid power control with different $\omega$ and $I^*$: Distribution of SINR

less power than cellular UEs. The purpose is to prevent cellular UEs’ SINR from degrading too much, which is visible in the right plot. The right plot shows the corresponding SINR convergence.

From Figure 6.8 we can also see that the convergence speed of hybrid power control algorithm is similar to that of utility-maximization power control, given that they both use the same value of $\epsilon$ (both simulations for hybrid and utility-maximization power control assume $\epsilon = 0.05$). It is reasonable because hybrid power control’s convergence is not disturbed by the fixed macro-cellular transmit power assigned by LTE power control. Hybrid power control maximizes the utility of D2D UEs only, as mentioned in section 3.3. In this sense, it can find the optimum D2D transmit power by simply treating the cellular links as additional noise.

**Effects of $\omega$ and $I^*$**

Figure 6.9 presents the SINR performance of hybrid power control with various values of $\omega$ and $I^*$. Let us first consider the case of $I^* = 500N_0$. This is the case where interference threshold is set at a high value, hence the expected performance would be close to that of utility-maximization power control. The figure shows that for the D2D UEs, the effect of $\omega$ on hybrid power control is exactly the same as in utility-maximization power control. Lower $\omega$ boosts higher SINR for D2D links.

However, for the cellular UEs, the opposite phenomenon occurs. Lower $\omega$ results in low cellular UE SINR. This is due to the fact that in hybrid power control, $\omega$ does not apply to the macro-cellular UEs. The utility-maximization is only carried out by D2D UEs. Therefore, when SINR target for each D2D link is gradually updated to reach maximum utility, D2D transmit power is always increased without taking the interference caused to the cellular links.
into account. Lower $\omega$ triggers higher D2D transmit power, which causes severe interference to cellular links. This is why it is important to have an additional constraint for D2D transmit power in hybrid power control.

The simulation considers three values of $I^*$: $500N_0$, $N_0$, and $N_0/500$. $500N_0$ is an extreme case in which the interference threshold is very high. When $I^* = 500N_0$, essentially no upper limit on D2D transmit power is imposed in the inner loops. Power optimization is let to run as if it would run in a conventional utility-maximization power control.

When $I^*$ is set to $N_0$, a lower transmit power threshold is defined for each D2D link, which is dependent on the link’s path gain to the base station. Simulation result proves that this approach can greatly reduce the interference generated to the cellular links. As seen in Figure 6.9, SINR of cellular UEs can be improved by up to 8 dB if $I^*$ is set to a sufficiently low value.

However, if $I^*$ is too low, D2D links can suffer very low SINR with little to no improvement brought to cellular links’ SINR. This is demonstrated by the extreme low case, $I^* = N_0/500$. While the cellular links’ SINR distribution is almost identical to $I^* = N_0$ case, the SINR distribution of D2D links is terrible. In fact, judging by the CDF curves of D2D’s SINR, it seems that all D2D transmitters transmit with minimum allowable power $P_{min}$. The threshold $I^* = N_0/500$ is simply too low for the inner loops to work properly.

### 6.1.4 Comparison of Power Control Algorithms

Figure 6.10 summarizes power and SINR performance of all power control algorithms considered in this thesis. LTE closed loop power control is shown to have better D2D SINR performance than the open loop power control.

For the D2D links, utility-maximization power control results in much better performance than LTE power control. Even when $\omega$ is set to 10—a high value—to aim for good energy efficiency, there is still around 3 dB gain achieved by the SINR. Utility-maximization power control tends to decrease cellular links’ SINR in the low SINR region (around 3 dB loss). However, it actually improves the cellular SINR in high SINR region.

Hybrid power control is proven to have superior performance in cellular links’ SINR. When $I^*$ is adjusted to a right value, cellular UEs can be protected while still gaining acceptable SINR in D2D links.

When $I^*$ is set to $500N_0$, which is a high value, hybrid power control and utility-maximization power control (with the same $\omega$) have identical SINR performance for the D2D links. However, the cellular UEs’ SINR performances are different. In terms of macro-cellular UEs’ SINR, utility-maximization power control performs better in high SINR region. This is caused by the fact that with this particular $\omega$, the utility-maximization power control allocates slightly higher power to the cellular UEs than the LTE open-loop power control. LTE open-loop power control is what is applied by the hybrid scheme to calculate the cellular UEs’ transmission power.
6.2 Resource Allocation

In order to compare the performance of resource allocation algorithms in a typical D2D communications scenario, simulation is done with the following setting:

