AMERICAN UNIVERSITY OF BEIRUT

A SMART RESOURCE ALLOCATION ALGORITHM FOR D2D COMMUNICATIONS IN CELLULAR NETWORKS

by
HRANT ROUPEN SULAHIAN

A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Engineering
to the Department of Electrical and Computer Engineering
of the Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
December 2015

AMERICAN UNIVERSITY OF BEIRUT

A SMART RESOURCE ALLOCATION ALGORITHM FOR D2D COMMUNICATIONS IN CELLULAR NETWORKS

by
HRANT ROUPEN SULAHIAN

Approved by:

Dr. Mohammad Mansour, Professor
Electrical and Computer Engineering
Advisor

Dr. Ayman Kayssi, Professor
Electrical and Computer Engineering
Member of Committee

Ali Chehab
Dr. Ali Chehab, Professor
Electrical and Computer Engineering
Member of Committee

Date of thesis defense: December 28, 2015

AMERICAN UNIVERSITY OF BEIRUT

THESIS, DISSERTATION, PROJECT RELEASE FORM

Student Name:	Sulahian	Hrant	Roupen
	Last	First	Middle

☒ Master's Thesis ○ Master's Project ○ Doctoral Dissertation

☒ I authorize the American University of Beirut to: (a) reproduce hard or electronic copies of my thesis, dissertation, or project; (b) include such copies in the archives and digital repositories of the University; and (c) make freely available such copies to third parties for research or educational purposes.

☐ I authorize the American University of Beirut, **three years after the date of submitting my thesis, dissertation, or project,** to: (a) reproduce hard or electronic copies of it; (b) include such copies in the archives and digital repositories of the University; and (c) make freely available such copies to third parties for research or educational purposes.

19/01/2016

Signature Date

ACKNOWLEDGMENTS

First of all, I would like to express my gratitude to my advisors, Dr. Mohammad Mansour and Dr. Ali Chehab, for their continuous help, useful comments, and guidance during my graduate studies at AUB. I would also like to thank Dr. Ayman Kayssi for being part of the committee.

Second, I would like to thank my family and relatives, particularly my mother, father, and aunt for their continuous support during the good and difficult times during my studies. Without their support it would have been very difficult to arrive at this point.

Finally, I would like to thank my close friends who always stood by me and helped me even when things seemed to get challenging.

AN ABSTRACT OF THE THESIS OF

Hrant Roupen Sulahian for Master of Engineering
Major: Electrical and Computer Engineering

Title: A Smart Resource Allocation Algorithm for D2D Communications in Cellular Networks

In LTE Rel-12, 3GPP proposed device-to-device (D2D) communications as a promising solution to the tremendous increase in the number of mobile users and bandwidth requirements, which has put strict limitations on the already congested spectrum. In D2D, users can directly communicate with each other bypassing the base station, which leads to many benefits regarding throughput, spectral efficiency, power consumption, and hop gain. However, this new technology introduces many challenges, one of which is resource allocation, whereby users communicate with each other on a particular band at a specific time interval. In this thesis, we address this problem and target to satisfy the aforementioned requirements, by implementing a smart spectrum reuse algorithm for both single-hop and two-hop communications in single and multi-cell scenarios where frequencies can be shared between cellular and D2D devices while guaranteeing a good link quality. We also introduce a clustering algorithm along with an optimal cluster head and resource selection and show the effect of the two optimizations. We simulate several case scenarios to validate the proposed algorithms. Compared to existing schemes, our results show an increase in throughput by 44% to 66%, spectral efficiency ranging from 17% to 24%, a better SINR and capacity distribution function, and a lower outage probability ranging from 10% to 62%.

CONTENTS

Chapter

ILLUSTRATIONS

TABLES

Table Page

CHAPTER I

INTRODUCTION

A. Motivation

With the explosive data traffic growth introduced by the rapid increase in the number of smart phones and networking applications, the Third Generation Partnership Project (3GPP) is facing a challenging task to meet this demand. A study in [1] showed that by 2016, the number of mobile subscriptions will exceed the world’s population, and by 2019, the number of mobile broadband subscriptions is expected to reach 7.6 billion. For these reasons, many new technologies are currently being studied as complementary solutions for existing standards. These include densifying base stations and the deployment of small cells [2], use of cognitive radios [3], carrier aggregation, advanced multiple-input multiple-output (MIMO), and D2D communication [4]. In this thesis, we focus on the D2D communication technology.

3GPP dedicated a working group to study and implement a new Rel-12 item [24]; named Proximity-Based Services (ProSe), to become competitive as a broadband wireless technology. IEEE task groups have started to standardize PHY and MAC specifications for peer-aware communications. However, a lot of technical details and challenges remain in the dark and need to be addressed as these standards continue to be enhanced. This item is expected be a promising update to LTE-A, providing various services like public safety, social networking applications, in addition to advertising of different types, while targeting the requirements for an operator to integrate Device-to-Device (D2D) communication into their existing cellular network [5].

D2D communications underlying cellular networks has been a hot topic of research recently [6-7, and 31] due to the several advantages it provides which can be summarized by the following points [8-9, and 23]:

- High Throughput
- Hop Gain (Low Delay)
- Low Power Consumption
- Spectral Efficiency
- Introduction of new Proximity Based Services

In D2D, UEs directly communicate with each other using cellular resources, bypassing the base station. This concept is illustrated in Figure 1.1. Users 2 and 3 are in proximity and have the possibility to directly communicate with each other through the D2D link (L) instead of going through the base station through the cellular links (D). Thus by increasing capacity and throughput, operators can generate more profit if they can serve more users in a cell provided that the degradation to the existing users is minimal.

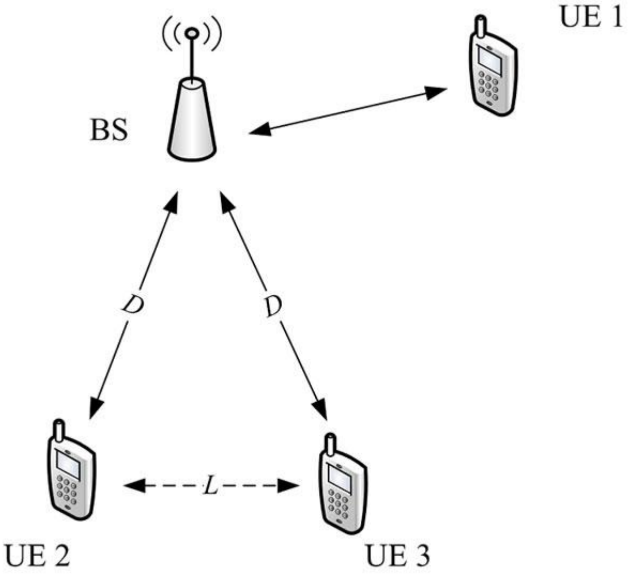

Figure 1.1 - D2D Concept

B. D2D Use Cases

Many publications discuss the use cases of D2D communications, which mainly include highly populated areas like airports, colleges, malls, game stadiums, and shopping areas. Figure 1.2 represents a good illustration on D2D use cases [10].

