SHARING

SELF-ORGANIZED HETEROGENEOUS ADVANCED RADIO NETWORKS GENERATION

D5.2 (Task T5.2)

Device-To-Device Communication Innovations

Date of delivery	12/02/2016
Contractual date of delivery	31/12/2014
Project number	
Editor(s)	
Author(s)	EURE, ORANGE, TCS
Dissemination level	
Workpackage	5
Version	0.6
Total number of pages	41

Abstract:

This report presents the main innovations and performance evaluation of Task 5.2 “Device-To-Device” inside WP5. D2D communications may cause very complex interference scenarios and without efficient interference control, overall cellular capacity and efficiency will suffer. We study interference management methods and their optimization allowing for the potential gains of D2D communications. We show the benefits of signal processing at the D2D receiver as well as fine-grain resource scheduling in terms of efficiently reusing the uplink frequency for D2D communications in several operational scenarios. Finally, we also assess the complexity and feasibility of deploying D2D-based services in the context of evolving 3GPP standardization.

Keywords:

Device-to-Device Communications, Interference Management, Resource Allocation, Distributed Caching, Content Offloading

Document Revision History

Version	Date	Author	Summary of main changes
0.1		EURE	First ToC
0.2		EURE	Second ToC
0.3	8/12/2014	TCS	Contribution on “Resource Allocation Schemes for "in and out of coverage" Scenario” – Currently in Section 4
0.4	18/12/2014	Orange	Contribution on Section 3
0.5	15/10/2015	EURE	Contributions to Sections 1,2,5,6
0.6	20/10/2015	EURE	Reorganization, editing, addition of scenarios, introduction and conclusions
0.7	03/11/2015	TCS	Correction of referencing issue after editing
0.8	12/11/2015	Orange	Correction of referencing issue for new Section 4
0.9			

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EXECUTIVE SUMMARY

This deliverable reports on the three main studies related to Device-to-Device (D2D) communications in the SHARING project, and in particular, provides three visions on the resource allocation problem for allowing D2D transmissions to share the uplink spectrum. The first study uses some classical and more recent results on interference channels to motivate the resource allocation problem for two unicast scenarios, namely where the eNodeB schedules D2D traffic for both known and unknown content. The case of known content applies to a future usage of memory in user-terminals as spatially-distributed cache. These caches are used to offload traffic to other user terminals in the vicinity of the relaying terminal. The other scenario is where the content is not known by the eNodeB and interference must be mitigated in both the eNodeB receiver and D2D receiver. In both cases, the regimes of interference where the D2D can benefit from sophisticated signal processing are shown.

The second study considers three-step optimal resource allocation framework when the eNodeB has perfect channel state information (CSI) of all links in the network. This is then relaxed for partial CSI information in the resource scheduler. In both cases the practical benefit of D2D communications sharing common frequency resources with regular cellular communications is very clearly demonstrated.

The final study examines the configuration and implementation complexity of practical uplink resource reuse scenarios in order to verify the feasibility of resource reuse. It also sets the scene for further work, where simulations will be performed in order to draw measurable conclusions expressed in terms of e.g. probability of reuse. It will be also showed through simulation that the pre-selection of equipment can been performed on a geographical basis.

1 INTRODUCTION

This report presents the main innovations and performance evaluation of Task 5.2 “Device-To-Device” inside WP5. D2D communications may cause very complex interference scenarios, and without efficient interference control, overall cellular capacity and efficiency will be limited. Thus, effective interference management plays a key role in realizing the potential gains of D2D communications. Existing works have not simultaneously considered the QoS requirements of UEs and the overall network performance. Thus, we will develop effective interference management and resource (frequency/subcarrier, power) allocation schemes for D2D communications which share common frequency resources with conventional cellular communications in order to optimize the network performance (Spectral Efficiency, coverage, and connectivity) while ensuring QoS requirements.

The document is split into four core sections. Section 2 provides the basic scenarios for which specific aspects are studied. Three scenarios are considered, the D2D unicast scenario where two end-user terminals communicate to each other using the uplink channel. The pair thus interferes with normal users transmitting to the basestation and, similarly, they are interfered by these users in the receiver of their point-to-point communications. A second scenario is focused on user seen as a broadcaster/multicaster for its vicinity. Finally, the third scenario describes the use of end-user terminals as caches for content offload and thus acting as relays under control of the basestation.

Section 3 provides an introduction to the analysis of spectral efficiency for D2D links sharing the uplink resource. This section provides information regarding the regimes of interference and the methods to mitigate them at the receiver side. In addition, we consider two important assumptions regarding the knowledge of the interference at the eNodeB. Firstly, we address the scenario where the D2D transmitter is a local cache of information on behalf of the network and the eNodeB scheduler is aware of the content that is being offloaded. In this case, the interference seen by eNodeB can be completely removed and thus does not impair the spectral-efficiency of the uplink channel. The second scenario is where the eNodeB is not aware of the content and thus cannot remove it. We describe the regimes of operation which are simply characterized as weak, medium and strong interference. We show that in both scenarios, the use of the sophisticated interference cancelling methods at the D2D receiver can provide significant benefits and can reduce the burden on the eNodeB scheduler in finding compatible users to schedule in conjunction with D2D transmissions.

Section 4 considers the resource allocation for D2D communications to maximize the overall network throughput while jointly guaranteeing quality of service of both regular cellular users and D2D users. A three-step optimal resource allocation framework when the eNodeB has perfect channel state information (CSI) of all links in the network is considered first. Afterwards we investigate resource allocation when only partial CSI is available at the eNodeB. A probability-based strategy utilizing the statistical characteristics of the channel and a user-selection limited feedback strategy are proposed, respectively, to deal with the channel uncertainty.

Section 5 provides a feasibility study of cellular-D2D reuse of radio resource, i.e. simultaneous use for cellular and D2D links, in the context of an LTE network. This feasibility study is first performed in terms of system architecture and protocol and will continue in terms of simulation results based on real constraints from recent 3GPP standardization activities. This work therefore investigates the conditions for such an allocation scheme to serve the expected Quality of Service (QoS) on both cellular and D2D links. Interference constraints have to be identified and new interference control techniques have to implemented along with a possible associated LTE system design (i.e. LTE network and User Equipments), including Message Sequence Charts (MSCs) and related protocols.

2 SCENARIOS AND CHALLENGES

2.1 D2D unicast scenario

Figure 1 describes the unicast scenario where a cellular user equipment UE-C is connected to eNodeB and two user-terminals (i.e. UE-S and UE-D) are involved in D2D communication, while camped on the same cell as UE-C. UE-C is transmitting using cellular uplink allocated resources by the eNB, and UE-S is reusing those resources for transmitting towards UE-D. This reuse will create additional interference at eNB side (i.e. from UE-S) but also at UE-D side (i.e. from UE-C). It may then be suitable to select a relevant UE-C so that both interferences are kept under the limits fixed by the QoS requirements for both cellular and D2D links. We denote by g_{cb} the channel gain between the UE-C and eNB, by g_{sb} the channel gain between the UE-S and eNB, by g_{cd} the channel gain between the UE-C and UE-D, and by g_{sd} the channel gain between UE-S and UED. Moreover, at eNB side and per each given UE-C, there is a minimum required Signal to Noise plus Interference Ratio (SINR) $\gamma_{b,req}$ to be respected, and at UE-D side there is a target SINR $\gamma_{sd,thres}$ to be considered, where the target is per each given UE-S reusing UE-C resources to transmit towards UE-D.

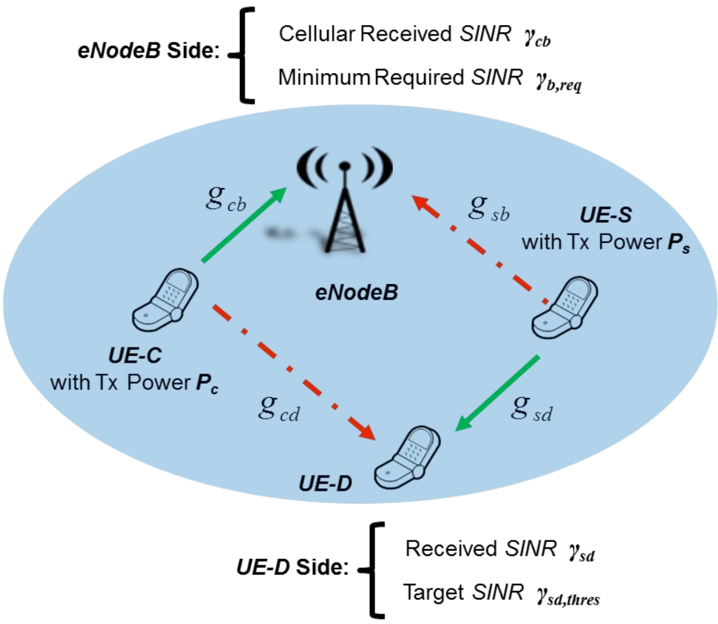


Figure 1 D2D communications reusing legacy LTE cellular Uplink resource: unicast scenario

2.2 D2D broadcast scenario

In the broadcast scenario (Figure 2) UE-S intends to broadcast to a set of UE-D within a certain communication range (3GPP distinguishes 3 classes of ranges: the short range (around 100 to 200 m), the medium range (around 500 m) and the long range (around 1000 m)). Because of the localized broadcast nature of the transmission, it is suitable to maintain the interference experienced at each UE-D (from UE-C) below a threshold so that the SINR experienced at each UE-D is greater than the required threshold.

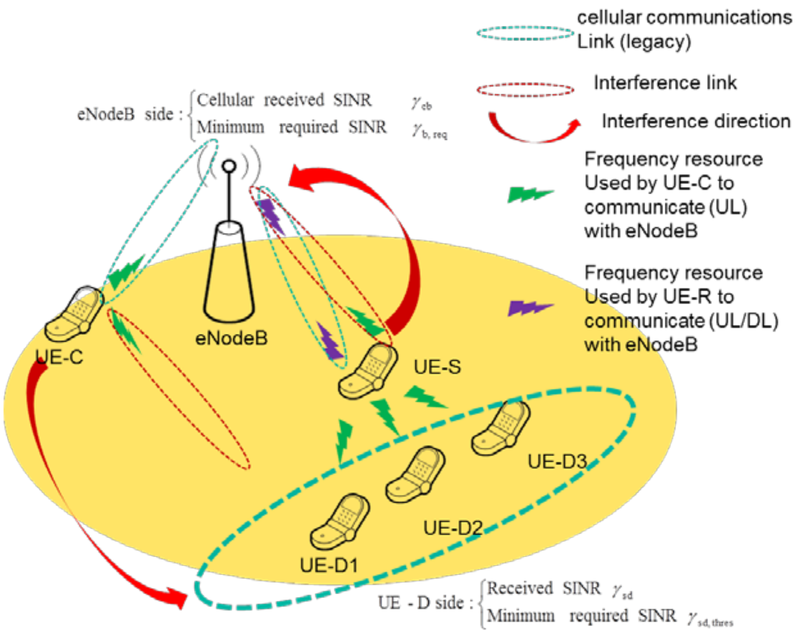


Figure 2 D2D communications reusing legacy LTE cellular Uplink resource: broadcast scenario

The main challenge faced is the selection of the relevant UE-C whose resource can be reused for D2D communications such that, on one hand we guarantee a required QoS for cellular communication (maintaining the interference from D2D below a threshold) and on the other hand we guarantee a certain QoS for D2D communication (select UE-C such that the interference experienced at the D2D receivers UE-D from UE-C is below a suitable threshold). Considering both the QoS of the cellular communication and the QoS of the D2D communication at the same time is quite challenging. Therefore, a particular attention is given to the investigation for the conditions of D2D communication and the selection of relevant UE-Cs to offer this double benefit.

The D2D-cellular spatial reuse concept has been investigated in previous research, [2]-[12], but the prior art is mainly focused on cellular protection against D2D interference. However, from the 3GPP requirements [1] , the network shall be able to determine whether the direct link can provide the necessary QoS to support the end user application. So an important contribution of our work considers two additional constraints: simultaneous protection of the QoS for both the cellular link and the D2D link. Many parameters such as distance, communication channel, maximum allowed power, and interference control are playing important roles in D2D communication, therefore it is challenging to achieve simultaneous QoS requirements for cellular and D2D. The approach of this contribution is quiet new and provides an algorithm that allows finding a relevant UE-C for resource reuse and at the same time it ensures that both the QoS (of cellular link and of D2D link) meet the required thresholds.

2.3 D2D Content Offload

Another scenario is where UEs are used by the infrastructure as distributed caches. We consider use of D2D links firstly to aid in the distribution of content by coverage extension due to the devices proximity. This can be seen as an instantiation of the two-hop relaying strategies considered in deliverable D5.1 [13]. The second usage of D2D links is to allow end-devices with cached content to exchange this content under the control of the local base stations either to aid in interference management of the overall network or due to the absence of the particular content in the local cache of the base stations. This communication would primarily be used to hide the content distribution in the background noise of the network and is made possible solely because of the combination of the proximity of the nodes and their capacity to store content with the macroscopic vision of base stations with respect to the nodes in their cells. We could consider both scheduled access and random-access multi-casting as a function of the number of nodes that are helping the eNB to deliver content.

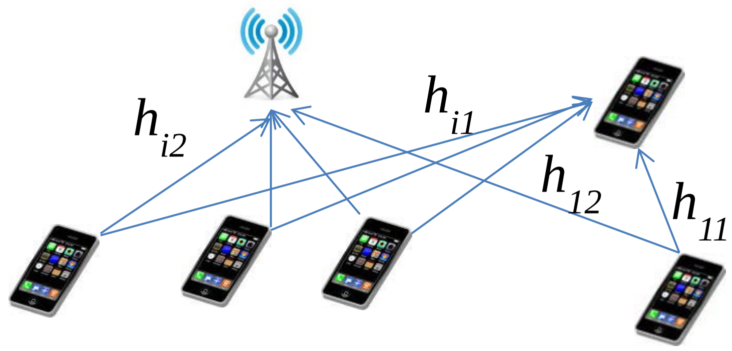


Figure 3: General D2D Scenario with Reuse of Uplink Frequency

3 Some Limits on Transmission with D2D Links

Consider the scenario shown in Figure 3 which corresponds to reuse of the uplink channel for a single D2D link for L nodes. Here the base station schedules the transmission of $L-1$ uplink users which interfere with one D2D link. The combined interference channel is given by

$$y_{in} = \sum_{j=1}^{L} \sqrt{P_{ij}} h_{ijn} x_{jn} + z_{in}, i = 1,2, n = 1 \dots N$$

Where P_{ij} and h_{ijn} are the average received power and instantaneous complex channel amplitude from node j to node i, and y_{in} and x_{jn} are received signal at node i and transmitted signal from node j. The signals are assumed to comprise N signaling dimensions, which can appropriately model OFDM or SC-FDMA transmission. All channels are assumed to be known perfectly by both receivers. The transmitted signals are assumed to satisfy the average power constraint

$$\sum_{n=1}^{N} E|x_{jn}|^2 \leq 1$$

and the noise is assumed to be circularly-symmetric Gaussian noise with variance σ^2.