- 7 cells with 8 resource blocks, 6 cellular UEs, and 6 D2D pairs per cell
- using LTE open-loop power control algorithm with $\alpha = 0.8$
- average distance between D2D transmitters and receivers is 50 m with 20 m degree of freedom

Based on these assumptions, the effect of resource allocation algorithms on SINR is presented in Figure 6.11. What we can observe in this figure is that MinInterf algorithm clearly has better SINR performance both for cellular and
6.2.1 Effects of the Number of D2D Pairs

It is expected that resource allocation algorithms would have greater effects on SINR if there were more instances of resource reuse in the system. In
order to prove this, a simulation is done by adding more D2D pairs in the 8-PRBs system. Figure 6.12 shows the SINR performance of a system with 8 resource blocks, 6 cellular UEs, and 16 D2D pairs in each cell. As seen in Figure 6.12, the superiority of MinInterf algorithm over other algorithms is even more apparent. The performance of other algorithms, however, is still almost identical. It would then be reasonable to use MinInterf algorithm in this situation, provided that all the path gains required by MinInterf are known. Otherwise, random resource allocation or BRA algorithm would be good options.

### 6.2.2 Effects of D2D Transmitter-Receiver Distance

![CDF curves of cellular UEs’ SINR show that MinInterf still has up to 3 dB gain over other algorithms. This time, the SINR curves of random resource allocation, BRA, and CPA algorithms are more distinguishable. CPA algorithm is shown to have poor performance in high SINR region. It is caused by the fact that CPA always prefers reusing the resource belonging to cellular UE with the highest path gain. In terms of D2D UEs’ SINR, CPA algorithm performs well—CPA’s performance is very similar to MinInterf’s.

Observing the D2D SINR curves in this high $r_{D2D}$ situation, we can start seeing how BRA performs better than random resource allocation, CPA performs better than BRA, and MinInterf performs better than CPA. However, the difference is still not significant.
6.2.3 Effects of High Interference from D2D Links

To emulate high interference from D2D links, instead of LTE open-loop power control, utility-maximization with low $\omega$ is chosen. $r_{D2D}$ is set to 50 m. Figure 6.14 presents the SINR comparison between resource allocation algorithms with these assumptions. MinInterf is shown to be more advantageous in this case; about 5-8 dB better SINR can be expected. This suggests that interference approximation carried out by MinInterf works well in a high interference situation.

6.3 Spectrum Efficiency and Energy Efficiency Gain of D2D

Having gone into the details of power control and resource allocation, it is interesting to see if D2D can really improve spectrum and energy efficiency in a cellular network. Two scenarios are evaluated:

1. There are orthogonal resources available for D2D candidates
2. There are no orthogonal resources for D2D candidates, i.e. resource reuse is needed

Power control and resource allocation algorithms implemented are LTE open loop and MinInterf respectively.

6.3.1 Without Resource Reuse

Figure 6.15 presents the simulation results related to how D2D can improve system performance by using only orthogonal resources.
Figure 6.15: Comparison of cellular mode, D2D mode, and mode selection when there is no resource reuse
In order to show the gain of D2D, a simulation is done to evaluate total system power and total system rate in three different situations:

1. All UEs—cellular UEs and D2D candidates—are forced to operate in cellular mode
2. D2D candidates are forced to operate in D2D mode
3. Mode selection is enabled; D2D candidates may operate in cellular or D2D mode depending on the link qualities

The simulation assumes that there are 8 resource blocks and 4 cellular UEs in each cell. The number of D2D candidates is varied between 1 and 4, which means that there are enough orthogonal resources for cellular and D2D UEs. Additionally, the average distance between D2D candidates’ transmitter and receiver \(r_{D2D}\) is varied between 10 and 250 m, with degree of freedom \(\Delta r_{D2D} = 5\) m. Aggregate system throughput and transmit power, averaged over 100 Monte Carlo iterations, are plotted in Figure 6.15.

Figure 6.15 shows that D2D mode can significantly increase the total system throughput and reduce the total transmit power when D2D receivers are close to their respective transmitters. The throughput gain and transmit power reduction are proportional to the number of D2D candidates in each cell and inversely proportional to \(r_{D2D}\). This clearly shows proximity gain of D2D communications.

However, if the transmitter-receiver distance exceeds a certain threshold (approximately 100 m in this particular simulation), D2D loses its ability to improve spectrum and energy efficiency. In fact, forcing D2D candidates to operate in D2D mode when \(r_{D2D}\) is too high will hurt system throughput and unnecessarily increase transmit power.