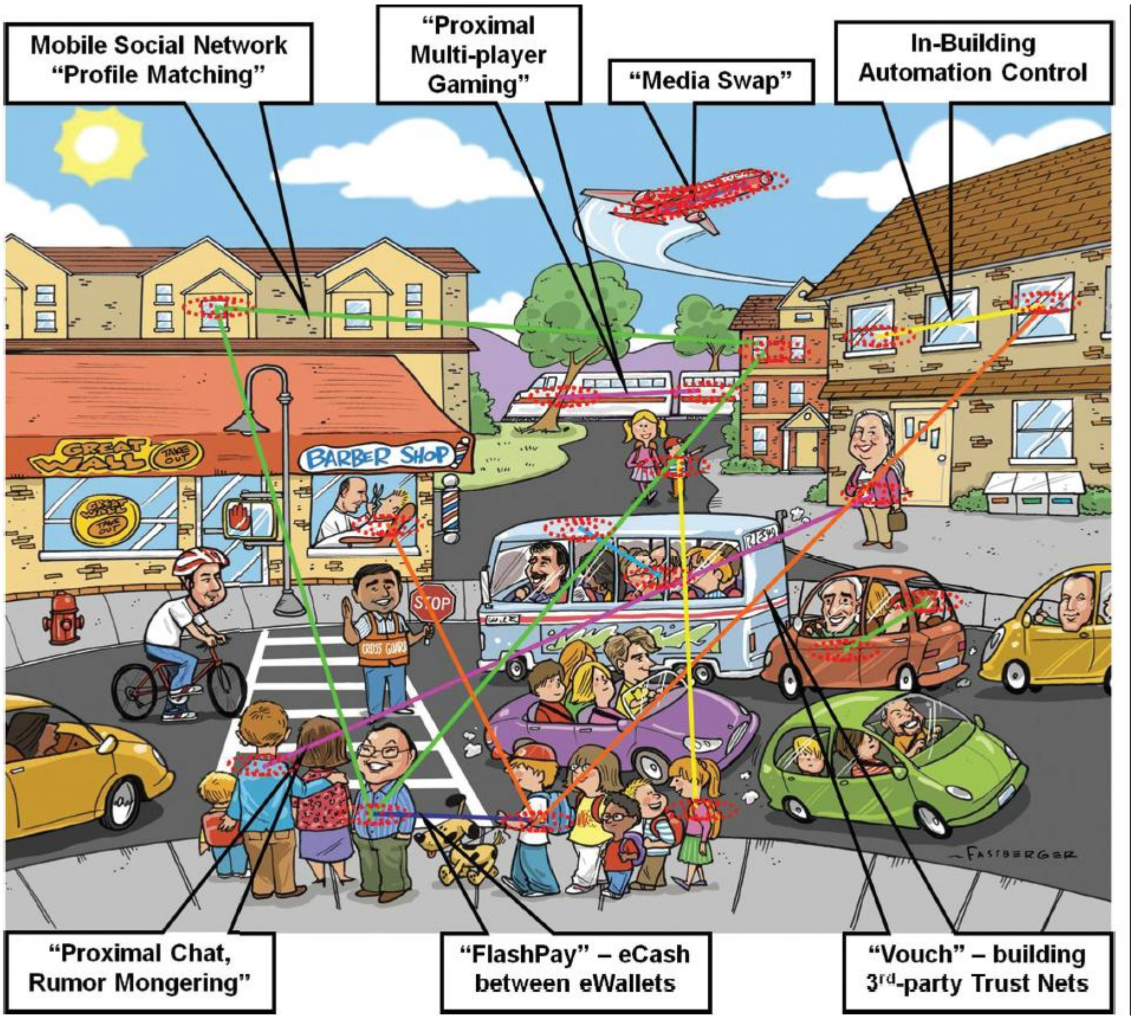

Figure 1.2 - D2D Scenarios [10]

C. LTE Resources

Orthogonal Frequency Division Multiplexing (OFDM) is a spread spectrum technology that distributes data over a large number of carriers that are separated apart at precise frequencies. The carriers are made orthogonal to each other allowing them to be spaced very closely together. As an example, LTE uses a subcarrier spacing of 15 kHz. Orthogonal Frequency Division Multiple Access (OFDMA) is the use of OFDM technology to multiplex traffic by allocating specific patters of sub-carriers in the time-frequency space to different users [11].

Figure 1.3 represents an LTE frame of length 10ms which is divided into 10 sub frames and 20 slots where each slot is 0.5ms long. Each slot consists of 7 OFDM symbols (normal cyclic prefix). Figure 1.4 shows the physical resource block. Each PRB consists of 12 tones and 7 symbols in time totaling to 84 resource elements. The minimum resource allocated to a user is 2 resource blocks (2 slots).

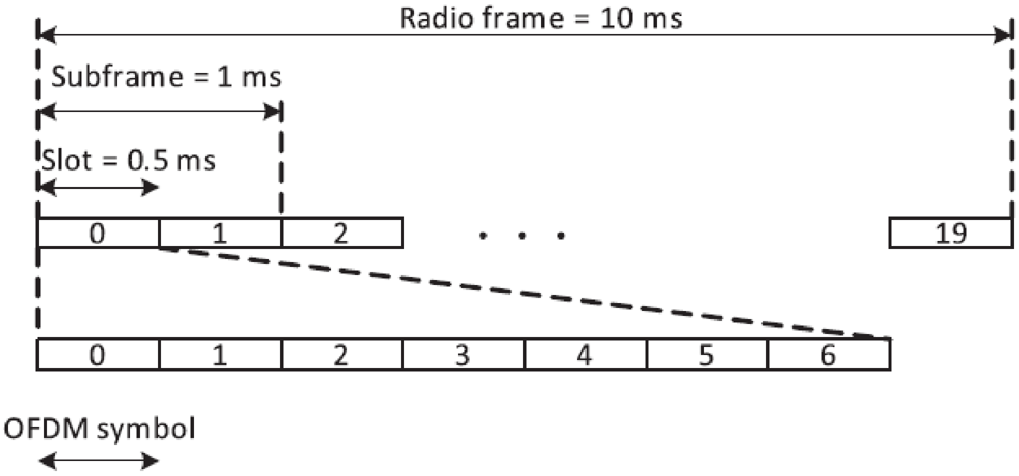

Figure 1.3 - LTE Frame Structure [11]

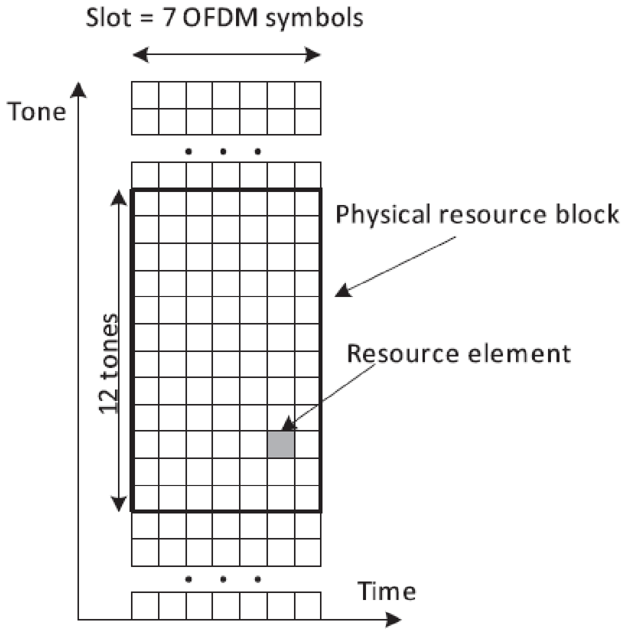

Figure 1.4 - LTE Resource Block [11]

The two types of bands that can be used by mobile users are the licensed (in-band) and unlicensed bands (out-band).

In in-band D2D, both D2D and Cellular UEs use the licensed (cellular) spectrum. Using in-band D2D allows good control over cellular spectrum, and hence interference can be managed, while in the unlicensed spectrum the interference is hard to manage which will degrade the link quality and hence decrease the achievable throughput thus imposing constraints for Quality of Service provisioning. In-band D2D is further divided into underlay and overlay categories [12].