At this point we can already highlight two cases. Firstly, we have the case where receiver 2, the base station, is scheduling a codeword coming from known content in node 1, the D2D transmitter. Here, the signal x_{1n} is known and thus $\sqrt{P_{i1}} h_{i1n} x_{1n}$ may be stripped out from the received signal at receiver 2. This will be termed the Z-channel case. Secondly we the general case that receiver 2 is scheduling a codeword that is unknown. The first case would correspond to using the D2D transmitter as a local cache of content that was previously sent to it for opportunistic offloading, whereas the second would correspond to content that is originating in the D2D transmitter.

In the following subsections we will provide bounds on the spectral efficiency that can be achieved in both cases. Specifically we are interested in evaluating the so-called sum-capacity in both cases. The information rate for node j in bits per dimension is denoted R_j and the sum-capacity is $\sum_{j=1}^{L} R_j$.

3.1 Using Known Results for the case $L = 2$

For the case $L = 2$ we can generalize the results from [55][33] (Z-Channel) to provide the sum-capacity exactly, albeit conditioned on a particular channel realization. This is given by

$$R_1 + R_2 = \begin{cases} \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2}\right)+\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2}\right), \text{if} \sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2}\right) < \sum_{n=1}^{N}\log_2\left(1+\frac{P_{21}|h_{21}|^2}{\sigma^2+P_{11}|h_{11}|^2}\right) \\ \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2}\right)+\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2+P_{21}|h_{21}|^2}\right), \text{if} \sum_{n=1}^{N}\log_2\left(1+\frac{P_{21}|h_{21}|^2}{\sigma^2}\right) < \sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2}\right) \\ \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2}+\frac{P_{21}|h_{21}|^2}{\sigma^2}\right), \text{otherwise} \end{cases}$$

The first condition corresponds to the case where the interference from the uplink user is strong enough to be decoded at the D2D link prior to decoding the desired signal. In the literature, this is known as the *strong interference condition*. Under this condition, the D2D receiver (1) can completely decode the interfering signal, re-encode the waveform corresponding to the uplink transmission and subtract it from the total received signal. This is known as *successive interference cancellation* and is commonly used in commercial UEs when receiving multi-layer coded streams in MIMO or in eNodeBs when multiple UEs are scheduled on common resources (multiuser detection). In order to benefit under this condition, specific signal processing is therefore required at the D2D receiver. Moreover, if the channel estimation is lossy, the residual error from interference cancellation can be significant if the interference level is high, reducing the benefit when exploiting this regime.

The second condition says that the interfering signal is very weak. Under this condition, the D2D receiver treats the interference from the uplink signal as additive noise, which is typically considered as non-Gaussian with known structure (i.e. quadrature-amplitude modulation) in practical scenarios. Such receivers are commonly understood and their performance can be readily assessed using standard techniques.

The third condition, finally, corresponds to a moderate interference level which is the most difficult regime to exploit efficiently. This is because the signaling techniques to achieve the spectral efficiencies predicted by this analysis would require that the eNodeB limit the code rate of the uplink user so that its signal component can be decoded by the D2D receiver (1) and stripped out prior to decoding the D2D signal. To see this, note that to be decoded by the D2D receiver, the rate of the first layer must satisfy

$$R_2 < \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{21}|h_{21}|^2}{\sigma^2+P_{11}|h_{11}|^2}\right)$$

and the rate of the D2D user is

$$R_1 < \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2}\right)$$

yielding the total rate sum rate

$$R_1 + R_2 < \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2}+\frac{P_{21}|h_{21}|^2}{\sigma^2}\right)$$

So, in this regime the uplink user pays the penalty to increase the rate of the D2D user which complicates the scheduling policy of the eNodeB. Moreover, in the other two regimes there is no such constraint on the uplink spectral efficiency as a function of the D2D link.

If now we turn to the case where interference is also experienced at the base station we must resort to bounding the capacity by generalizing the results of [55][34]. This yields the following upper-bound to the sum-capacity

$$R_1 + R_2 \le \min\left(\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{21}|h_{21}|^2}{\sigma^2}+\frac{P_{11}|h_{11}|^2}{\sigma^2+P_{12}|h_{12}|^2}\right) + \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{12}|h_{12}|^2}{\sigma^2}++\frac{P_{22}|h_{22}|^2}{\sigma^2+P_{21}|h_{21}|^2}\right), \frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2}\right)+\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2}\right),\right)$$

We can see two regimes of operations. In the case of very strong interference or very weak interference at both ends we are governed by the point-to-point channels (second term in the minimization). The very strong interference regime corresponds to where both receivers decode the interference and remove it prior to decoding the desired signals (similar to the case of known content). It is, in fact, the capacity of this interference channel. In a medium-interference scenario, we see a similar behavior to the known content case, however this is only a bound to the channel capacity.

We can mimic the known channel case where we use either single-user decoding (interference as noise) or interference cancellation at the D2D receiver. This will result in the following achievable rate

$$R_1 + R_2 \geq \max\left(\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2+P_{12}|h_{12}|^2}\right)+\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2+P_{21}|h_{21}|^2}\right),\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{11}|h_{11}|^2}{\sigma^2}\right)\right.$$
$$\left.+\min\left(\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{22}|h_{22}|^2}{\sigma^2}\right),\right)\frac{1}{N}\sum_{n=1}^{N}\log_2\left(1+\frac{P_{21}|h_{21}|^2}{\sigma^2+P_{11}|h_{11}|^2}\right)\right)$$

The first term in the maximization is the achievable rate with both receivers treating interference as noise. This will be a good strategy when both interference terms are very weak. The second term is where the D2D user first must decode the uplink signal, which puts a constraint on the spectral-efficiency of the uplink user and results the minimization term on the rate of the uplink user. We could add a third term where we impose decoding of the D2D user at the eNodeB, but this is neglected here as it would likely not be beneficial in most practical scenarios.

3.1.1 Numerical Evaluation for the case where content is known at the eNodeB

At this point we can already say that the most favorable conditions are either very strong interference when the D2D receiver is capable of performing successive interference cancellation or very weak interference since they both provide virtually orthogonal channels. The intermediate case suffers from a loss in dimensionality of the signal-space. This is depicted in Figure 4 where we show the influence of the strength of the interference on spectral-efficiency for the special case of $\frac{\mathrm{P}_{11}}{\sigma^2} = 20\text{dB}$, $\frac{\mathrm{P}_{22}}{\sigma^2} = 6\text{dB}$ and variable interference levels. These correspond to the case where we choose transmit powers yielding a high signal-to-noise ratio on the D2D link and a moderate one on the uplink. This highlights the need for scheduling of compatible uplink users with a D2D link since the UL or D2D links can be severely impaired and would hurt the overall efficiency. The overall spectral-efficiency, $R_1 + R_2$, in the three regimes of operation are shown by the three solid curves. The effect on the D2D user (R_1) is shown by the dotted curve in all three regimes and the UL link $R_2$by the dash-dotted curve. We see that in the weak interference regime the D2D link starts to suffer progressively as the interference strength increases. At a certain point it is the UL user that radically loses capacity at the expense of giving full rate to the D2D user. The UL capacity progressively increases with the interference level until reaching its maximum.

In practice, if we can schedule the uplink user so that it is below the noise floor of the D2D link, we can achieve the total sum capacity to within 1 bit. Similarly, for very strong interference, in this case greater than 5 dB above the desired D2D signal, we can also achieve a very high spectral-efficiency. In practical situations, however, this may be difficult to exploit, firstly because of the dynamic range requirements of the D2D receiver which may be costly, and secondly because of timing asynchronism of the incoming uplink signal which will be advanced for the receiver of the base station. A successive interference cancelling receiver is also required in both medium and strong interference regimes. The latter and other similar practical considerations will be studied in D5.3.

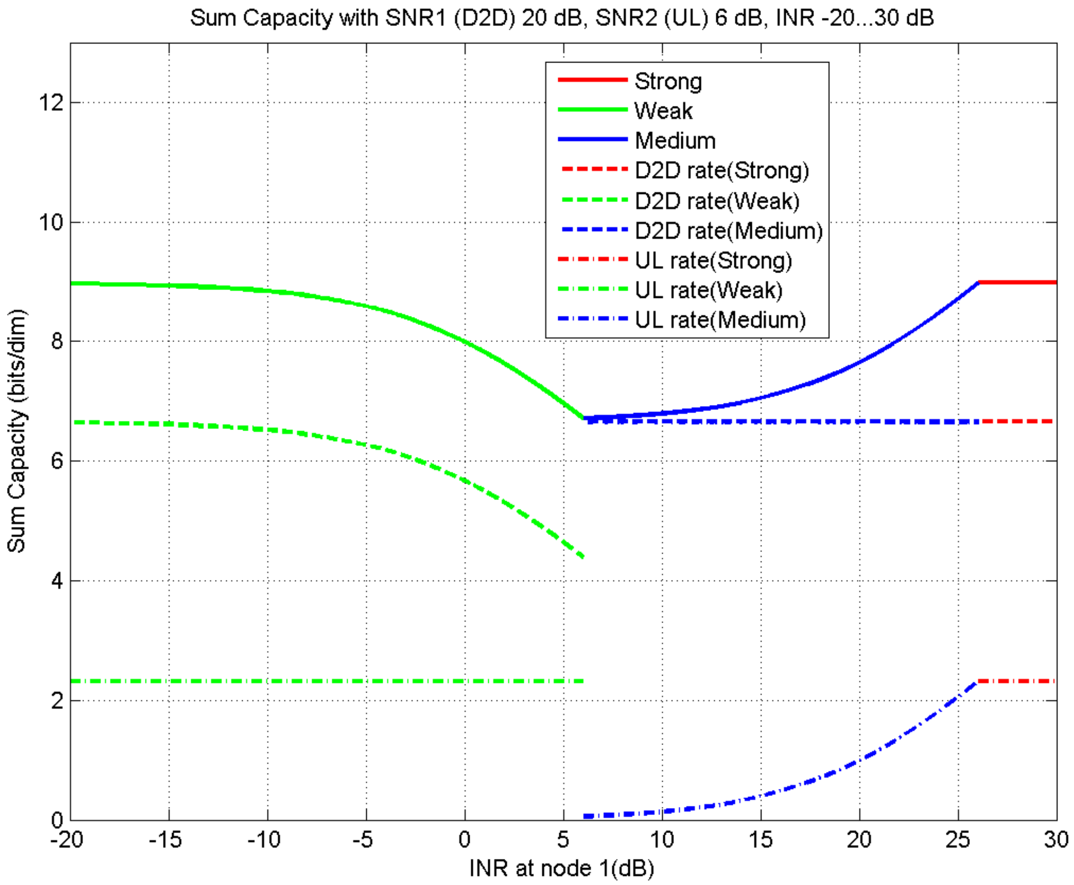


Figure 4: Sum-Capacity comparison known D2D content at the eNodeB.

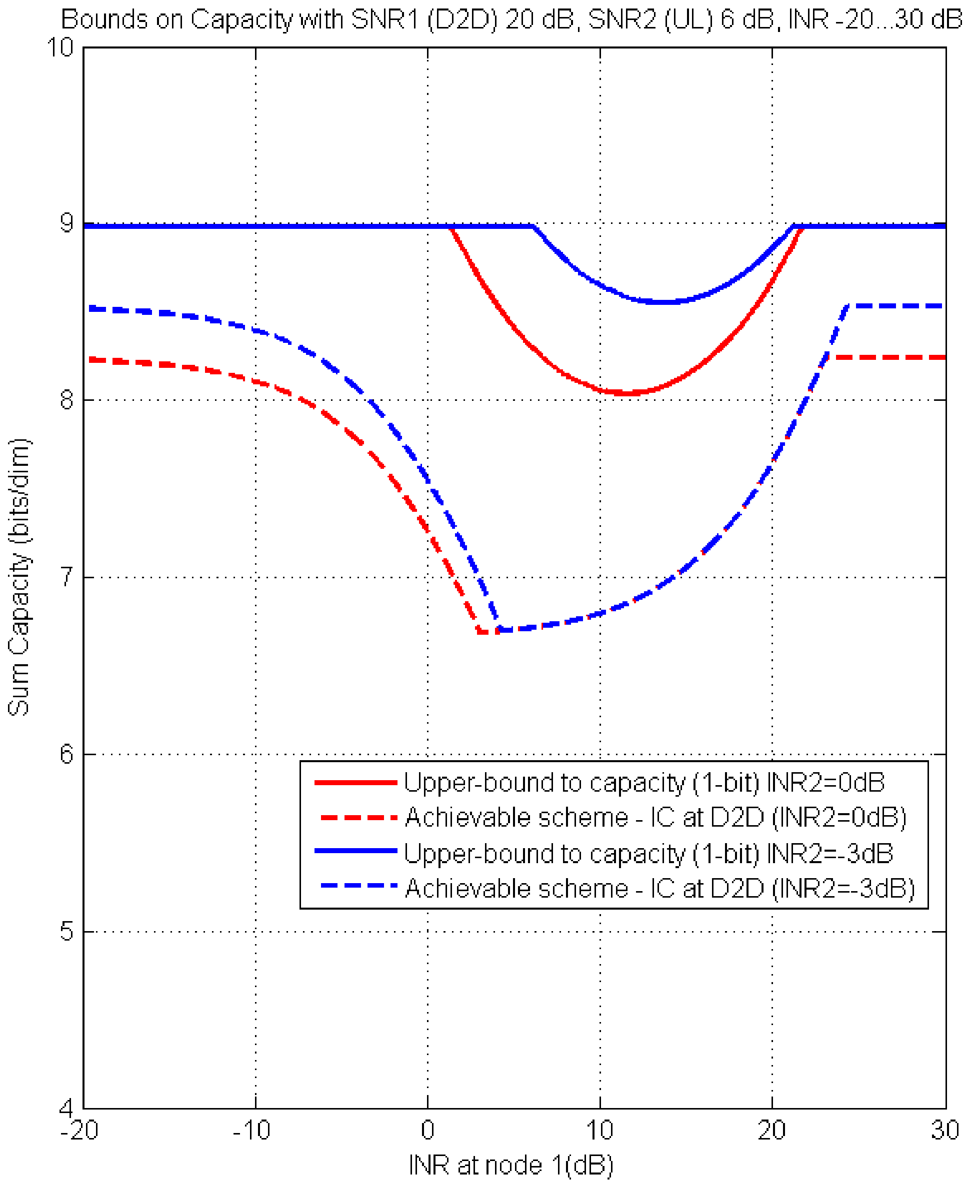


Figure 5: Sum-capacity bound and simple achievable scheme for unknown D2D content at the eNodeB

3.2 Extension to multi-user case and motivation for scheduling

The above analysis highlights the requirement to perform appropriate scheduling and potentially sophisticated interference cancellation at the D2D receiver. As a result, we extend this analysis to the multi-user case with a single D2D pair in Deliverable D5.3. The objective is to determine the scheduling policies that can exploit the different regimes for resource allocation as a function of the UL-D2D interference. Furthermore we aim to elucidate the practical implications of such advanced techniques in support of co-channel D2D transmission.