Figure 6.15 also shows that mode selection is the best solution—it always results in higher throughput and lower transmit power compared to traditional cellular mode. How much mode selection can improve throughput and transmit power depends on the distance between D2D transmitter and receiver, as well as the number of D2D candidates in the system. Mode selection becomes more advantageous when there are more D2D candidates and \(r_{D2D}\) is small.

### 6.3.2 With Resource Reuse

Although there are no orthogonal resources left for D2D candidates, it is still possible to allow D2D communications by reusing the resources which are already allocated to cellular UEs and/or other D2D UEs. A general trend that can be expected from resource reuse is that total system capacity can be increased at the expense of higher transmit power. In order to prove this, a simulation is done by adding more D2D candidates in the system.

The simulated system is set to have 8 resource blocks and 4 cellular UEs per cell, as previously done for no-reuse case. This time, 6 to 16 D2D candidates are dropped in each cell to impose resource reuse. The simulation is
repeated for various $r_{D2D}$ distances in the range of 10 to 150 m. Total system throughput and total system power are calculated, averaged over 100 Monte Carlo iterations, and compared against the non-reuse case. Power control and resource allocation algorithms implemented are LTE open loop and MinInterf respectively.

Figure 6.16 presents the results of this simulation. The x-axes represent $r_{D2D}$, which is the average distance between D2D transmitters and receivers (with 5 m degree of freedom). Red lines on the plots indicate the no-reuse case applied as a benchmark. The chosen benchmark case has 4 D2D candidates in each cell which are all allocated orthogonal resources. y-axis of the left figure is the ratio between calculated total throughput in each reuse case and the corresponding total throughput in the benchmark case. Hence, the left figure essentially shows the throughput gain that can be expected if D2D links are allowed to reuse radio resources. Similarly, y-axis of the right figure also represents the total power ratio between reuse and no-reuse situations.

Based on the results shown in Figure 6.16, it can be concluded that resource reuse should only be allowed when D2D transmitters and receivers are close to each other. To be specific, resource reuse is only reasonable to do when $r_{D2D}$ is around 70 m or less. In fact, when $r_{D2D}$ is very small (20 m or less), resource reuse can be done as many times as possible, harvesting the throughput gain...
without increasing the transmit power. This result suggests that resource reuse for close-distance D2D communications is a promising concept. It also highlights the importance of resource allocation algorithms.

6.3.3 Effects of Power Control Algorithms

Figure 6.17: Comparison of power control algorithms: average spectrum efficiency and energy efficiency

Figure 6.17 illustrates the general behaviour of each power control algorithm based on average spectrum efficiency and average energy efficiency. Figure 6.17 shows that there is no perfect power control algorithm with the best spectrum efficiency as well as the best energy efficiency. Each power control algorithm boosts one performance metric, either spectrum or energy efficiency, in exchange of the other. If we prefer a ”balanced” power control algorithm that can achieve sufficiently high spectrum efficiency with acceptable energy efficiency, it would be reasonable to choose hybrid power control algorithm with $I^* = N_0$. 
Chapter 7

Conclusions

7.1 Summary

Integrated into a cellular network, D2D communications would allow a transmitter and receiver to exchange information through a direct link instead of having to use the base station as a relay. This improves the spectrum and energy efficiency of the network. It is also possible for D2D links to reuse the radio resource. However, D2D links in a cellular system generate interference to existing macro-cellular UEs. Therefore, it is important to investigate radio resource management techniques that can handle the interference.

This thesis addresses the issue of radio resource management for D2D communications in cellular networks, particularly about power control and resource allocation. LTE power control, utility-maximization power control, and hybrid power control schemes are considered. Four resource allocation algorithms are considered: random resource allocation, BRA algorithm, CPA algorithm, and MinInterf algorithm. The mode selection is carried out as a part of resource allocation mechanism.

Numerical results are obtained by performing Monte Carlo simulations. The system is modelled as a hexagonal grid of cells with a fixed number of resource blocks, macro-cellular UEs, and D2D candidate pairs in each cell. UEs are randomly dropped within the cell, with uniform distribution, while keeping a distance constraint between D2D transmitters and their receivers. Uplink resources are assumed to be the ones allocated for D2D links. The channel model includes distance-dependent path gain and random shadowing. Performance metrics of interest are spectrum efficiency and energy efficiency, which corresponds to SINR and transmit power respectively.