In underlay D2D, cellular and D2D users share the same radio resources. In contrast, D2D links in overlay communication are given dedicated resources. Underlay D2D increases the spectral efficiency of cellular spectrum since the resources can be dynamically allocated to users; however, this introduces the problem of interference between the two types when resources are shared. In overlay D2D, both cellular and

D2D resources might be wasted if there would not be enough users to use the available spectrum.

In out-band D2D; D2D users exploit the unlicensed spectrum. The motivation behind using out-band communications is to eliminate the interference issue between D2D and cellular links. Technologies that use the unlicensed bands include Wi-Fi Direct (2.4, 5 GHz), ZigBee (868/915 MHz, 2.4 GHz), and Bluetooth (2.4 GHz) [10, 13]. However, as stated, interference is hard to manage, thus in this work we will focus on the in-band underlay approach.

A comparison of these technologies is given in Table 1.1.

Table 1.1 - Comparision of Different Technologies [13]

	D2D	Wi-Fi Direct	Bluetooth	ZigBee
Licensed	✓	✗	✗	✗
Interference Management	✓	✗	✗	✗
Security	✓	✗	✗	✗
Income for Operator	✓	✗	✗	✗

Regarding the choice of band, several options have been proposed. One can use the uplink, downlink, or both. If we choose the downlink bands, then the victims will be cellular subscribers using frequencies corresponding to D2D pairs, which complicates the allocation and leads to lower quality links. On the other hand, if we use the uplink bands, the only victim will be the BS, which is easier to manage as the BS has the benefit of being immobile and the ability to decode signals with very low SINR. Additionally, the uplink bands are less utilized than the downlink ones. Hence, we will utilize the uplink bands [12].

D. D2D Phases

The two main phases of D2D communications are the discovery phase and the communication phase.

1. *D2D Discovery*

In the discovery phase, D2D candidates look for potential neighbors in their proximity. In general there are two approaches for the discovery phase. In direct discovery, the device communicates with each other directly without the assistance of network. The discovery can be made possible by using a random procedure and one of the peers takes the responsibility of sending the beacon. The UE broadcasts its identity periodically so that other UEs know of its existence and decide whether it shall start a D2D communication with it. This approach is distributed and does not require the involvement of the BS.

In the network assisted discovery, the devices detect and identify each other with the assistance of network. The UE informs the BS about its intention to communicate with another UE and sends the beacon signal. Then the BS orders some message exchanges between the devices, in order to acquire identity and information about the link between them. This approach is centralized or semi centralized, and the network can mediate in the discovery process by recognizing D2D candidates, coordinating the time and frequency allocations for sending/ scanning beacon signals, and providing identity information [12].

Network assisted Discovery can further be divided into fully controlled discovery and loosely controlled discovery. In the former, the whole process is initiated and fully controlled by the BS. The network provides as much assistance in the discovery process as possible. This scheme is illustrated in figure 1.5.

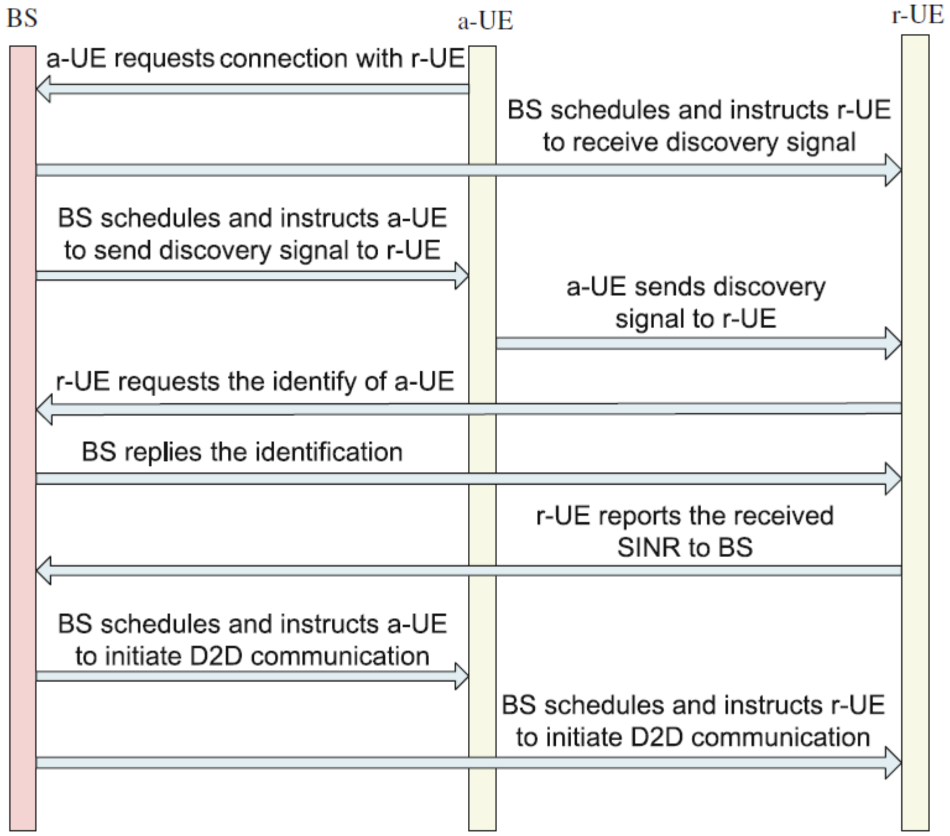

Figure 1.5 – Fully Controlled Procedure [12]

In the loosely controlled scheme, different levels of network involvement can be defined. First, the announcing UE can initiate the discovery process by broadcasting its beacon signals without the intervention of the BS, except that the BS reserves a resource pool for discovery procedure of UEs by broadcasting the beacon resources in the coverage area of the cell, and provides some information about the UEs for beacon transmission probability. Second, the beacon signal may include the device identity so that the UEs do not need to inquire the BS about this information. Finally, the link quality information can be exchanged between the UEs before reporting to the BS. This scheme is illustrated in figure 1.6.

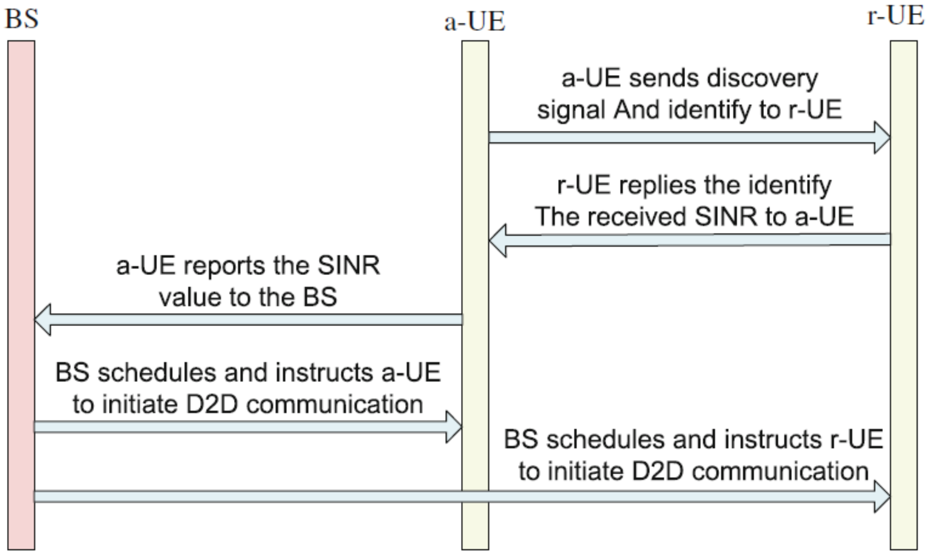

Figure 1.6 – Loosely Controlled Procedure [12]

2. *D2D Communication*

In the communication phase, the actual data transmission between the users takes place. There are several issues that should be addressed in this phase such as power control, channel estimation, mode selection, and resource allocation [25-30]. Similar to the discovery phase, the network can be involved in several aspects for the communication phase. In our design we will implement a loosely controlled scheme in which the base station is responsible for allocating resources to D2D users for the communication phase.