4 RESOURCE ALLOCATION AND INTERFERENCE MANAGEMENT FOR OFF-LOADING SCENARIO

In this work, we consider the resource allocation for *device-to device* (D2D) communications underlaying cellular networks to maximize the overall network throughput while guaranteeing the *quality of service* (QoS) of both regular *cellular users* (CUs) and D2D users. Firstly, we develop a three-step optimal resource allocation framework when considering *base station* (BS) has perfect *channel state information* (CSI) of all links in the network. Then, we investigate the resource allocation for D2D communications with only partial CSI available at BS. Probability based strategy by utilizing channel statistical characteristics and user selection based limited feedback strategy are proposed, respectively, to deal with the channel uncertainty. Simulation results have demonstrated that the proposed algorithms are promising and there are substantial benefits by D2D communication.

4.1 Introduction

Recently, the tremendous popularity of smart phones and electronic tablets has spurred the explosive growth of high-rate multimedia wireless services. According to a recent report by Bell Labs [20], global mobile traffic is increasing by 25 times from 2011 to 2016. To alleviate the huge infrastructure investment for the exponential growth of mobile traffic and improve local service flexibility, *device-to-device* (D2D) communications have been considered one of the key techniques in the *Third Generation Partnership Project* (3GPP) *Long Term Evolution Advanced* (LTE-Advanced)[21].

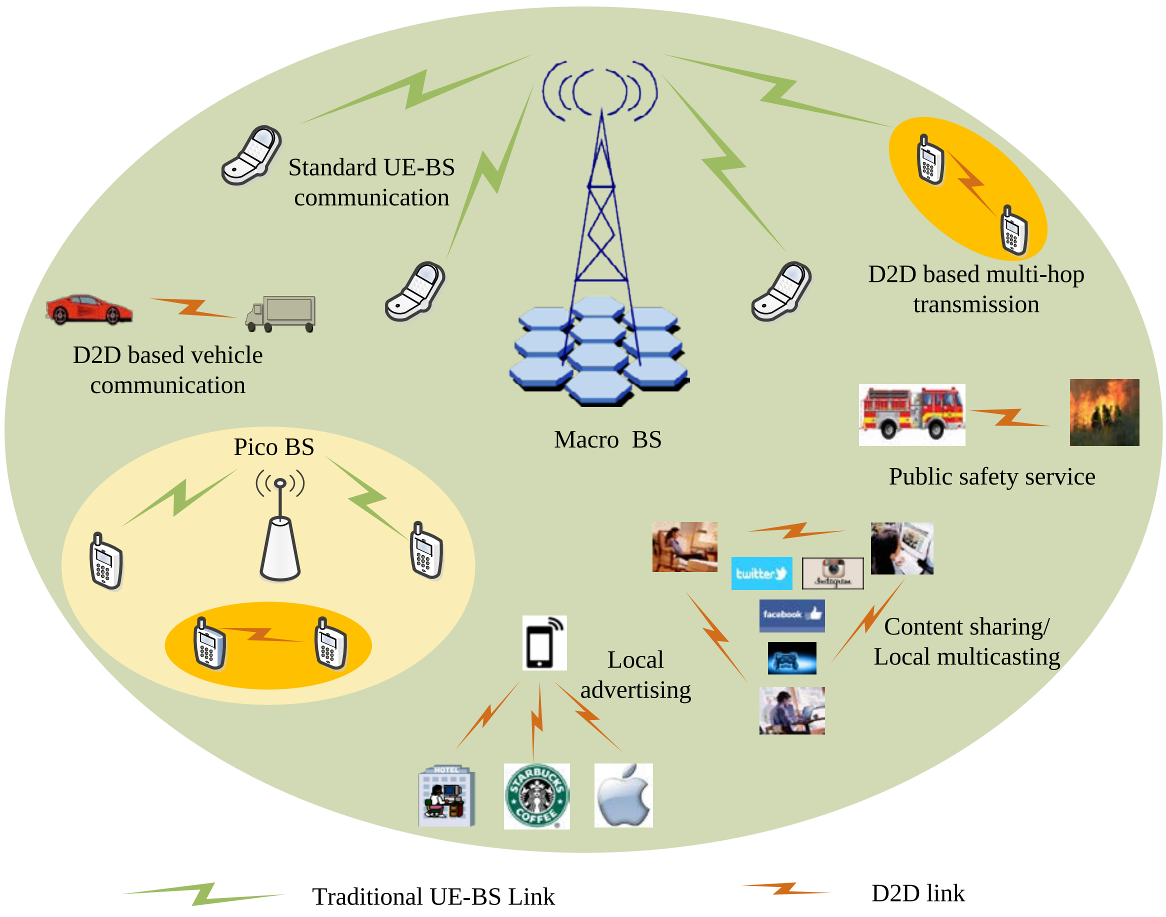


Figure 4.1: D2D communications in HetNets and its applications

Fig.4.1 from [36] illustrates the concept of D2D communications in heterogeneous networks (HetNets) and its applications. From the figure, apart from the standard base station (BS) relaying communications, user equipment (UE) in close proximity can also communicate directly through D2D communications. Due to the physical proximity and the potential reuse gain and hop gain [33], D2D communications can significantly increase network spectral-efficiency (SE) and energy-efficiency (EE) [33],[2] [22]. Similar to the existing short range wireless transmission techniques (e.g., Wi-Fi Direct, Bluetooth, and UWB), D2D communications can also bring low transmission delay. Furthermore, D2D communications utilize the licensed spectrum bands and thus can guarantee uniform of service provision and quality of service (QoS). Moreover, by using the licensed bands, the operators can easily design the charging mechanism to get new revenue opportunities and encourage users to offload their traffic by D2D connections to avoid congestion in the core network. In addition, as the reliable feature, D2D communications has also been considered as cost effective solution for public safety service in case of lack of network coverage [21]. To better understand the differences between D2D communications and the existing short range transmission techniques, their main features are compared and outlined in Table 4.I.

Table 4.I: Comparison of Short Range Wireless Transmission Techniques

Feature Name	D2D	Wi-Fi Direct	NFC	ZigBee	Bluetooth	UWB
Standardization	3GPP LTE-Advanced	802.11	ISO 13157	802.15.4	802.15.1	802.15.3a
Frequency band	Licensed band for LTE-A	2.4 GHz, 5GHz	13.56 MHz	868/915MHz, 2.4GHz	2.4GHz	3.1-10.6 GHz
Max transmit distance	10-1000m	200m	0.2m	10-100m	10-100m	10m
Max data	1Gbps	250Mbps	424kbps	250kbps	24Mbps	480Mbps
Device discovery	BS coordination	ID broadcast and embed soft access point	Radio-frequency identification	ID broadcast or coordinator assistant	Manual paring	Manual paring
Uniformity of service provision	Yes	No	No	No	No	No
Application	Smart metering, Content sharing, Local advertising, Cellular relay	Content sharing, Group gaming, Device connection	Contactless payment systems, Bluetooth and Wi-Fi connections	Home Entertainment and Control, Environmental monitoring	Object Exchange, Peripherals connection	Wireless USB, High-definition video, Precision location and tracking systems, Auto Radar

4.2 Literature Review

D2D communications can bring great potential benefits to the cellular system in terms of Spectral Efficiency and Energy Efficiency. However, it also leads to more complex interference situations and may interfere the existing cellular networks if not designed properly [22], [11]. Thus, efficient resource allocation and QoS guaranteeing are the most challenging but also importance issue in D2D communications. Many works have been done to deal with this issue.

Power control is a direct way to limit interference. In [2], restricting the transmit power of D2D users is suggested. Optimal power control along with mode switching with respect to the overall network throughput is investigated in [37]. In [23], fixed power margin scheme is proposed to coordinate interference among D2D pairs and basestations for the scenarios with multiple D2D pairs and multiple RCUs. For the scheme in [23], it is supposed that there exists a power margin in the transmit power of regular RCUs to counteract the interference from D2D pairs and D2D pairs are aware of the power margin and can adjust their transmit power to satisfy the minimum SINR requirements. This scheme is simple but not necessarily optimal since it is hard to find a suitable power margin. A higher margin will reduce the number of RCUs those are capable to share resources with D2D users while a lower one will decrease the probability that the minimum SINR of D2D users can be satisfied.

Efficient scheduling is also an effective way to mitigate interference. In [24], a time hopping based method is used to randomize the interference generated by D2D pairs while a *successive interference canceling* (SIC) based receive mode selection scheme is introduced in [25] to assist the reliable demodulation at the D2D receivers. In [26], a heuristic scheduling algorithm is proposed to pair D2D users and RCUs while guaranteeing the QoS for both types of users, where the BS marks the CU with highest channel power gain of the CU-BS link a high priority to share resource with the D2D pair with the lowest interference channel power gain of the RCU-D2D receiver link. These schemes are easy to be implemented, however, the power cooperation among D2D pairs and RCUs, which may further improve the network performance, has not been considered.

4.3 System Model

We investigate spectrum sharing for D2D communications underlaying cellular networks, where *M* D2D pairs coexist with *N* CUs. In particular, uplink (UL) resource sharing is considered since UL spectrum is under-utilized comparing to that of downlink (DL) in the frequency division duplexing (FDD) based cellular systems [26], [9]. Furthermore, UL resource sharing in D2D communications only affects the BS and incurred interference can be mitigated by BS coordination. We also assume a fully loaded cellular network scenario similar to [37]. That is, N active cellular users occupy the N orthogonal channels in the cell and there is no spare spectrum. In the following, we use C = {1, ..., N} and D = {1, ..., M} to denote the index sets of active cellular users and D2D pairs, respectively. In addition, we assume both CUs and D2D pairs have their minimum QoS requirements.

We consider independent block fading for all links in the network. Thus, the instantaneous channel gain between CU *i* and the BS can be expressed as

$$g_{i,B} = C \cdot \beta_{i,B} d_{i,B}^{-\alpha}, \tag{1}$$

where C is a constant determined by system parameters, $\beta_{i,B}$ is the channel fading component, α is the pathloss exponent, and $d_{i,B}$ is the distance between CU *i* and the BS. Similarly, we can express the channel gain of D2D pair *j* when reuse the channel of CU *i*, $g_{dj,i}$, and the channel gains of the interference links, from the transmitter of D2D pair *j* to the BS, $h_{d\,j,i}$, and that from CU *i* to the receiver of D2D pair *j*, $h_{i,j}$. The power of additive white Gaussian noise on each channel is assumed to be σ^2 .

4.4 Optimal Resource Allocation with Perfect CSI

D2D communications can be used to improve the performance of fully loaded cellular networks. When the base station has the perfect CSI of all links in the system, the QoS of both D2D pairs and CUs can be guaranteed in terms of minimum SINR requirement. A D2D pair is set up only when the minimum SINR requirement can be guaranteed and incurred interference to the CUs is below a threshold. In this case, we call it the admissible pair and the CU to be shared resource as reuse partner. The overall throughput optimization problem can be formulated as follows

$$\max_{\rho_{i,j},P_{ci},P_{dj}} \{\sum_{i\in \mathrm{C}} \log_2(1+\xi_{ci}) + \sum_{j\in S} \log_2(1+\xi_{dj})\} \tag{2a}$$

$$s.t.\ \ \xi_{ci} = \frac{P_{ci} g_{i,B}}{\sigma^2 + \rho_{i,j} P_{dj} h_{dj,i}} \geq \xi_{ci,\min}, \forall i \in \mathrm{C}, \tag{2b}$$

$$\xi_{dj} = \frac{P_{dj} g_{dj,i}}{\sigma^2 + \rho_{i,j} P_{ci} h_{i,j}} \geq \xi_{dj,\min},\ \forall j \in \mathrm{S}, \tag{2c}$$

$$\rho_{i,j} \in \{0,1\},\ \ \sum_j \rho_{i,j} \leq 1,\ \forall i \in \mathrm{C}, \tag{2d}$$

$$\rho_{i,j} \in \{0,1\},\ \ \sum_i \rho_{i,j} \leq 1,\ \forall j \in \mathrm{S}, \tag{2e}$$

$$P_{ci} \leq P_{c,\max}, \forall i \in \mathrm{C}, \tag{2f}$$

$$P_{dj} \leq P_{d,\max}, \forall j \in \mathrm{S}, \tag{2g}$$

where S $(\mathrm{S} \subseteq \mathrm{D})$ denotes the set of admissible D2D pairs, $\rho_{i,j}$ is the resource reuse indicator for CU *i* and D2D pair *j*, $\rho_{i,j} = 1$ when D2D pair *j* reuses the resource of cellular user *i*; otherwise, $\rho_{i,j} = 0$. $\xi_{ci,\min}$ and $\xi_{dj,\min}$ denote the minimum SINR requirements of CU *i* and D2D pair *j*, respectively, and $P_{ci,\max}$ and $P_{dj,\max}$ denotes the maximum transit power of CU and D2D pair, respectively. Constraints (2b) and (2c) represent the QoS requirements of cellular users and D2D pairs, respectively. Constraint (2d) ensures that the resource of an existing cellular user can be shared at most by one D2D pair. While constraint (2e) indicates that a D2D pair shares at most one existing cellular user's resource. Constraints (2f) and (2g) guarantee that the transmit powers of cellular users and D2D pairs are within the maximum limit.

The problem in (2) is a nonlinear constraint optimization problem. It is difficult to obtain the solution directly. In the following, we will divide the problem into three sub-problems and solve them one by one.

4.4.1 QoS-Aware Admission Control

If D2D pair *j* can share the spectrum with CU *i*, these constraints in (2b), (2c), (2f), and (2g) are satisfied, that is,

$$\begin{cases} \xi_{ci} = \dfrac{P_{ci} g_{i,B}}{\sigma^2 + P_{dj} h_{dj,i}} \geq \xi_{ci,\min}, & \text{(3a)} \\ \xi_{dj} = \dfrac{P_{dj} g_{dj,i}}{\sigma^2 + P_{ci} h_{i,j}} \geq \xi_{dj,\min} & \text{(3b)} \\ P_{ci} \leq P_{c,\max},\ \ P_{dj} \leq P_{d,\max}, & \text{(3c)} \end{cases}$$

It means that a D2D pair can share resource with an existing user only when both their SINR requirements are satisfied. Let R_j denote the set of reuse candidates for D2D pair *j*. D2D pair *j* is admissible ($j \in \mathrm{S}$) if and only if $\mathrm{R}_j \neq \emptyset$. In the following, we will demonstrate how to find the reuse candidates.