In principle, the performance of all power control algorithms can be controlled by tuning the algorithms’ parameters. For instance, we can increase the path-loss compensation factor in LTE power control to achieve better SINR in D2D links, in exchange of higher D2D transmit power. Meanwhile, utility-maximization power control and hybrid power control are controlled by $\omega$, a parameter which dictates the design priority—low $\omega$ results in high spectral
CHAPTER 7. CONCLUSIONS

efficiency but low energy efficiency, and vice versa.

Hybrid power control has been proposed in this thesis, with two objectives: allowing the macro-cellular UEs to keep using the standard LTE power control and protecting the macro-cellular links by imposing an interference threshold. Simulation results have shown that the cellular links can indeed be protected, i.e. the SINR is high, by choosing a sufficiently low interference threshold value.

In contrast to the power control algorithms, random resource allocation algorithms considered in this thesis do not depend on any parameter. They are also rather heuristic, having not been derived from optimization problems. The most important thing that distinguishes the resource allocation algorithms is practicality, which is based on what kind of input is required. MinInterf algorithm is the most difficult to implement as it requires the path gains of cellular and D2D links, as well as the number of times each resource has been used. CPA has lower complexity than MinInterf because it does not need to know D2D path gains. BRA algorithm only needs the information of how many times each resource has been used. Random resource allocation is the most practical resource allocation scheme as it needs no input.

7.2 Findings

1. Mode selection is very important in D2D communications, because it guarantees the improvement of spectrum and energy efficiency regardless of the distance between D2D pairs or the number of D2D pairs in the cell.
2. The gains of D2D are best achieved when D2D transmitter and receiver are close to each other, e.g. less than 100 m. If the distance between communicating UEs is too large, forcing D2D communications would in fact decrease system throughput and increase required transmit power.
3. D2D UEs should not be allowed to reuse radio resources when the distance between them is too large, e.g. more than 70 m. In this situation, the throughput gain is not worth the high power required for transmission.
4. In an LTE power control mechanism, higher path-loss compensation factor $\alpha$ results in better D2D performance. It is recommended to use $\alpha$ at least 0.8, because otherwise most D2D UEs would experience less than 0 dB SINR, which is not desirable.
5. Utility-maximization power control requires a considerably large number of outer-loop iterations in order to reach optimality. Faster convergence can be achieved by setting high $\epsilon$ (SINR step size), but $\epsilon > 0.05$ would result in steady state oscillation. It would even hinder the convergence. With $\epsilon = 0.05$, the minimum number of outer loop iterations that can achieve convergence is 70.
6. For utility power control and hybrid power control, high $\omega$ results in low transmit power and low transmission rate, while low $\omega$ results in high transmit power and high rate. $\omega = 1$ would allocate similar transmit power for cellular UEs as the transmit power allocated by LTE open-loop power control with $\alpha = 0.8$. If $\omega$ is too high, all UEs will transmit with minimum possible power, and vice versa.

7. Parameter $I^*$ in hybrid power control can protect macro-cellular links if it is set to a sufficiently low value. $I^* = N_0$, where $N_0$ is the thermal noise power, guarantees that better cellular UEs’ SINR performance than that of LTE power control. If $I^*$ is too low, D2D UEs will transmit with extremely low power, causing them to have poor SINR.

8. MinInterf always results in the best SINR performance, compared to other resource allocation algorithms.

9. Random resource allocation, despite being the simplest one, performs reasonably well and is therefore applicable for D2D communications. Random resource allocation also has a big advantage, which is the possibility to implement it in a fully distributed fashion.

10. BRA resource allocation algorithm performs better than random resource allocation, although the difference is not significant.

11. In terms of cellular UEs’ SINR, CPA algorithm performs badly in high SINR region due to its behaviour of ”sacrificing” the cellular UEs with high path gains.

7.3 Future Work

Although the system model implemented in this system is relatively elaborate, there are still rooms for improvement. For example, fast fading can be incorporated in the channel model. In this case, utility-maximization power control algorithm will most likely not work, hence it is interesting to design an optimal power control algorithm that works in fast-fading environment. Additionally, the algorithms could be tested in a bigger system, with more number of cells, resource blocks, and users.

The number of iterations required by utility-maximization power control to achieve convergence is quite high. Therefore, it is important to design a faster algorithm. This algorithm is preferably optimal and is derived from an optimization problem which is similar to the utility-maximization power control’s. If an iterative procedure is required, then the number of iterations should be less than 20 or 30.

Deriving an optimum resource allocation algorithm could also be an appealing research direction. However, based on the results of this thesis, we could say that resource allocation does not have a big impact on system performance in a typical situation. In this sense, perhaps it is best to focus future work on power control.
Bibliography