E. Objectives

In this thesis, we address the resource allocation problem by implementing a smart spectrum reuse algorithm whereby we divide a single cell into seven smaller sub-cells (partitions) based on the discovery range of the devices. Then, we propose an allocation scheme based on the location and channel gains of the users within the sub-cells. We also extend the algorithm to multiple adjacent cells. To handle the longer distances allowed now between D2D pairs, we also enable two-hop communications which leads to better results than single-hop in many cases like D2D pairs with no line of sight (LOS) within the same or different cells. We also propose a clustering algorithm, whereby users with common interests can form a cluster. We show the advantages of choosing an optimal cluster head in addition to an optimal frequency. The main advantages of our algorithms include: high spectral efficiency, long communication range, achieving high throughput, and guaranteeing high SINR values with a low probability of outage. We simulate several case scenarios to validate the proposed algorithms. We also compare our results to those of existing solutions to highlight the strengths of the proposed algorithm.

In the rest of this report, Chapter II discusses some schemes proposed in the literature along with their shortcomings that we address in our model. Chapter III gives an overview of the system model along with the optimization parameters. Chapter IV states the proposed algorithms in addition to a section on complexity analysis. Chapter V shows the simulation results, along with analysis and comparisons with existing schemes. And finally, Chapter VI concludes the report and presents directions for future work.

CHAPTER II

RELATED WORK

A. LTE Frequency Reusing

The concept of reusing frequencies has been used in LTE as shown in [14]. As illustrated in figure 2.1, users located in the middle regions of the cell have the possibility to transmit on the same frequencies due to the distances between them. The power level is moderate since the users will close to the base stations relative to users located at the cell edge. Users located in peripherals of the cells need to have a larger power to transmit due to their distance from the base stations. However, as shown in Figure 2.1, the three cells (2, 4, and 6) can reuse the same spectrum at the edge, and the same applies to cells 3, 5, and 7. This is known as fractional frequency reusing (FFR) in LTE.

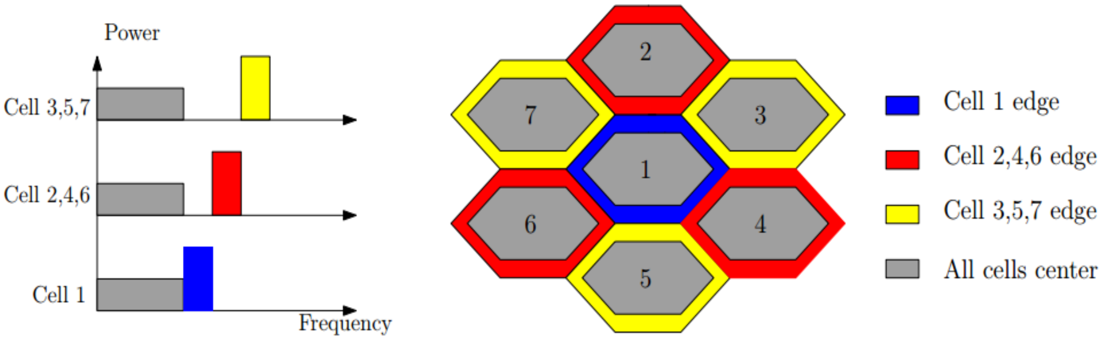

Figure 2.1 - Frequency Reusing in LTE [14]

B. Literature Review

Recent publications proposed different resource allocation algorithms mainly for the reason of increasing cell capacity. In [15], the authors proposed a radio resource allocation scheme for D2D communications underlying cellular networks using FFR whereby, D2D and cellular UEs use the different frequency bands chosen as users' locations. Through simulations, the authors showed that the proposed scheme improves the performance of D2D and cellular UEs by reducing interference between them. However, this scheme has many limitations which we address in our model. These include:

- Distance between any D2D pair is limited to 20-50m only.
- Users can only communicate with other users in the same region (i.e. users in inner regions can only communicate with user in inner regions, and users in outer regions can only communicate with those in outer regions).
- Resources are randomly picked based on location only.
- SINR CDF (Cumulative Distribution Function) shows low values.
- Frequencies can only be reused once.

The proposed algorithm can be summarized by the Figures 2.2 and 2.3:

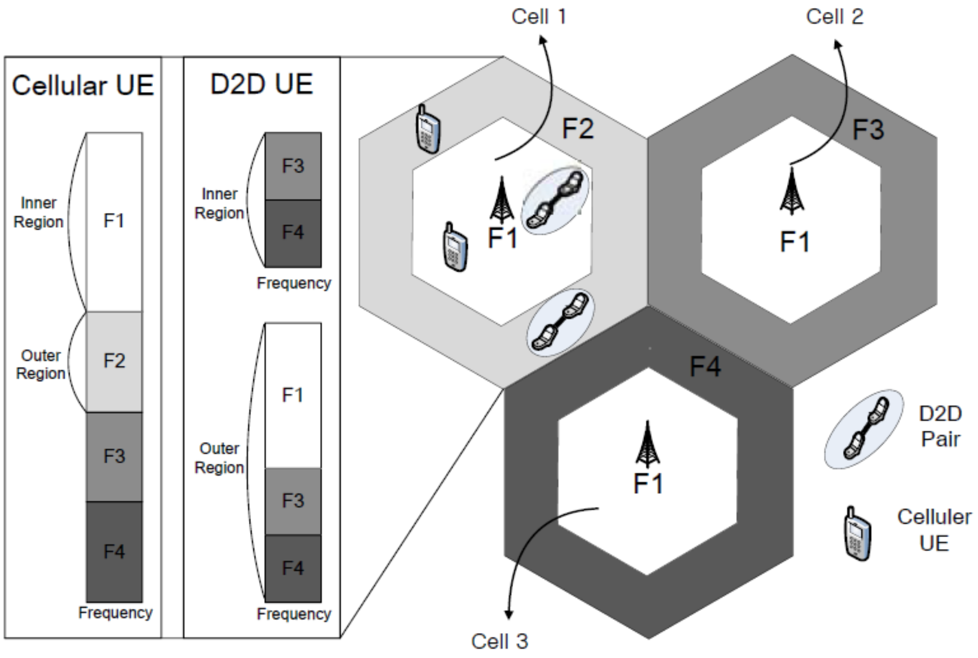

Figure 2.2 - Allocation Figure [15]