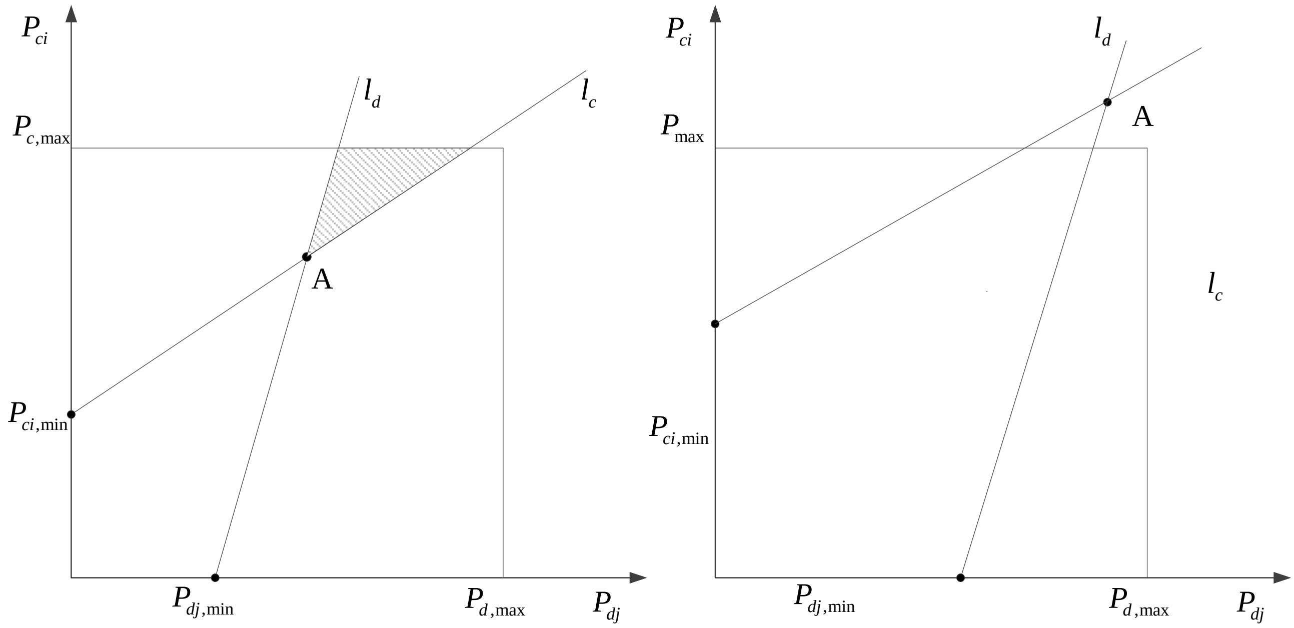
Without D2D user sharing resource with CU *i* $(P_{dj} = 0)$, the SINR of CU *i* can be guaranteed by transmitting a signal at the power,

$$P_{ci,\min} = \frac{\xi_{ci,\min}\sigma^2}{g_{i,B}}. \tag{4}$$

Similarly, without CU *i*, the minimum SINR of D2D user *j* can be reached by transmitting a signal at the power,

$$P_{dj,\min} = \frac{\xi_{dj,\min}\sigma^2}{g_{dj,i}}. \tag{5}$$

The admission constraints in (3) can be shown as in Fig. 4.2, where lines l_c and l_d represent constraints (3a) and (3b) with equality, respectively. The area on the right of line l_d is where the minimum SINR for D2D pair *j* is satisfied. The area above line l_c is where the minimum SINR of CU *i* is satisfied. The square area denotes the maximum power constraints for CU *i* and D2D pair *j*.



(a) with admissible area (b) without admissible area

Figure 4.2: D2D Communication Admissible Area.

Denote point A to be the intersection of l_c and l_d. To ensure l_c and l_d to have an intersection point in the first quarter, the slope of l_d must be larger than that of l_c, that is

$$\frac{\xi_{ci,\min} h_{dj,i}}{g_{i,B}} < \frac{g_{dj,i}}{\xi_{dj,\min} h_{i,j}} \tag{6}$$

which is the condition for CU *i* and D2D pair *j* to be possible to share resource without transmission power constraints. The coordinates of A, $(P_{dj,A}, P_{ci,A})$ can be found by

$$
\begin{cases}
\dfrac{P_{ci} g_{i,B}}{\sigma^2 + P_{dj} h_{dj,i}} = \xi_{ci,\min}, \\
\dfrac{P_{dj} g_{dj,i}}{\sigma^2 + P_{ci} h_{i,j}} = \xi_{dj,\min}.
\end{cases}
\tag{7}
$$

Therefore,

$$
\begin{cases}
P_{ci,A} = \dfrac{(g_{dj,i}\xi_{ci,\min} + h_{dj,i}\xi_{ci,\min}\xi_{dj,\min})\sigma^2}{g_{dj,i} g_{i,B} - \xi_{ci,\min}\xi_{dj,\min} h_{i,j} h_{dj,i}}, \\
P_{dj,A} = \dfrac{(h_{i,j}\xi_{ci,\min}\xi_{dj,\min} + g_{i,B}\xi_{dj,\min})\sigma^2}{g_{dj,i} g_{i,B} - \xi_{ci,\min}\xi_{dj,\min} h_{i,j} h_{dj,i}},
\end{cases}
\tag{8}
$$

which are the minimum transmission powers for CU *i* and D2D pair *j* to satisfy the minimum SNIR requirements if the maximum transmission power constraints are not considered.

If point A is within the square area as in Fig. 4.2a, then it is possible to find transmit powers for CU *i* and D2D pair *j* to satisfy all constraints in (3). In that case, any point in the shaded area will satisfy (3), if point A is beyond the square area as in Fig. 4.2b, D2D pair *j* is not admissible to share the spectrum with CU *i* due to the maximum power limit.

In summary, the admissible conditions will be

$$
\begin{cases}
0 \le \dfrac{(g_{dj,i}\xi_{ci,\min} + h_{dj,i}\xi_{ci,\min}\xi_{dj,\min})\sigma^2}{g_{dj,i} g_{i,B} - \xi_{ci,\min}\xi_{dj,\min} h_{i,j} h_{dj,i}} \le P_{c,\max}, \\
0 \le \dfrac{(h_{i,j}\xi_{ci,\min}\xi_{dj,\min} + g_{i,B}\xi_{dj,\min})\sigma^2}{g_{dj,i} g_{i,B} - \xi_{ci,\min}\xi_{dj,\min} h_{i,j} h_{dj,i}} \le P_{d,\max}.
\end{cases}
\tag{9}
$$

Then, simplifying the two inequalities in (9), we can get following minimum distance requirement for D2D pair *j* to select reuse candidates.

$$
d_{i,j}^{\min} =
\begin{cases}
\left[\dfrac{C\beta_{i,j}\xi_{ci,\min}\xi_{dj,\min}P_{c,\max}h_{dj,i}}{(P_{\max}g_{i,B} - \xi_{ci,\min}\sigma^2)g_{dj,i} - \xi_{ci,\min}\xi_{dj,\min}\sigma^2 h_{dj,i}}\right]^{\frac{1}{\alpha}} & \text{if} \quad \dfrac{P_{c,\max}g_{i,B}}{\sigma^2 + P_{d,\max}h_{dj,i}} \le \xi_{ci,\min}, \\
\left[\dfrac{C\beta_{i,j}\xi_{ci,\min}\xi_{dj,\min}(\sigma^2 + P_{c,\max}h_{dj,i})}{g_{i,B}(P_{d,\max}h_{dj,i} - \xi_{dj,\min}\sigma^2)}\right]^{\frac{1}{\alpha}} & \text{if} \quad \dfrac{P_{c,\max}g_{i,B}}{\sigma^2 + P_{d,\max}h_{dj,i}} > \xi_{ci,\min},
\end{cases}
\tag{10}
$$

Let $d_{i,j}$ denote the distance between CU *i* and the reviver of D2D pair *j*. When $d_{i,j} \ge d_{i,j}^{\min}$, D2D pair *j* can be accessed by reusing the channel of CU *i* while both the minimum SINR can be satisfied.

4.4.2 Optimal Power Allocation

In the last subsection, we have addressed admission control for a D2D pair. Here, we investigate how to allocate power for the D2D transmitter and the corresponding reuse partner to maximize the overall throughput. Mathematically, the problem can be expressed as:

$$(P_{ci}^*, P_{dj}^*) = \arg\max_{P_{ci}, P_{dj}} \{\log_2(1+\xi_{ci}) + \log_2(1+\xi_{dj})\}, \tag{11}$$

$$s.t. \quad \xi_{ci} = \frac{P_{ci} g_{i,B}}{\sigma^2 + P_{dj} h_{dj,i}} \geq \xi_{ci,\min}, \tag{11a}$$

$$\xi_{dj} = \frac{P_{dj} g_{dj,i}}{\sigma^2 + P_{ci} h_{i,j}} \geq \xi_{dj,\min} \tag{11b}$$

$$P_{ci} \leq P_{c,\max}, \quad P_{dj} \leq P_{d,\max}, \tag{11c}$$

In the previous subsection, we have addressed admission control for CU *i* and D2D pair *j*, from the discussion there, three possible shapes of admissible area are shown as in Fig. 4.3a-c. Note that all power pairs within the admissible area satisfy constraints (11a)-(11c). Therefore, the optimization problem in (11) is to find the power pair in the admissible area.

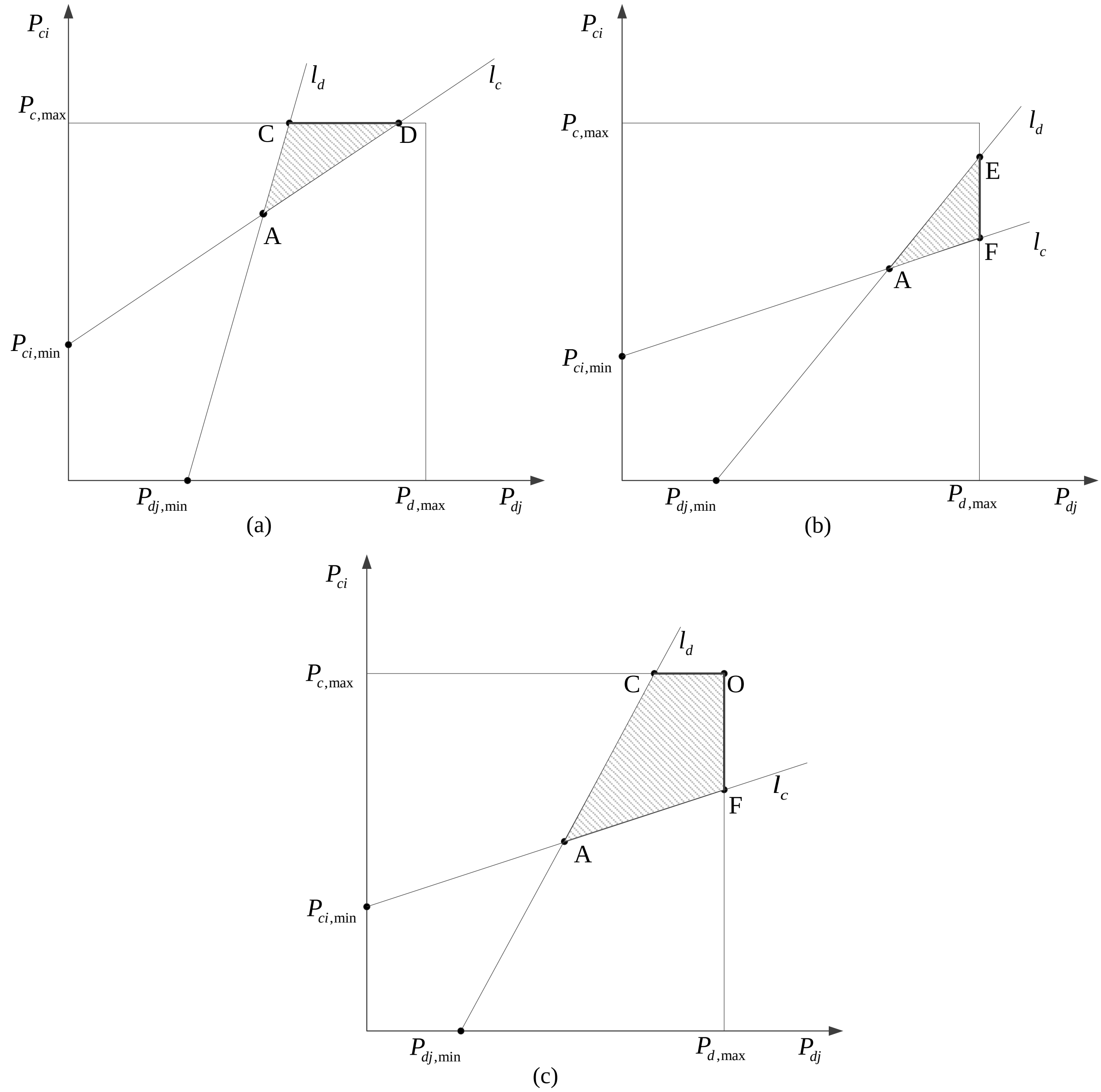


Figure 4.3: Optimal Power Allocation for Cellular User D2D User.