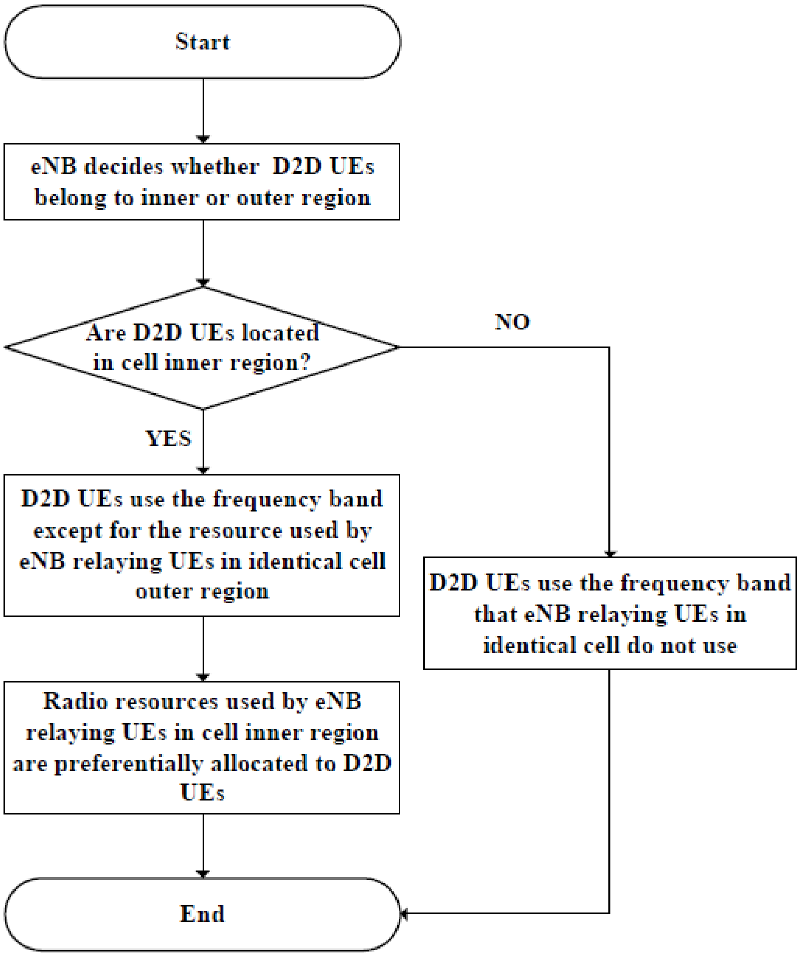

Figure 2.3 - Allocation Algorithm [15]

Authors in [16] propose two novel resource allocation (RA) schemes: the first RA scheme (cell level) mitigates the interference between D2D and CU and the second RA scheme (user level or scheduling) schedules the resources in an energy efficient way between D2D users and CUEs. These RA schemes increase the throughput and reduce the overall energy cost per bit of the system. Afterwards, these schemes are compared with the conventional methods and the simulation results show that the proposed schemes obtain higher throughput and save significant amount of energy per bit. The proposed cell level frequency allocation scheme is shown in the Figure 2.4.

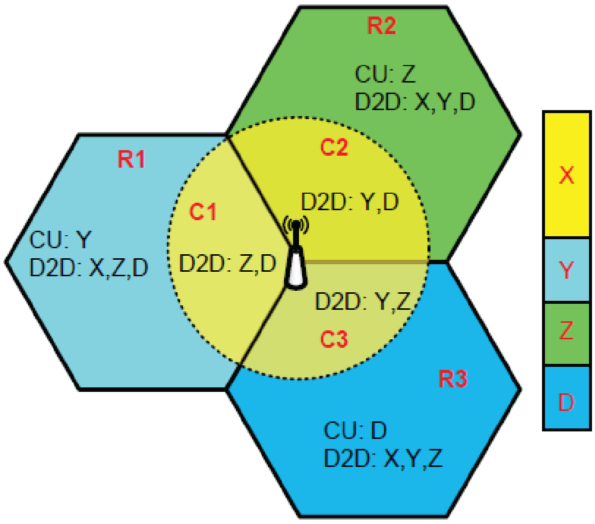

Figure 2.4 - Allocation Figure [16]

In step 1 of the D2D communication approach, the available frequency resources (PRB) are allocated in each cell based on 3-sectored FFR. Once this allocation is done, the other frequency allocation for D2D users will be completed after optimal allocation of cellular users (CUEs). CUEs have a priority over D2D users so this allocation order is acceptable. This order decreases the complexity of the optimal allocation problem in mixed CU/D2D user system.

In step 2, the LTE cell coverage is divided into “cell center region” and “cell edge region” including three sub-areas per region, denoted by C1, C2, and C3 for cell center region and R1, R2, and R3 for cell edge region. The whole frequency band is divided into four parts, denoted by X, Y, Z and D. Under the assumptions of uniform and static user distribution and the optimal pre-allocation of LTE cell users, the basic idea is to allocate a frequency resource in practically disjoint ways in order to reduce interference between cellular users and D2D users. So, the D2D user chooses the resources which are not used in the CU sub-area. For CUs, different resources are allocated to each LTE-A cell sub-area according to the sectored-FFR. For the CUE, part of resources X is used in the cell center region (C1, C2, and C3), and resources Y, Z and D are applied in the sub-areas of R1, R2 and R3, respectively. The main idea is that if D2D users are located in cell center region, the D2D user excludes the resided resource which is used already by CU in both cell center and edge sub-areas of the current sector. The reason is that the signal strength of the two related resources is so high that can seriously interfere with the D2D users in the inner sub-area. Under this basic rule, resources are reused by D2D as much as possible since the transmit power of D2D is very small. Therefore, the interference between CU and D2D is greatly avoided. Moreover, resources are allocated to the D2D users located in the cell edge region in order to improve their performance. However in this model, the D2D distance is limited to [1-20] meters only and limits the frequency reusing to 1 D2D pair only. Additionally, the distance between any two different D2D pairs is set to 50m which is not realistic as D2D pairs can be located anywhere.

In [17], the authors introduce a clustering algorithm and a resource allocation method in two stages to mitigate the interference during the uplink transmission period, as shown in Figure 2.5. In the first stage, the clustering algorithm is based on a similarity measure in order to reduce the BS signaling overhead. In the second stage, the authors formulate a problem to maximize the spatial reuse efficiency by allowing the data transmission of D2D pairs on the same resources. Simulation results showed that the proposed clustering scheme outperformed the other schemes for different configurations of D2D. The distance between D2D pairs is limited to 20m.

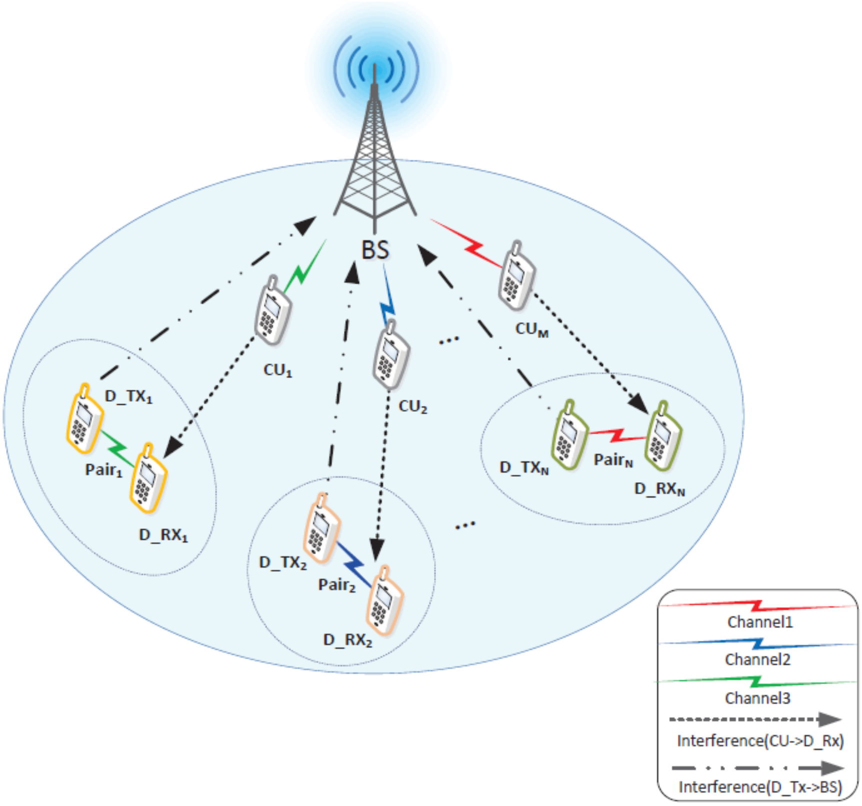

Figure 2.5 - D2D interference during Uplink [17]

In [18], the authors proposed a joint power and channel allocation for multicast D2D communications sharing uplink resource in a fully loaded cellular network with the objective to maximize the sum throughput of all users in the cell. The authors formulate the problem of power and channel allocation as a mixed integer non-linear programming (MINLP) where each D2D can share at most one frequency with a CUE. Simulation results showed improvements over previous unicast models.