Denoting $f(P_{ci}, P_{dj}) \triangleq \log_2(1+\xi_{ci})+\log_2(1+\xi_{dj})$, the optimal power vector (P_i^{c*}, P_j^{d*}) in (11) is derived as follows,

$$
(P_{ci}^*, P_{dj}^*) = \begin{cases} \arg\max\limits_{(P_{ci}, P_{dj})\in \mathsf{P}_1} f(P_{ci}, P_{dj}) & \text{if} \quad \dfrac{P_{c,\max} g_{i,B}}{\sigma^2 + P_{d,\max} h_{dj,i}} \le \xi_{ci,\min}, \\ \arg\max\limits_{(P_{ci}, P_{dj})\in \mathsf{P}_2} f(P_{ci}, P_{dj}) & \text{if} \quad \dfrac{P_{c,\max} g_{i,B}}{\sigma^2 + P_{d,\max} h_{dj,i}} > \xi_{ci,\min} \text{ and } \dfrac{P_{c,\max} g_{gj,i}}{\sigma^2 + P_{d,\max} h_{dj,i}} < \xi_{dj,\min}, \\ \arg\max\limits_{(P_{ci}, P_{dj})\in \mathsf{P}_3} f(P_{ci}, P_{dj}) & \text{if} \quad \dfrac{P_{c,\max} g_{i,B}}{\sigma^2 + P_{d,\max} h_{dj,i}} > \xi_{ci,\min} \text{ and } \dfrac{P_{c,\max} g_{gj,i}}{\sigma^2 + P_{d,\max} h_{dj,i}} < \xi_{dj,\min}, \end{cases} \tag{12}
$$

where

$$
\mathsf{P}_1 = \{(P_{c,\max}, P_1), (P_{c,\max}, P_2)\}, \quad \mathsf{P}_2 = \{(P_3, P_{d,\max}), (P_4, P_{d,\max})\},
$$

$$
\mathsf{P}_3 = \{(P_{c,\max}, P_1), (P_{c,\max}, P_{d,\max}), (P_4, P_{d,\max})\},
$$

$$
P_1 = \frac{(\sigma^2 + P_{c,\max} h_{i,j})\xi_{j,\min}^d}{g_{dj,i}}, \qquad P_2 = \frac{P_{c,\max} g_{i,B} - \xi_{ci,\min}\sigma^2}{\xi_{ci,\min} h_{dj,i}},
$$

$$
P_3 = \frac{P_{d,\max} g_{dj,i} - \xi_{dj,\min}\sigma^2}{\xi_{dj,\min} h_{i,j}}, \qquad P_4 = \frac{(\sigma^2 + P_{d,\max} h_{dj,i})\xi_{ci,\min}}{g_{i,B}},
$$

From the above proposition, the optimal power pair for CU *i* and D2D pair *j* resides on one of the corner points of the admissible area as points C, D, O, E, and F in Fig. 4.3. Besides, at least one user is transmitting at the peak power for maximizing the overall throughput.

4.4.3 Maximum D2E Pairs and CUs Match

For a CU *i* ($i \in \mathsf{R}_j$), when there is no D2D, the maximum throughput on the used spectrum is

$$
T_{i,\max} = \log_2(1+\frac{P_{c,\max} g_{i,B}}{\sigma^2}). \tag{13}
$$

When it shares resource with D2D pair *j*, the maximum achievable sum throughput, $T_{i,j}^{sum}$, can be expressed as

$$
T_{i,j}^{sum} = \log_2(1+\frac{P_{ci}{}^* g_{i,B}}{P_{dj}{}^* h_{dj,i} + \sigma^2}) + \log_2(1+\frac{P_{dj}{}^* g_{dj,i}}{P_{ci}{}^* h_{i,j} + \sigma^2}), \tag{14}
$$

where $(P_{ci}{}^*, P_{dj}{}^*)$ is given by the equation (12). Thus, the D2D throughput gain can be expressed as

$$
T_{i,j}^{G} = T_{i,j}^{sum} - T_{i,\max}. \tag{15}
$$

Hence, we can find the optimal reuse partner of D2D pair *j*,

$$
i^* = \arg\max_{i\in \mathsf{R}_j} T_{i,j}^{G}. \tag{16}
$$

By now, we can get the optimal solutions of (2) for a single D2D scenario. If there are multiple D2D pairs in the system, the optimal resource allocation problem turns to be a maximum weight bipartite matching problem. It can be formulated as

$$\begin{aligned} &\max_{i \in \mathcal{C}', j \in \mathcal{S}} \rho_{i,j} T_{i,j}^{G}, \\ s.t. \quad &\sum_{j} \rho_{i,j} \leq 1,\ \rho_{i,j} \in \{0,1\},\ \forall i \in \mathcal{C}', \\ &\sum_{i} \rho_{i,j} \leq 1,\ \rho_{i,j} \in \{0,1\},\ \forall j \in \mathcal{S}, \end{aligned} \tag{17}$$

where $\mathcal{C}'$ is the union of all the reuse candidate sets of D2D pairs. Fig. 4.4 explains the maximum weight bipartite matching problem in (17), where the set of D2D pairs and the union of all the reuse candidate of D2D pairs are assumed as the two groups of vertices in the bipartite graph. Vertex *i* is joined with vertex *j* by an edge *ij*, when the user *i* is a reuse candidate of D2D pair *j*. D2D throughput gain $T_{i,j}^{G}$ is considered as the weight of edge *ij*. We can use the classic Kuhn-Munkres algorithm [27] to solve (17). Thus, the solution of the optimal resource allocation problem for multiple D2D pairs with targeted QoS requirements can be derived and illustrated by the algorithm 4.1 in Table 4.II.

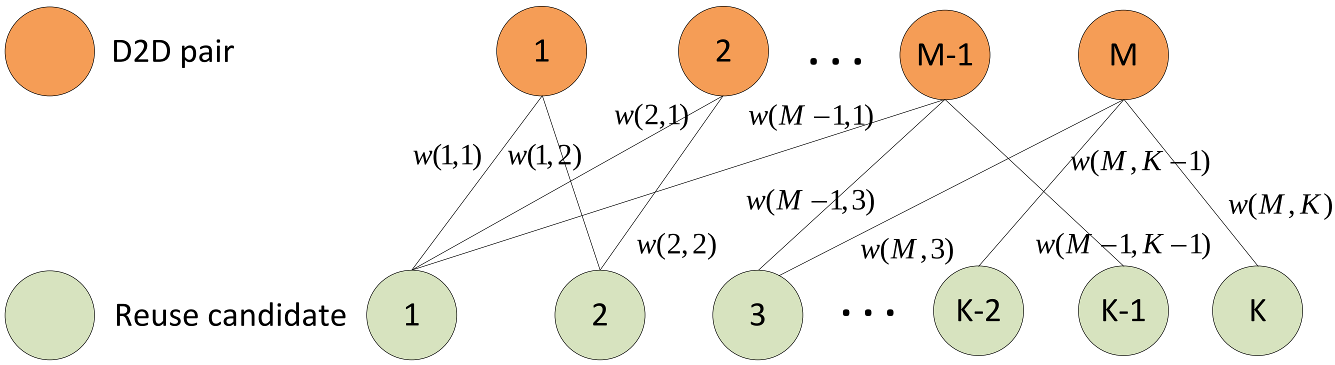


Figure 4.4: Bipartite graph for D2D pairs and the reuse candidates matching problem.

Table 4.II: Optimal Resource Allocation Algorithm

Algorithm 4.1 Optimal Resource Allocation Algorithm

$\mathcal{C}$: The set of existing cellular users
$\mathcal{D}$: The set of D2D pairs
$\mathcal{R}_j$: The set of reuse candidates of D2D pair *j*
$\mathcal{C}'$: The set of reuse candidates of D2D pair *j*
Step 1
for all $j \in \mathcal{D}$ and $i \in \mathcal{C}$ **do**
  calculate $d_{i,j}^{\min}$ $\leftarrow$ **Proposition 1**
    if $d_{i,j} < d_{i,j}^{\min}$ **then**
      $i \in \mathcal{R}_j$ (Find reuse candidates)
    end if
end for
if $\mathcal{R}_j \neq \varnothing$ **then**
  $\mathcal{D} = \mathcal{D} - j$ (Delete not accessible candidates)
end if
Step 2
for all $j \in \mathcal{D}$ and $i \in \mathcal{R}_j$ **do**
  calculate (P_{ci}^{*}, P_{dj}^{*}) $\leftarrow$ **Proposition 2**
end for

Step 3

if $|\mathsf{D}| = 1$ **then**

$i^* = \arg\max_{i \in \mathsf{R}_j} T_{i,j}^G$ (For only one D2D pair)

else

get i^* from (17) (Kuhn-Munkres algorithm)

end if

4.5 Resource Allocation with Partial CSI

For the optimal resource allocation strategy in [22], the accurate CSI information of all links is imperative. In general, BS can collect the CSI of users by the classic channel training and estimation. Nevertheless, for the interference links between CUs and D2D pairs that are not connected to the BS the traditional methods are not applicable and obtaining the instantaneous CSI is difficult and causes high overhead [25], especially when the number of CUs and D2D pairs are large. Thus, it is more reasonable to assume the BS only have partial CSI, including distance based pathloss and shadowing, which can be obtained by empirical measurements. In the following, we will investigate the resource allocation strategies for the BS only knows partial CSI of links between the regular CUs to D2D receivers that are not connected to the BS [28, 29].

4.5.1 User Selection Based Limited Feedback

To solve the problem in (2), the interference channel gain of $h_{i,j}$ is indispensable; however, this will require lots of feedback and cause high overhead. Note that the CSI of each CU-D link within the same D2D pair is not equally important. For example, the CUs that are far away from the D2D receivers are more likely to be the reuse partners, and thus the CSI of CU-D links belong to these faraway CUs may be more important. Thus, to reduce the feedback overhead, the key is to find the best potential partner CUs for each D2D pair and then to feed the corresponding CSI back. To choose the most potential partner CUs, one intuitive method is to choose the CUs farthest away from the D2D receiver and we call this method, KFAR. However, other factors, such as the QoS requirements of CUs and the channel power gain of CU-BS link, will also affect the access of the D2D pair. In (10), we have derived a minimum distance metric to evaluate the access ability for a D2D pair *j* sharing resource with a regular CU *i*. This metric has comprehensively considered all the factors that may affect access of the D2D pair.

With the minimum distance metric in (10), the BS can easily decide whether D2D pair *j* can share the resource with CU *i* or not. However, this metric depends on the fading components , $\beta_{i,j}$ which are not known at the BS. Therefore, we derive a modified distance metric $D_{i,j}^{\min}$, which is the required minimum distance between CU *i* and the receiver of D2D pair *j* to satisfy all the access constraints in (2) without considering the fading effect of CU-D link by setting $\beta_{i,j} = 1$. The modified metric can be expressed as,

$$D_{i,j}^{\min} = \begin{cases} \left[\dfrac{C\xi_{ci,\min}\xi_{dj,\min}P_{c,\max}h_{dj,i}}{(P_{\max}g_{i,B} - \xi_{ci,\min}\sigma^2)g_{dj,i} - \xi_{ci,\min}\xi_{dj,\min}\sigma^2 h_{dj,i}}\right]^{\frac{1}{\alpha}} & \text{if } \dfrac{P_{c,\max}g_{i,B}}{\sigma^2 + P_{d,\max}h_{dj,i}} \le \xi_{ci,\min}, \\ \left[\dfrac{C\xi_{ci,\min}\xi_{dj,\min}(\sigma^2 + P_{c,\max}h_{dj,i})}{g_{i,B}(P_{d,\max}h_{dj,i} - \xi_{dj,\min}\sigma^2)}\right]^{\frac{1}{\alpha}} & \text{if } \dfrac{P_{c,\max}g_{i,B}}{\sigma^2 + P_{d,\max}h_{dj,i}} > \xi_{ci,\min}, \end{cases} \tag{18}$$

When the $D_{i,j}^{\min}$ is calculated, the BS can select the K CUs with the largest maximum distance ratio (MDR) between the actual distance and the required minimum distance without considering fading, $d_{i,j} / D_{i,j}^{\min}$, as the best potential partner CUs for each D2D pair. We use MDR as the user selecting metric is for the following two reasons:

1) As $D_{i,j}^{\min}$ is required minimum distance to satisfy all the access constraints without considering the fading effect, thus the bigger the ratio, the more ability shows to counteract the fading;

2) A lower $D_{i,j}^{\min}$ implies that the CU can tolerant more D2D interference, and can get higher D2D throughput gain if the CU is selected.

After the user selection procedure is finished, each D2D pair can trace and report the CSI of the respective *K* selected CUs. When the CSI is available at BS, the optimal power allocation and CU and D2D pair match algorithms can be used. Thus, the problem in (2) can be solved by the selected-*K* feedback with MDR metric (KMDR) scheme, and the whole procedure is illustrated as in Algorithm 4.2.

Table 4. III : Resource Allocation with Limited Feedback

Algorithm 4.2 Optimal Resource Allocation with KMDR

1: C : The set of existing cellular users
2: D : The set of D2D pairs
3: MDR : The maximum distance ratio ($d_{i,j} / D_{i,j}^{\min}$)
4: C_j : The selected K CU set for D2D pair j
5: R_j : The set of reuse candidates of D2D pair j
6: Step 1 *K CU Selection*
7: **for all** $j \in D$ and $i \in C$ **do**
8: calculate $D_{i,j}^{\min}$ and MDR;
9: **sort** (MDR, column, 'descend') ;
10: $C_j \leftarrow$ the first K sorted list in jth column of MDR
11: **end for**
12: Step 2 *Optimal Power Allocation*
13: **for all** $j \in D$ and $i \in C_j$ **do**
14: calculate $d_{i,j}^{\min}$;
15: **if** $d_{i,j} \geq D_{i,j}^{\min}$ **then**
16: calculate (P_{ci}^{*}, P_{dj}^{*})
17: **end if**

if $\mathrm{R}_j \neq \varnothing$ **then**
  $\mathrm{D} = \mathrm{D} - j$
end if
end for
Step 3 Optimal Match for Regular CU and D2D Pair
if $|\mathrm{D}| = 1$ **then**
  $i^* = \arg\max_{i \in \mathrm{R}_j} T_{i,j}^G$
else
get i^* from Kuhn-Munkres algorithm
end if

4.5.2 Probability-based Resource Allocation

In this subsection, we consider to utilize channel statistical characteristics as an alternative to deal with channel uncertainty.

We assume that BS provides guaranteed QoS for each CU and D2D pair. For CUs, since all the related channel power gains, $g_{i,B}$ and $h_{dj,i}$, are known at the BS, minimum SINR, $\xi_{c,\min}$, can be guaranteed. For D2D pairs, the channel fading component, $\beta_{i,j}$, is unavailable at the BS and therefore the exact SINR cannot be determined. Thus, outage probability is used to provide QoS for D2D users. When D2D pair *j* use the channel *i* ($\rho_{i,j} = 1$), the outage probability can be expressed as, $\Pr\{\xi_{dj} < \xi_{\text{th}}\} \le \psi$.

where ψ denotes the maximum acceptable outage probability for D2D users.

When an admissible D2D pair *j* is accessed on channel *i*, eliminating the throughput in outage state, the ergodic (expected) throughput of D2D pair *j* can be expressed as,

$$\mathrm{E}\left\{[\log(1+\xi_j^d)] \,\middle|\, \xi_j^d \ge \xi_{\text{th}}\right\}$$

where $\mathrm{E}\{\bullet \mid \bullet\}$ denotes conditional expectation.

Therefore, the optimal resource allocation problem for maximizing the overall network throughput of regular CUs and the admissible D2D pairs with guaranteed QoS in fading channels can be expressed as

$$\max_{\rho_{i,j},P_i^c,P_j^d}\left\{\sum_{i\in C}\log(1+\xi_i^c)+\rho_{i,j}\sum_{j\in S}\mathrm{E}\{[\log(1+\xi_j^d)]\,\big|\,\xi_j^d\ge\xi_{\mathrm{th}}\}\right\}, \tag{19}$$

$$\begin{aligned}
\text{s.t.}\quad & \xi_i^c=\frac{P_i^c g_i}{\sigma^2+\rho_{i,j}P_j^d h_{j,i}^d}\ge\xi_{i,\min}^c,\forall i\in C,\\
& \Pr\{\xi_j^d \triangleq \frac{P_j^d g_{j,i}^d}{\sigma^2+\rho_{i,j}P_i^c h_{i,j}}<\xi_{\mathrm{th}}\}\le\psi,\ \forall j\in S,\\
& \rho_{i,j}\in\{0,1\},\quad \sum_j\rho_{i,j}\le 1,\ \forall i\in C,\\
& \rho_{i,j}\in\{0,1\},\quad \sum_i\rho_{i,j}\le 1,\ \forall j\in S,\\
& P_i^c\le P_{\max}^c,\forall i\in C,\quad P_j^d\le P_{\max}^d,\forall j\in S
\end{aligned}$$

Without considering the channel fading component of the CU-D link, ($\beta_{i,j}=1$), the admissible D2D pairs can be found by the minimum distance metric derived in the previous subsection.

Obviously, when channel fading, $\beta_{i,j}$, is considered, the minimum distance, $D_{i,j}^{\min}$, should be changed by a distance factor, γ , that is $\hat{d}_{i,j}=\gamma D_{i,j}^{\min}$ to counteract the fading effect and thus to satisfy the access constraints in (19). In this case, the corresponding channel gain will be $\bar{h}_{i,j}=C\beta_{i,j}(\gamma L_{i,j}^{\min})^{-\alpha}$. The distance factor can be determined by

$$\begin{aligned}
&\Pr\{\frac{P_{dj}g_{dj,i}}{\sigma^2+P_{ci}\bar{h}_{i,j}}<\xi_{\mathrm{th}}\}=\Pr\{\frac{P_{dj}g_{dj,i}}{\sigma^2+P_{ci}\bar{h}_{i,j}}<\frac{P_{dj}g_{dj,i}}{\sigma^2+P_{ci}C(D_{i,j}^{\min})^{-\alpha}}\}\\
&=\Pr\{\bar{h}_{i,j}>C(D_{i,j}^{\min})^{-\alpha}\}=\Pr\{C\beta_{i,j}(\gamma D_{i,j}^{\min})^{-\alpha}>C(D_{i,j}^{\min})^{\alpha}\}\\
&=\Pr\{\beta_{i,j}>\gamma^{\alpha}\}\le\psi
\end{aligned} \tag{20}$$

Denote $\gamma_{\min}$ to be the minimum distance factor satisfying the outage probability. Then, it can be found by $\Pr\{\beta_{i,j}>\gamma_{\min}{}^{\alpha}\}=\psi$ .From the above, the distance factor depends on the pdf of fading. For Rayleigh fading channel $\beta_{i,j}$ is exponentially distributed. Here, assuming it is with unite mean, thus the cdf can be expressed as

$$F_R(\beta_{i,j})=1-e^{-\beta_{i,j}},\beta_{i,j}>0. \tag{21}$$

Substituting it into (20), the minimum distance factor in Rayleigh fading can be expressed as

$$\gamma_R=(-\ln\psi)^{1/\alpha}.$$

When the minimum distance factor is obtained, we can express the modified minimum distance metric for D2D access in fading channels as follows

$$\hat{d}_{i,j}^{\min}=\gamma D_{i,j}^{\min}. \tag{22}$$

Then, we can determine whether a D2D pair can be accessible or not and also find all the potential partner CUs for the D2D pair if it is accessible by this metric. Fig. 4.5 illustrated the modified admissible area in the heavy shaded pattern.

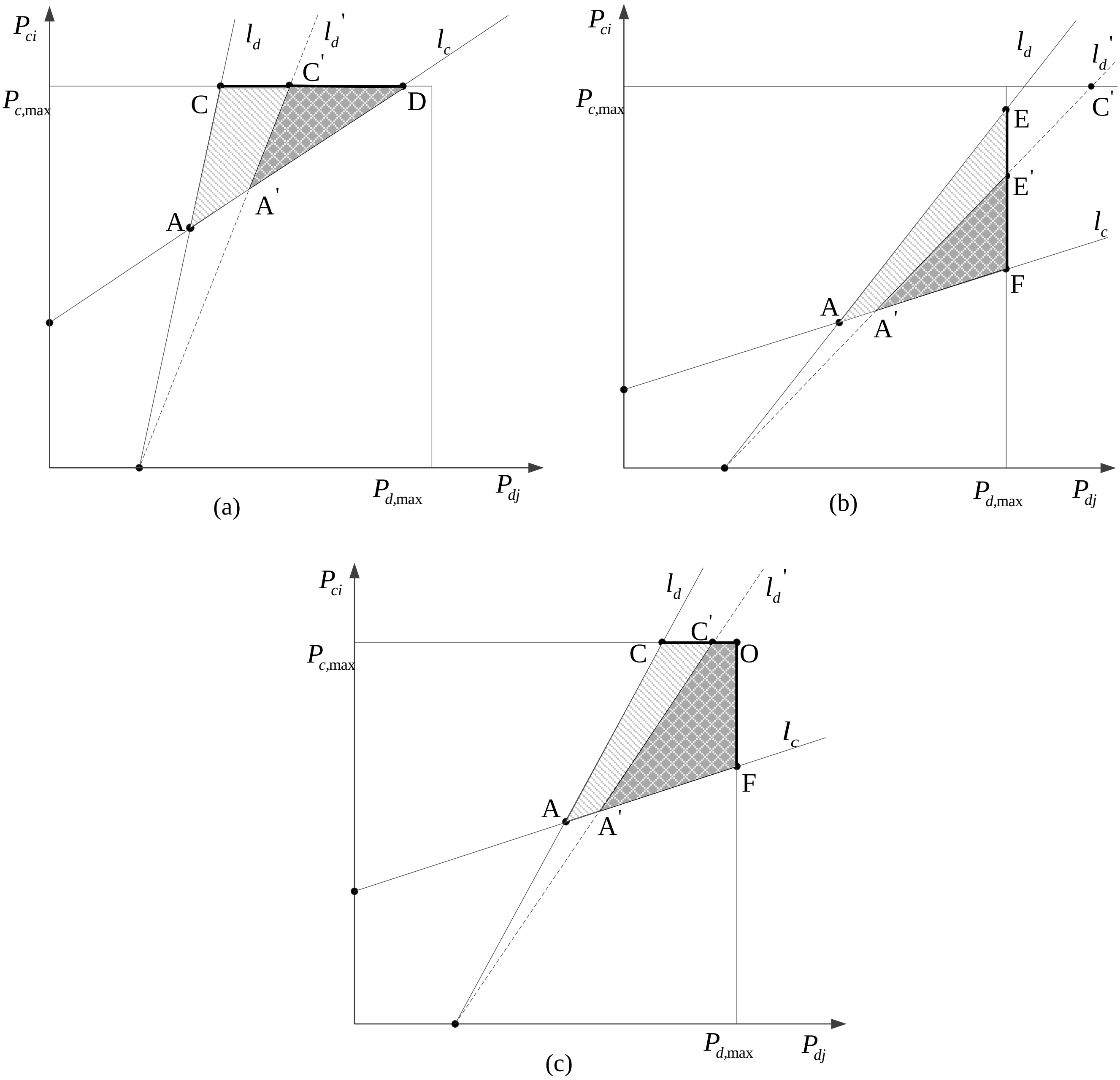


Figure 4.5: D2D admissible area. Light- and heavy- shaded patterns represent the admissible area without and with fading, respectively.

Similar to the power allocation with perfect CSI, denoting $g(P_{ci}, P_{dj}) \triangleq \log_2(1+\xi_{ci}) + \mathrm{E}\{[\log(1+\xi_{dj})] \,|\, \xi_{dj} \geq \xi_{\text{th}}\}$, the maximum of this function g is achieved by the optimal power vector (P_i^{c*}, P_j^{d*}) which can be derived as follows,

$$(P_{ci}^*, P_{dj}^*) = \begin{cases} \arg \max\limits_{(P_{ci},\, P_{dj}) \in \mathrm{P}_1} f(P_{ci}, P_{dj}) & \text{if} \quad \dfrac{P_{c,\max} g_{i,B}}{\sigma^2 + P_{d,\max} h_{dj,i}} \le \xi_{ci,\min}, \\ \arg \max\limits_{(P_{ci},\, P_{dj}) \in \mathrm{P}_2} f(P_{ci}, P_{dj}) & \text{if} \quad \dfrac{P_{c,\max} g_{i,B}}{\sigma^2 + P_{d,\max} h_{dj,i}} > \xi_{ci,\min} \text{ and } P_{dj,C'} \ge P_{d,\max}, \\ \arg \max\limits_{(P_{ci},\, P_{dj}) \in \mathrm{P}_3} f(P_{ci}, P_{dj}) & \text{if} \quad \dfrac{P_{c,\max} g_{i,B}}{\sigma^2 + P_{d,\max} h_{dj,i}} > \xi_{ci,\min} \text{ and } P_{dj,C'} < P_{d,\max}, \end{cases}$$

where

$$\mathrm{P}_1 = \{(P_{c,\max},\, P_{dj,C'}),\ (P_{c,\max},\, P_{dj,D})\}, \quad \mathrm{P}_2 = \{(P_{dj,E'},\, P_{d,\max}),\ (P_{dj,F},\, P_{d,\max})\},$$

$$\mathrm{P}_3 = \{(P_{c,\max},\, P_{dj,C'}),\ (P_{c,\max},\, P_{d,\max}),\ (P_{dj,F},\, P_{d,\max})\},$$

$$P_{dj,C'} = \frac{[P_{c,\max} \bar{h}_{i,j} F^{-1}(1-\psi) + \sigma^2]\xi_{\text{th}}}{g_{dj,i}}, \qquad P_{dj,D} = \frac{P_{c,\max} g_{i,B} - \xi_{ci,\min}\sigma^2}{\xi_{ci,\min} h_{dj,i}},$$

$$P_{dj,E'} = \frac{P_{d,\max}(P_{d,\max} g_{dj,i} - \xi_{\text{th}}\sigma^2)}{\xi_{dj,\min} \bar{h}_{i,j} F^{-1}(1-\psi)}, \qquad P_{dj,F} = \frac{(\sigma^2 + P_{d,\max} h_{dj,i})\xi_{ci,\min}}{g_{i,B}}.$$

After obtaining the power allocations for a D2D pair and its corresponding partner CUs, we can estimate the D2D throughput gain brought by the D2D pair. However, in this report, we cannot obtain the exact throughput gain since the channel gain of CU-D link is unknown. Instead, we estimate the expected D2D throughput gain, defined as the difference between the maximum expected sum throughput and the maximum throughput of the partner CU without D2D, that is,

$$T_{i,j}^G = g(P_{ci}^*, P_{dj}^*) - \log_2\left(1 + \frac{P_{c,\max} g_{i,B}}{\sigma^2}\right)$$

Finally, we can obtain the optimal D2D pair and CU match by the classic Kuhn-Munkres algorithm. The whole procedure of the probabilistic strategy can be illustrated in the following Table.

Table 4.IV : Probabilistic Resource Allocation

Algorithm 4.3 Probabilistic Resource Allocation Scheme

1: C : The set of existing cellular users
2: D : The set of D2D pairs
3: γ : Accepted maximum outage probability for D2D pairs
4: Step 1 *D2D Admission control*
5: **for all** $j \in \mathrm{D}$ and $i \in \mathrm{C}$ **do**
6: calculate $\hat{d}_{i,j}^{\min}$ with given γ ;
7: **if** $d_{i,j} \ge \hat{d}_{i,j}^{\min}$ **then**
8: $i \in \mathrm{R}_j$;
9: **end if**
10: **if** $\mathrm{R}_j \ne \varnothing$ **then**

$D = D - j$

end if

end for

Step 2 *Power control*

for all $j \in D$ and $i \in R_j$ **do**

calculate (P_{ci}^*, P_{dj}^*)

end for

Step 3 *Optimal Match for Regular CU and D2D Pair:* Kuhn-Munkres algorithm)

4.6 Numerical Results

Figure 4.6 shows the access rate and the throughput improvement of D2D communications with the simulation parameters of [28]. From the figure, in a fully loaded cellular network, the number of D2D pairs that can access the network based on our proposed optimal resource allocation algorithm with perfect CSI is up to 70% of the number of existing non-D2D UEs and the *quality-of-service* (QoS) requirements of all the users can be guaranteed. Compared to the fixed margin scheme in [23] and heuristic scheme in [26], the proposed one brings significant performance gains. It is also seen that for a fixed number of active CUs, N, when the number of D2D pairs, M, increases to a certain threshold, the network will be saturated, no more D2D pairs can be accessed and the multi-D2D pair diversity can only provide some secondary increase on the throughput gain. In addition, for any proportion of D2D pairs, the performance slightly increases with the increase of the number of the active CUs due to the increase of the potential multiuser diversity gain.

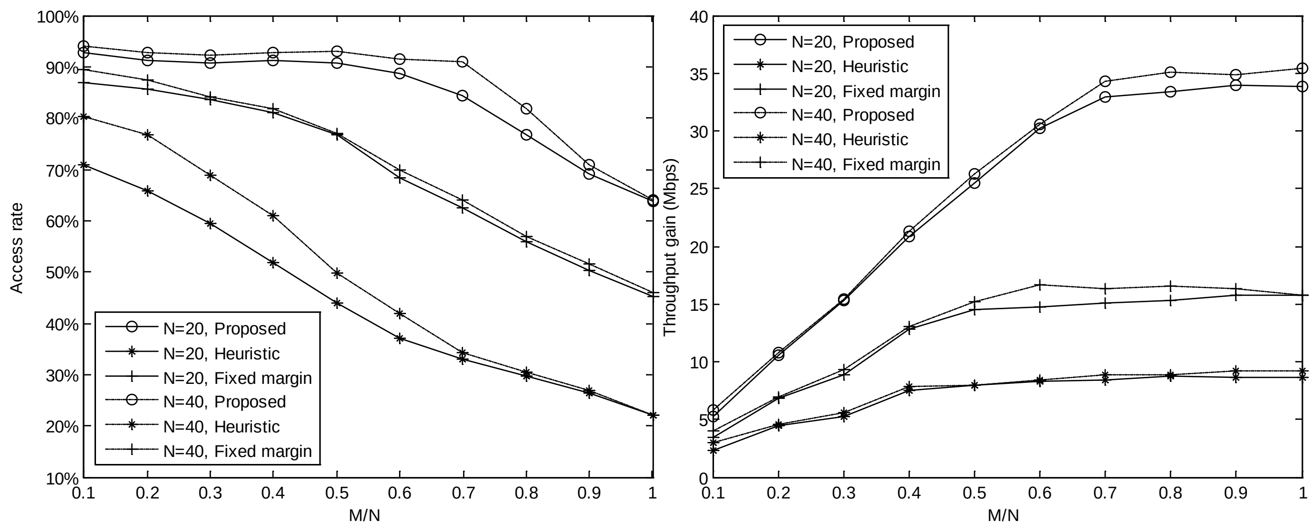


Figure 4.6: D2D access rate and throughput gain for different number of active cellular user and D2D pairs.