In [19], the authors proposed an interference avoidance allocation scheme based on graph-coloring to show performance gain of spatial reusing. By assigning multiple D2D pairs to a single D2D resource, interference can’t be avoided, which leads to low throughput and quality degradation. Therefore, the authors propose a resource allocation scheme based on graph-coloring theory, which is used to eliminate the interference and hence increase the throughput. Simulation results show a higher sum rate and a reduction in the outage probability.

In [20], the authors proposed a semi-distributed resource allocation scheme for D2D communications where the BS allocates resources for cellular links and D2D links in a centralized manner while the modulation and coding scheme level are distributive and decided by the devices. They formulated the scheme as a well-known multiple set covering problem with the objective of maximizing the spatial reuse of radio resources. The simulation results showed a higher network throughput.

In all of the above schemes, there is a recurring constraint that a resource can be shared only once between cellular and D2D devices. Additionally, most of them consider only small distances for D2D pair. In our model, we relax these constraints and opportunistically search if we can reuse the same frequency more than once while guaranteeing good link quality between relatively far users.

CHAPTER III

SYSTEM MODEL

A. System Parameters

Before describing the model, we state the main parameters to be evaluated which lead us to calculate the cell throughput and spectral efficiency. Since we will use the uplink channels, we will have a scenario similar to figure 2.5. We define the following quantities:

$$SINR_{BS} = \frac{Pt_{CUE} \cdot G_{CUE,BS}}{N_o + \sum_{i=1}^{\#\text{interferers}} Pt_{D2D,S} \cdot G_{BS,D2DS_i}} \tag{1}$$

$SINR_{BS}$:	Signal to (interference + noise) ratio at the BS
Pt_{CUE}:	Transmission power of the cellular user equipment
$G_{CUE,BS:}$	Gain between base station and the UE
$Pt_{D2D,S:}$	Transmission power of the D2D sender
$G_{BS,D2DS}$:	Gain between BS and the cellular D2D sender
N_0:	Noise power spectral density

$$SINR_{D2D} = \frac{Pt_{D2D,S} \cdot G_{D2D}}{N_o + Pt_{CUE} \cdot G_{D2DR,CUE} + \sum_{i=1}^{\#\text{interferers}} Pt_{D2DSi} \cdot G_{D2DSi,D2DR}} \tag{2}$$

$SINR_{D2D}$:	SINR at the D2D receiver
Pt_{CUE}:	Transmission power of the cellular user equipment
$Pt_{D2D,S}$:	Transmission power of the D2D sender
G_{D2D}:	Gain between D2D sender and D2D receiver
$G_{D2DR,CUE:}$	Gain between D2D receiver and the UE
$G_{D2DS,D2DR:}$	Gain between D2D receiver and the D2D sender (interferer)
N_0:	Noise power spectral density

We need to maximize SINR_{BS} and SINR_{D2D} which leads to rate maximization. The total cell capacity can be calculated using the following equations:

$$D2D_{throughput} = \sum_{i=1}^{\#D2Dlinks} BW \cdot \log_2(1 + SINR_i) \tag{3}$$

$$Cellular_{throughput} = \sum_{i=1}^{\#Cellularlinks} BW \cdot \log_2(1 + SINR_i) \tag{4}$$

$$Throughput_{total} = D2D_{Throughput} + Cellular_{Throughput} \tag{5}$$

Also, we define the spectral efficiency, which indicates how much throughput can be achieved per unit bandwidth.

We also define the outage probability which is the probability of having a variable below a specific threshold value.

B. System Design

In the case of a single cell, we can see from the above equations that the throughput and spectral efficiency are a function of the SINR, which itself is a function of the channel gains between different users communicating on the same band.

The channel gain is a function of several parameters, such as distance, shadowing, and fading. Hence, we try to use these three parameters to devise an efficient algorithm to maximize the rate, spectral efficiency, and guarantee a good link quality between users. If the channel gain between the D2D transmitter and the BS, and D2D receiver and the CUE, is low, then the interference level will be low and hence we can achieve more throughput and spectral efficiency.

We propose dividing one single cell into seven smaller and equal sub-cells as shown in Figure 3.1 (we use hexagons for the sub-cells for illustration purposes). With such a division, we limit the D2D users to be located within the same sub-cell or at most across two adjacent sub-cells.

Users transmitting at diametrically opposite sides at the outer edge of the cells (e.g. D2D users in partition 2 and cellular users in partition 5 or vice versa) might have the opportunity to use the same resource blocks (frequencies) at the same time, since their signals will not interfere severely with each other. Users belonging to the same partition will be assigned orthogonal resources and hence eliminating intra-cell interference. We will also cover cases when D2D users are not located in the same partition.

Assuming we have a cell radius of around 500m, each partition has a radius of around 150m. The discovery range of users is about the size of a partition (~150m); hence users can discover neighbors, and thus communicate with, up to the adjacent partition.

After the discovery phase, the base station has to allocate resources for the D2D users so that they can start to communicate. This is a challenging task as we chose to use the underlay approach where resources will be shared between cellular and D2D users. We assume that BS has access to the coordinates of all the users in its cell along with channel quality indicators that are constantly reported by the users, and hence, it can calculate the distance between them along with channel quality parameters. The transmission power of the devices (whether Cellular or D2D) is set to guarantee a specific minimum power received P_{Rmin} at the receiving end, whether eNB or the D2D receiver.

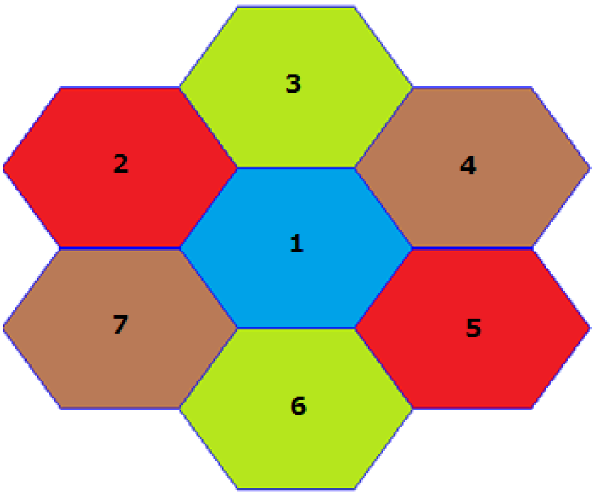

Figure 3.1 - Single Cell Partition

Due to large distances allowed in our model for the D2D pairs (up to 150m), sometimes users that are far away from each other or have a bad channel quality between them might not be able to communicate reliably. Instead of denying them the chance to communicate or waiting till they get a good channel, we propose applying a two-hop algorithm, whereby idle users located between the transmitter and receiver might have the opportunity to relay information. The criteria for choosing the relay user will explained in Chapter IV. We assume that all the idle users have the incentives to act as relays. The main advantages of relaying include less interference due to the smaller distances, more throughput, and lower transmission power.

Afterwards, we investigate clustering schemes, whereby users become part of a cluster and one of them is assigned to be the head cluster to broadcast the information. We propose an algorithm where we show the effect of choosing a random cluster head along with a random resource, a random cluster head with an optimized resource, and finally an optimized cluster head with an optimal resource. The criteria for selecting the optimal cluster head and resource will be explained in Chapter IV.