Fig. 4.7 compares the performance of the proposed KMDR scheme with the optimal resource allocation and also an intuitive method, KFAR scheme under different channel fading models. In the figure, since the optimal scheme has the full CSI and the KFAR scheme only relates to the distance between users, their performance does not change with channel models. As the more fading are brought from Rayleigh fading, lognormal fading, and Rayleigh-lognormal channels models, the performance of the probabilistic scheme also decreases in turn. Note that when K=6, for all the channel models, the performance of the KMDR scheme is almost the same as that of the optimal algorithm. That implies KMDR scheme can reduce significant feedback information, around 70% of total feedback information at the D2D receivers, while providing a near optimal performance. It is also seen that the performance of KMDR scheme is much better than that of KFAR scheme.

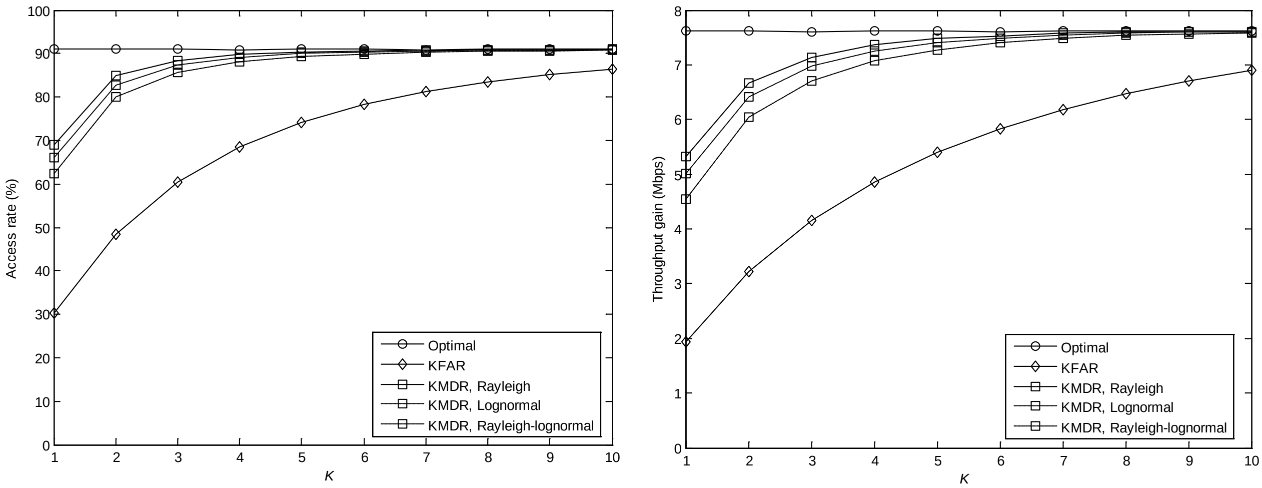


Figure 4.7: D2D access rate and throughput gain versus the number of feedback CUs under different channel models for the limited feedback schemes.

Fig. 4.8 compares the performance of the proposed probabilistic resource allocation scheme under different channel fading models with the optimal scheme. From the figure, both access rate and D2D throughput gain for the probabilistic scheme increase with outage probability threshold at first, and then decrease after the maximum values. As a result, there exists an optimal threshold of the outage probability.

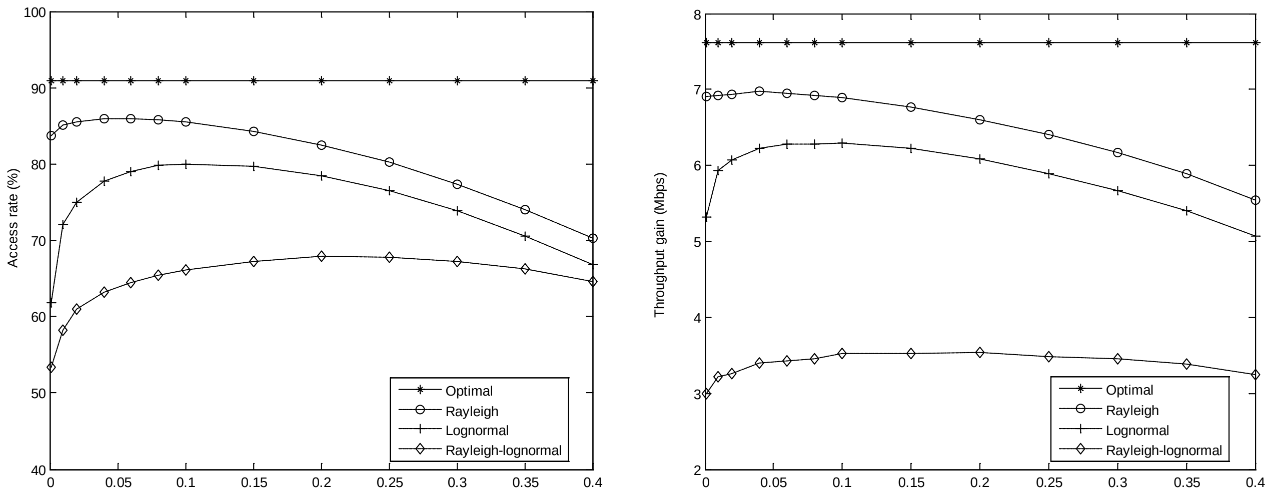


Figure 4.8: D2D access rate and throughput gain versus outage threshold under different channel models for the probabilistic algorithm.

Fig. 4.9 illustrates the actual D2D outage rates under different channel models and different outage threshold. From the figure, in all the channel models, the actual D2D outage rate increases with the outage threshold. This is because that as the outage threshold increase , the required minimum distance between CU and the D2D receiver for the D2D to access decreases, thus increasing the outage probability.

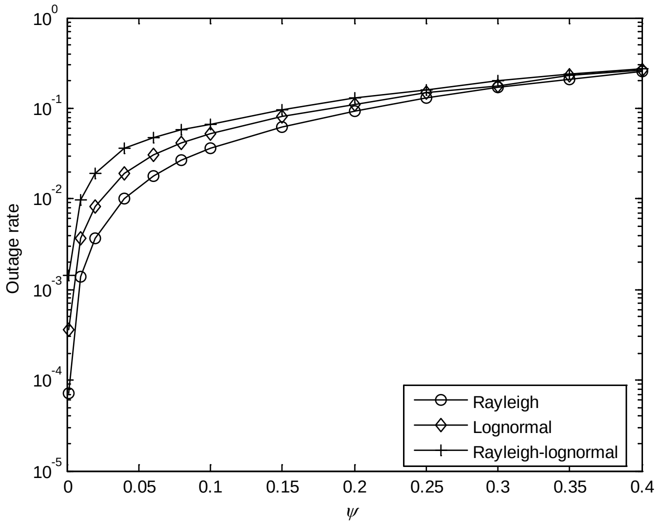


Figure 4.9: D2D actual outage rate versus outage threshold under different channel models for the probabilistic algorithm.

4.7 Conclusions

In this work, we have discussed the resource allocation strategies for D2D communications underlaying cellular networks to optimize the overall network performance. The results of our preliminary research are promising and have shown that there are substantial benefits by D2D communications.

5 Resource Allocation Schemes for Centralized Scheduling of Uplink and D2D Traffic

5.1 Introduction on D2D communication

One of the major features to be developed in 3GPP Release-12 is direct Device-to-Device (or D2D) communication, as a support for so-called 3GPP Proximity Services (or ProSe). The main advantage of using direct D2D communication is the provision of higher data rates and radio resource usage rates, thanks to the proximity of communicating users, but also the radio resource reuse or resource sharing.

In this work we provide a feasibility study of cellular-D2D reuse of radio resource, i.e. simultaneous use for cellular and D2D links, in the context of an LTE network. This feasibility study is first performed in terms of system architecture and protocol and further (in the next deliverable) in terms of simulation results based on real constraints from recent 3GPP standardization activities. This work therefore investigates the conditions for such an allocation scheme to serve the expected Quality of Service (QoS) on both cellular and D2D links. Interference constraints have to be identified and new interference control techniques have to implemented along with a possible associated LTE system design (i.e. LTE network and User Equipments), including Message Sequence Charts (MSCs) and related protocols.

During the past few years, direct D2D communication as an underlay of a cellular network emerged as an important research topic and many publications described and investigated the theoretical advantages of direct D2D communication over cellular ones, e.g. higher data rates and power saving, due to shorter radio path, or better resource usage [2], [3]. The work provided in this section focuses on the coexistence of both D2D and cellular links, and refers specifically to the impact of direct D2D communications on the cellular network and cellular communications.

5.1.1 Short Scientific D2D-related State Of the Art

Many previous works studied the impact of direct D2D communications and cellular communications and provided few Key Performance Indicators to measure this impact. For example, [4] evaluates the number of permitted D2D connections considering the average interference caused by a D2D pair and an interference threshold. [2] evaluates the D2D throughput as a function of D2D distance and then it compares the D2D throughput with cell's total throughput as a function of maximum allowed D2D distance, while [3] evaluates the feasibility ratio of a D2D communication and the energy efficiency as a function of both cellular User Equipment (UE) position and maximum D2D distance. It has been therefore shown that the system performance for up to 100 m maximum D2D distance is significantly better when the network is in D2D mode (i.e. allowing D2D communication) and that D2D communication can increase the total throughput observed in a cell under certain conditions. Several works use Cumulative Distribution Function (CDF) as Key Performance Indicator (KPI) and represent it with respect to Signal to Noise Interference Ratio (SINR) as in [5], with respect to user spectral efficiency such as in [6], or with respect to total sum rate of both D2D and cellular communication such as in [7]. As part of the research on D2D-cellular interference management, the choice of spectrum was discussed, e.g. in [8] which recommended to reuse LTE cellular UpLink (UL) resources for D2D transmission rather than the DownLink (DL) resources because UL band is generally underutilized compared to DL band. There are mainly (at least) two important reasons for using UL resources for D2D transmission instead of DL resources:

1) For example, spectrum occupancy measurements performed in Europe have shown [9] that a Power Spectral Density (PSD) measured in UL bands is 20 dB lower than the one measured in DL bands.
2) Another advantage for reusing UL bands is also to ease the control of interference and to allow a fast resource allocation by the eNodeB, which would be more difficult in DL bands [10].

5.1.2 Short 3GPP D2D-related State Of the Art

This research paved the way to the standardization of D2D technology in 3GPP [11], strongly pushed forward by the recent key move made by the public safety ecosystem, starting in the US, towards LTE for the development of next generation of public safety networks, as shown in [15]. 3GPP started the work on D2D in late 2011, first in Working Group SA1, building a set of service scenarios and requirements, recorded mainly in TS 22.278 [1], for so-called Proximity Services (or ProSe). From these requirements, other Working Groups (WGs) started feasibility studies and gathering of possible solutions, such as SA2 for system architecture in TR 23.703 [16], or RAN1 for the physical layer of the new D2D air interface in TR 36.843 [17]. Some of these works have been already integrated in Release-12. However, the normative work for 3GPP on D2D is expected also for Release-13 and beyond, as a result of the complexity of the subject but also due to important activities in the radio access area, not only due to proximity services.

The D2D features under development in 3GPP are D2D discovery and D2D communication, and these features are considered for use in scenarios related to public safety and critical communications (replicating and enhancing the services available in legacy public service networks, e.g. for policemen or firemen in the field), but also for commercial use (e.g. for localized advertisement services). With respect to 3GPP work on direct D2D communication there are two important aspects to be recalled:1) First of all, direct D2D communication function can be split in two features, which are the direct 1:1 communication and the direct 1:many communication. Both features are being designed to support the usual data communication service, respectively between two users (1:1) and within a group (1:many), and both can be offered with or without network assistance, i.e. signaling and control, but always under operator's control. Secondly, on top of direct communication, 3GPP ProSe defines a UE relaying feature which is used for public safety scenarios. This feature is applicable in situations such as UE-to-Network relaying (when a UE is relayed to the network by a UE with relaying capabilities called UE-Relay) or UE-to-UE relaying (when a UE is relayed to another UE with the help of a UE-Relay). To some extent this can be already included to the direct communication features. However, this can be seen as a different feature at least from the viewpoint of the control: a UE relaying another UE could also be able to perform e.g. Radio Resource Control (RRC) functions that normally a legacy UE cannot support by itself.

Both one-to-many communication and UE-Relay features are required in Release-12 for Public Safety scenarios. D2D standardization in 3GPP is work in progress, but already some key elements are available (e.g. see [18]), and these key elements have been chosen as the basis of this work: decision to use of UL spectrum for D2D communication, option to have an eNB-centralized resource allocation scheme for D2D, identification of a "D2D class range" with discrete values.

Please also note that work on D2D channel models has started but has not (by the time of our study) yet delivered a standard model.

On top of the benefits mentioned previously, direct D2D communication, being short range compared to the macro-cellular link, opens the possibility to perform spatial reuse of radio resources, i.e. to allocate the same radio resources simultaneously to a cellular link and a direct D2D link, under the condition that none of them would cause unacceptable interference to the other. This concept is a promising way to increase the cell capacity and the spectrum usage (and already applied to some extent to the concept of heterogeneous networks), but, beyond the theory, it is necessary to build a view of the feasibility and possible gains in real life, as well as of possible tools (for network planning or scheduling) for an operator to practically implement the reuse scheme. The D2D-cellular spatial reuse concept has been investigated in previous research, but, as mentioned earlier, it has been focused on cellular protection against D2D interference: this is insufficient with regard to 3GPP requirements [1] to offer D2D the same QoS of cellular communications.

5.2 Feasibility of D2D communication in a 3GPP context – protocol and architecture view

As previously mentioned, this work considers two additional constraints: 1) symmetrical protection of QoS (and not only at cellular side) and 2) latest 3GPP constraints. Also, as many parameters such as distance, communication channel, maximum allowed power and interference control play important roles in direct D2D communication, it is difficult to conclude which is the best Key Performance Indicators (KPIs) to use as it depends on the situation and the goal of the proposed algorithm, e.g. sum rate throughput maximization, cellular QoS, or fairness of use between cellular and D2D users.

The approach of this work is different from previous works as it considers both:

1) the QoS of the cellular communication and
2) the QoS of the D2D communication at the same time.

D2D communication should be used only if there are clear benefits for both operator and D2D user and therefore the work further investigates the conditions for D2D communication to offer this double benefit. Moreover, the use cases considered by this work are a subset of those covered by 3GPP ProSe: both 1:1 and 1:many features are supported, with D2D peers under coverage of the same cell. For generalization purposes, this work considered that one of the two UEs involved in D2D communication can be “in” or “out-of-coverage”.

Figure 6 describes, by the means of a Message Sequence Chart (MSC), a possible control-plane supporting a distributed algorithm (i.e. between eNB and UE-S) for the verification of reuse opportunities. On the MSC is represented a User Equipment UE-D not necessarily connected to eNB (and which serves as destination of the D2D communication between UE-S and UE-D), a User Equipment UE-S connected to eNB (and which serves as source of the D2D communication between UE-S and UE-D), two User Equipments UE-C connected to eNB and transmitting using cellular allocated resources (i.e. UE-C1 and UE-C2) and an eNodeB (or simply called eNB).

The sequence starts with the need for UE-S to transmit some data over the D2D link (the choice of D2D link instead of cellular link is out of the scope of our study), and then the UE-S sends a request for D2D resources to eNB with the information of the expected range for the transmission (3GPP parameter "D2D class range"). The MSC also assumes that together with UE-S which has some data waiting for D2D transmission, UE-C1 and UE-C2 also have some pending data waiting for UL transmission. On reception of the UE-S request for D2D resources, eNB will search for a candidate UE-C (also with a pending resource request) to share resources with UE-S, i.e. with low probability of interference with UE-D given the UE-S class range.

Possibly (but not necessary) as a reply to the requests made by different UE-Cs to transmit UL data, eNB pre-selects candidate cellular equipment(s) for cellular reuse purpose and candidate cellular equipment(s) for normal cellular resource use only. In the case of the MSC from Figure 6, it is supposed that UE-C1 has been selected for reuse purpose (i.e. at the same time with D2D communication) and UE-C2 for normal cellular use only (i.e. without any D2D communication). In other words, eNB pre-selects the candidate UE-C1 for cellular resource reuse purpose from all available UE-Cs (or UE-Cs willing to transmit something toward the eNB). Moreover, the selection can be performed on a geographical basis (e.g. based on geo-location) or a more complex scheduling algorithm. Results further obtained through simulation will show that this kind of selection based on geographical basis is possible.

The rest of the procedure aims at verifying the conditions of reuse between the candidate UE-C and UE-S/UE-D: this verification is based on legacy concept of LTE Sounding Reference Signals SRS [19]. SRS are used in LTE for uplink channel quality assessment, typically to feed some frequency-selective scheduling algorithm and here they are used for sounding all involved channels, i.e. UE-C-to-UE-D, UE-S-to-eNB and UE-C-to-eNB, enabling measurements to feed the conditions of reuse.

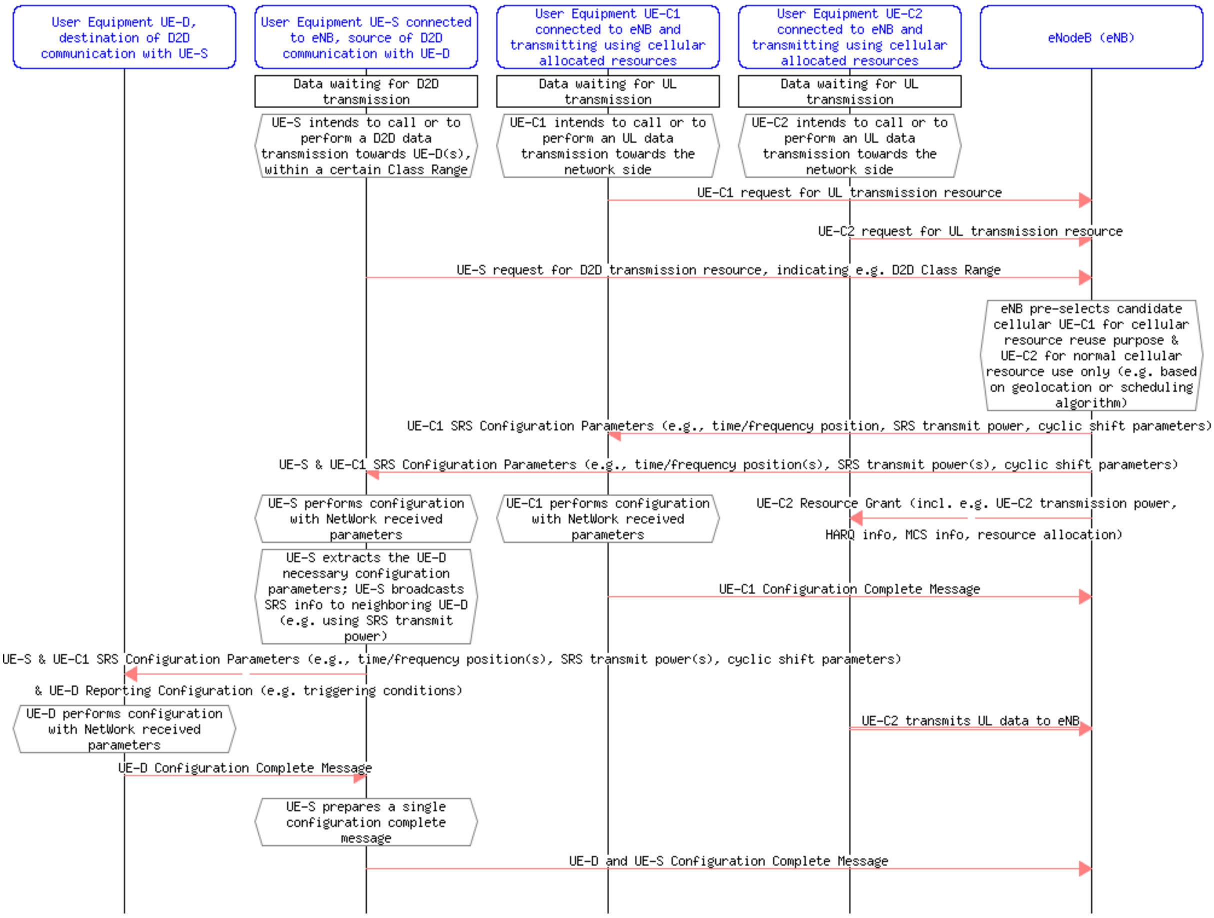


Figure 6. Protocol and Signalization Procedures – Part I

The configuration of the SRS parameters [19] may include time/frequency information for SRS generation, SRS transmit power, and cyclic shift. eNB sends SRS configurations to selected UE-C and UE-S, and the latter forwards both configurations to UE-D(s) using the maximum transmit power allowed by its D2D class range.

Upon to these configurations, UE-C1 could reply to eNB with a UE-C1 configuration complete message indicating to eNB that the SRS configuration has been performed. Similarly, UE-S could reply to eNB with a configuration complete message, indicating to eNB that both UE-S and UE-D have been configured with the necessary SRS parameters. In the MSC from Figure 6 is this therefore supposed that UE-S extracts the UE-D necessary configuration parameters and broadcasts to neighboring UE-D the required SRS information together with the UE-D reporting configuration (necessary for UE-D measurement report as seen further in Figure 7) by using e.g. the SRS transmit power provided by the eNB. Moreover, the MSC from Figure 6 supposes that UE-S prepares a single configuration complete message (i.e. including configuration complete message from UE-D) but this is not compulsory. However, for generalization purposes, this work considered that one of the two UEs involved in D2D communication can be “in” or “out-of-coverage”.

Meanwhile, the UE-C which has not been selected for cellular resource reuse purpose (i.e. UE-C2) can already start to transmit UL data to eNB, in response to a resource grant including for example UE-C2 transmission power, Hybrid Automatic Repeat Request (HARQ) information, Modulation and Coding Scheme (MCS) information, resource allocation, etc.

At some point in time according to the configurations, and represented in Figure 7, UE-C and UE-S start transmitting the required SRS which are received by the other stakeholders. The configurations from Figure 6 therefore allowed:

1) for UE-D to listen to UE-C1 and UE-S SRS;
2) for UE-S to listen to UE-C1 SRS;
3) for eNB to listen to UE-C1 and UE-S SRS.

On UE-D side, the measurements performed by UE-D on UE-Cs and UE-S (see Figure 7) allow for creating a SRS measurement report including for example UE-C1 and UE-S received powers. UE-C1 and UE-S received (and measured) powers are included in the measurement report of UE-D and sent to UE-S in order to enable UE-S to decide if the D2D transmission from UE-S will be correctly received by UE-D in presence of interference from UE-C1.

On UE-S side, using the measurement report provided by UE-D, UE-S estimates UE-C1-to-UE-D channel and UE-S-to-UE-D channel. At the same time, using the local measurements performed on UE-C1, UE-S could also estimate UE-C1-to-UE-S channel. However, this latter information would be useful only in scenarios where UE-S is close or nearby UE-D and/or the measurement report is not available or is lost. In such situations, UE-S could use this measurement (i.e. UE-C1-to-UE-S, not represented on Figure 7) instead of the UE-C1-to-UE-D measurement performed by UE-D.

On eNB side, the measurements of UE-C and UE-S SRS allow for estimating UE-C1-to-eNB channel and UE-S-to-eNB channel and for checking that the required UE-S power for D2D communication is inferior to the maximum transmission power for D2D purposes, including the determination of maximum transmission power for D2D purposes. At this stage, eNB inserts UE-C/UE-S in its scheduling algorithm and sends the grant (time/frequency-defined resource) for data transfer to both UEs with associated transmission (Tx) power constraints.

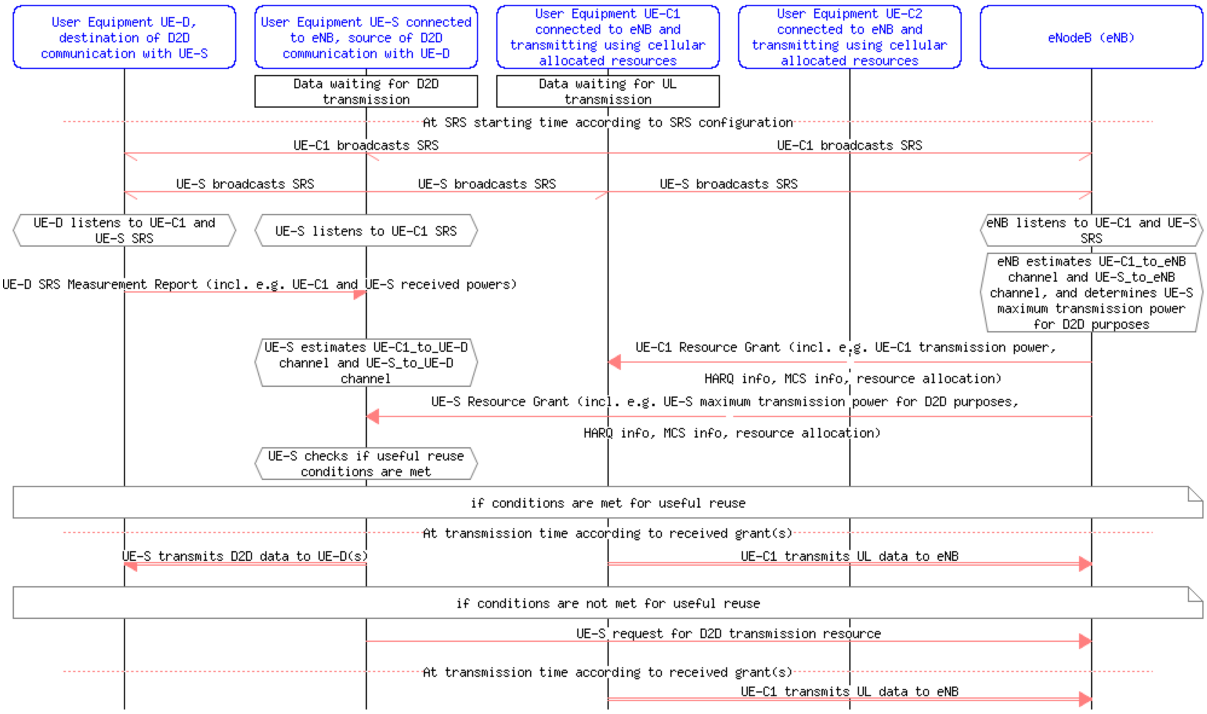


Figure 7. Protocol and Signalization Procedures – Part II

Then again, at UE-S side, UE-S still have to determine whether the received maximum transmission power constraint is compatible with the SINR at UE-D side, i.e. if the useful reuse condition at D2D communication side is met for useful reuse. If this checking is positive, UE-S will use the received grant to transmit its data (in same resources as UE-C), if not UE-S will request new resources to eNB, re-initializing the whole procedure. In this procedure, all eNB-to-UE exchanges could be supported by legacy signaling, and only UE-D-to-UE-S exchanges would require new signaling protocol. The timing performance and constraints of such procedure is for further study.

For the purpose of clarification, we assume that the etwork has already the means of performing “scheduling”, and therefore the intention was not to study scheduling algorithms in this work. Moreover, the configuration is centralized (e.g. at Network side) but the decision of whether a D2D UE transmits (or not) is not. For this reason, the work provided in this section is supporting a distributed algorithm (i.e. between eNB and UE-S) for the verification of reuse opportunities.

5.3 Preliminary Conclusions and Next Steps

The main contributions of this work were 1) to check the configuration/implementation complexity of such UL resource reuse scenarios, but also 2) to verify the feasibility of resource reuse scenarios. In a further work, simulation will be shown and analyzed in order to draw measurable conclusions expressed in terms of e.g. probability of reuse. It will be also showed through simulation that the pre-selection of equipment can been performed on a geographical basis.

6 CONCLUSION

This deliverable reported on the three main studies related to D2D communications in the SHARING project, and in particular, gave three visions on the resource allocation problem for allowing D2D transmissions to share the uplink spectrum. The first study uses some classical and more recent results on interference channels to motivate the resource allocation problem for two unicast scenarios, namely where the eNodeB schedules D2D traffic for both known and unknown content. The case of known content applies to a future usage of memory in user-terminals as spatially-distributed cache. These caches are used to offload traffic to other user terminals in the vicinity of the relaying terminal. The other scenario is where the content is not known by the eNodeB and interference must be mitigated in both the eNodeB receiver and D2D receiver. In both cases, we show the regimes of interference where the D2D can benefit from sophisticated signal processing.

The second study considers three-step optimal resource allocation framework when the eNodeB has perfect channel state information (CSI) of all links in the network. This is then relaxed for partial CSI information in the resource scheduler. In both cases the practical benefit of D2D communications sharing common frequency resources with regular cellular communications is very clearly demonstrated.

The final study examines the configuration and implementation complexity of practical uplink resource reuse scenarios in order to verify the feasibility of resource reuse. It also sets the scene for further work, where simulations will be performed in order to draw measurable conclusions expressed in terms of e.g. probability of reuse. It will be also showed through simulation that the pre-selection of equipment can been performed on a geographical basis.

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