Since all cells have neighboring cells, we need to account for the adjacent cells as well for a more realistic environment. We assume that the base stations of adjacent cells are always in contact and exchange information about the available frequency bands through their backbone connection. Thus, we extend our algorithm from a single cell scenario to a multi-cell scenario consisting of the middle cell and the six neighboring cells.

For cellular users, we allocate resources according to FFR in LTE as explained in Chapter II. We show the resource allocation of cellular users in Figure 3.2. Benefiting from this concept, we use a similar concept for D2D resource allocation as shown in Figure 3.3.

Due to the distance between cells, the two sets consisting of three outer cells (e.g. the red and yellow parts of the cells) can reuse the same spectrum in the outer regions; hence the total available bandwidth can be divided into 3 parts (one for the middle cell, and 2 for the outer cells). Users in the middle partition of the cell can use the same spectrum in all 7 cells.

In our model, users are randomly and uniformly distributed within each cell and partition, and D2D users are randomly paired depending on the distance constraint between them. The allocation procedure is dynamic where the allocated resources depend on the instantaneous location and channel gains of users at every scheduling period.

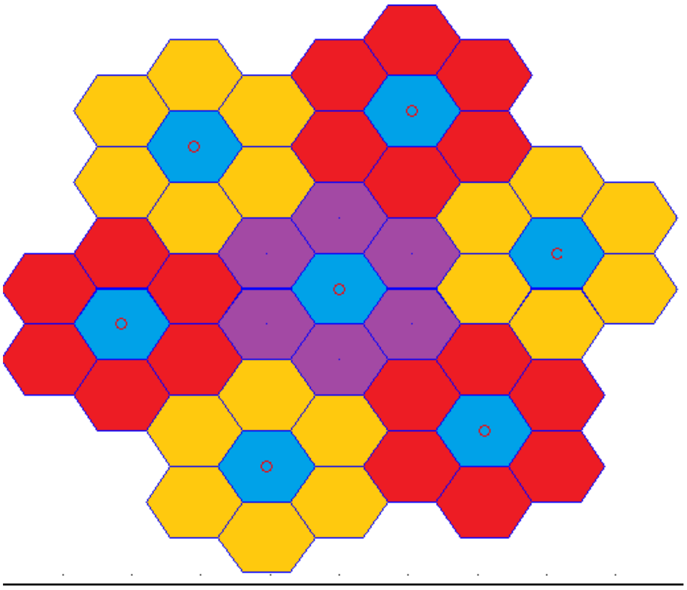

Figure 3.2 - Inter-cell Cellular Frequency Allocation

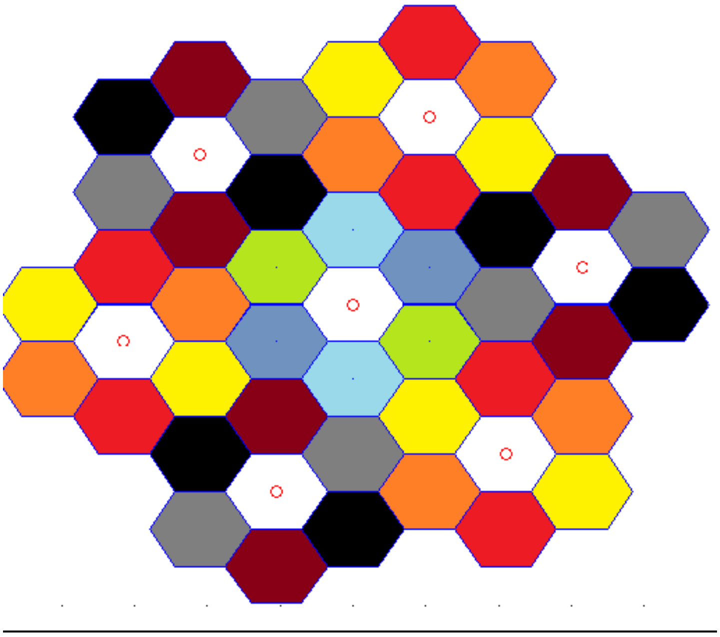

Figure 3.3 -Inter-cell D2D frequency allocation

CHAPTER IV

PROPOSED ALGORITHMS

A. Resource Allocation in a Single Cell

In the case of a single cell, we first divide the users according to their locations. Then, we allocate frequencies to cellular users as they have the priority. Then, we allocate frequencies to D2D users in the outer regions based on their locations and channel gains. Next, we allocate frequencies to D2D pairs who have at least one user in partition 1. Finally, we search for D2D pairs who are still not assigned a frequency and try to allocate them frequencies which will minimize the interference level. The following steps give a detailed explanation of the proposed algorithm which is later summarized in the box Algorithm-1.

Step 1: After receiving the request from the users following the discovery phase, the BS maps all the users (D2D and Cellular) into their corresponding partitions (one to seven).

Step 2: Since the cellular users have priority, resources are first allocated to them (based on the channel gains with the BS).

Step 3: After pairing the D2D users, the BS checks whether there are pairs which are relatively far from each other without a reliable channel quality between them, along with the possibility of finding a relay user in between the two users which is closest to the midpoint joining the two users. If found, the BS schedules the new pair (Initial Transmitter, Relay) for the current round of allocation and schedules the pair (Relay, Initial Receiver) for the next round.

Step 4: After determining the final D2D pairs, the BS starts allocating resources to the D2D users according to the following criteria

a. If the two D2D UEs belong to the same partition then a search for a cellular user in the opposite partition having a minimum channel gain between the cellular UE and the D2D receiver will be performed and a corresponding resource will be allocated. (e.g. D2D pair in partition 2 will be allocated a resource from a cellular user in partition 5, if available)

b. If the two D2D UEs belong to adjacent partitions in the outer region, then a resource from either of the two opposite partitions (based on availability and channel gain) may be allocated. (e.g. D2D pair located across partitions 2 and 3 will be allocated a resource from partition 5 or 6 depending on interference level and resource availability).

c. Since D2D users that have at least one user in the middle partition can't share frequencies with any cellular users due to the high level of interference, we allocate unused frequencies to D2D pairs in the center partition or users between central partition and any of the outer partition (if available). (e.g. D2D pair in partition 1 or a D2D pair where one user is in partition 1 and the other in partition 2).

Step 5: If we still have resources that are unoccupied along with D2D pairs at any partition at the edge, these frequencies can be reused twice (i.e. the frequency can be given to any two D2D pairs belonging to diametrically opposite partitions). (Ex: if we have two pairs located for example in partition 4 and the other pair in 7, and we have an unused band, then this frequency can automatically be allocated to both pairs).

Step 6: If there are still D2D pairs without an allocated resource then the following two rules can be applied:

- **a.** A search will be performed in an area close to the BS (i.e. small radius around the BS in the middle partition), since the transmission power will be small and hence it will not cause major interference to a D2D pair communicating in the outer partitions. (e.g. a pair in partition 3 still doesn't have a resource, and we have a cellular user located in partition 1 within a small distance of the BS and using frequency x; then assign frequency x to the pair in partition 3).
- **b.** If (a) fails then a search will be performed in any of the adjacent sub-cells of the opposite partition and if the degradation in performance (SINR) is low (<5 dB) then the resource can be used for D2D (i.e. a resource will be chosen that will cause the minimum interference). (e.g. a pair in partition 3 does not have a resource yet, and no cellular band is available for sharing in partition 6, then perform a search in partitions 5 and 7 (which are relatively far), and if a frequency is found that satisfies the required criteria, then allocate this resource to the D2D pair).

The Algorithm can be summarized in the box below (Algorithm-1):

Algorithm-1: Resource Allocation in a Single Cell (RASC)

```
INPUT: Users with their coordinates and mode selection type (Cellular or D2D) with Channel Quality Indicators
OUTPUT: Distributing resources to the maximum numbers of users
1. Map users to their corresponding partition based on their coordinates
2. Allocate resources to cellular users
3. If two-hop mode is on
       If reliable link establishment between a pair(A,B) is not possible
           Search for an idle Relay UE (R) such that $min(X_A,X_B) < X_R < max(X_A,X_B)$ and $min(Y_A,Y_B) < Y_R < max(Y_A,Y_B)$
               with $X_R, Y_R$ as close as possible to the midpoint joining A and B with good links
               Schedule the pair (A,R) for the current allocation round and the pair (R,B) for the next allocation round
       Else
               Keep the initial receiver (B)
4. If a D2D pair is in partitions 2-7 then
       If within the same partition then
           Search for a CUE frequency in the opposite partition having minimum Channel gain $G_{D2DR,CUE}$
           In case of a tie choose the frequency that maximizes $G_{D2D}$
       Else
           Search for a CUE frequency in both opposite partitions choosing based on availability and channel gain
   Else
           Allocate unused frequencies to D2D pairs in the center partition or between the center and any outer partition
5. Allocate unused resources to D2D pairs reusing the same frequency in opposite partitions for partitions 2-7
6. If D2D pairs without an allocated frequency still exist then
       Search for CUE resource in an area close to the BS such that it won't degrade link quality (<5 dB)
       if it fails then
           Search for a CUE in the adjacent partitions of the opposite partition for D2D pairs within the same outer partition
           Search for a CUE in the opposite partition for D2D pairs between the center and any outer partition
```

B. Resource Allocation in Multi-cells

As explained earlier, we need to account for the adjacent cells for a more realistic environment. The algorithm adds on that of a single cell with a few modifications that can be summarized as follows:

Step 1: If the D2D pair is located in the same cell then simply apply Algorithm-1.

Step 2: After applying Step 3 of Algorithm-1 which determines if a suitable relay is found between two users without the possibility of a reliable connection, we apply the following two rules:

- **a.** If the pair at hand is located in the same cell, then apply Algorithm 1
- **b.** If the pair at hand is located across two cells, then find the best frequency (minimum interference) from the opposite partitions of the devices within their respective cells. And in case of a tie, choose the frequency that maximizes the channel gain between the D2D pair.

The Algorithm can be summarized in the box below (Algorithm-2):

Algorithm-2: Resource Allocation in Multi-Cells (RAMC)

```
INPUT: Users with their coordinates and mode selection type (Cellular or D2D) with Channel Quality Indicators
OUTPUT: Distributing resources to the maximum numbers of users
1. If a D2D pair is located in the same cell then
       Apply Algorithm-1
2. Else
       Apply Step 3 of Algorithm-1
       If a new pair exists and located within the same cell
           Apply Algorithm-1
       Else
           Search for the best available frequency (Minimum interference) in the opposite partitions of the devices within their respective cells
           In case of a tie choose a frequency that maximizes $G_{D2D}$
```

C. Clustering Algorithm

Due to the common interest in many cases, like in a mall, airport, or school; it would be useful to think about broadcasting scenarios. Instead of forming multiple D2D pairs, we might think of a clustering approach whereby a user can take the initiative to broadcast information to other users. However, this is not straightforward as the selection of the cluster head and the resource block might be a critical factor in deciding many parameters such as interference and transmission power.

For the first scenario, we choose a random resource block from the opposite side of the cell while having a random cluster head (based on location only). For the second case, we select an optimal resource block based on the fixed cluster head. By optimal, we formulate our cost function to be the interference caused by the cellular user to the cluster. This can be expressed by equation (6).

$$R^* = \arg\min \sum_{i=1}^{\#clusterusers} Pt_{CUE} \cdot G_{D2DRi,\,CUE} \qquad (6)$$

To solve equation (6), as in Algorithm-1, we first look at the location of the cluster and the partition it is located in. And accordingly search for an optimized frequency in the opposite partition or the adjacent partitions to it.

For the final and optimal solution, we optimize for the cluster head and resource together. First, we look at the frequencies that have minimum interference to the cluster users (e.g. set of users that are far from the cluster), and then accordingly we select a cluster head that has the best channel qualities with the other users in the cluster (equation (7)).

$$R^* = \arg\max \sum_{i=1}^{\#clusterusers} G_{D2DRi,\,D2DS} \tag{7}$$

The Algorithm for the optimal solution can be summarized in the box below (Algorithm-3):

```
Algorithm-3: Resource Allocation for Clustering Scenarios (Optimal)
INPUT: Users with their coordinates and mode selection type (Cellular or D2D)
with Channel Quality Indicators
OUTPUT: Distributing resources to the maximum numbers of users
1. Form the cluster of users based on interest and the maximum allowable range
   (150 m)
2. Find the set of frequencies (users) that minimize the interference level to the
   cluster by solving equation (1)
3. Among the selected frequencies find an optimal cluster head to broadcast the
   information by solving equation (2)
```

D. Complexity Analysis

Regarding complexity for single-hop single-cell case, finding the optimum allocation is an NP-hard problem [18], hence authors propose algorithms to show the gains they achieve relative to others. In our algorithm, we try to limit the number of searches (iterations) while achieving good results. We can approximate the number of iterations in our algorithm using equation (8):

$$6\left(\sum_{i=0}^{N-1}\left(C-i\right)+\sum_{i=0}^{J-1}\left(2C-i\right)\right)+\min\left(B,R\right)+\min\left(T,\left|R-B\right|\right)+T\left(P\right)+E\left(2C\right)+V\left(C\right) \tag{8}$$

where *N* represents the average number of D2D pairs within outer partitions, *C* represents the average number of cellular users in each partition, *J* represents the average number of D2D pairs located across outer partitions, *B* represents the unused bands in the cell, *R* represents the number of D2D pairs having one user in partition 1, *T* represents the number of D2D pairs without resources after step 4, *P* represents the number of UEs close to the BS. *E* and *V* represent the number of D2D pairs remaining for the final round of allocation.

Authors in [16] and [20] performed a search on many links until specific conditions are met which results in a worst-case complexity with the number of iterations approximated by:

$$\sum_{i=1}^{6N+J+R} \sum_{j=0}^{7C-i} \left(7C - j\right) \tag{9}$$

where *6N+J+R* represents the total number of D2D pairs in the cell, while authors in [15] perform the allocation based on location only; hence the complexity level is lower, however, this happens at the expense of achieving a good allocation.

Now adding two-hop communications will increase the complexity since suitable relay users, if available, should be found during the allocation procedure. The increased complexity depends on the number of D2D pairs without a reliable link between them.

Adding multi-cell scenarios will also increase complexity, since coordination among base stations will become a must. In addition to that, determining whether two-hop communication is better than a single-hop will increase complexity since the candidate relay users might be located in different cells.

As for the clustering algorithm, the complexity will increase since it requires additional steps compared to the basic model which include optimizing for the interference level in addition to the channel gains between the cluster head and the remaining users in the cluster.

For example, in the single-hop case, having 50 D2D pairs and 50 cellular users in a cell along with a set of values for the variables in (8) and (9) will result in around 600 iterations in our algorithm, 1275 in [17] and [21], and 50 in [15]. We can see that we are reducing the number of iterations by a factor of 2 compared to [17] and [21]. Although we are performing around 10 times more iterations than [15], the gains obtained validate this increased complexity.

CHAPTER V

EXPERIMENTAL RESULTS

A. Simulation Parameters

For modeling the channel we use the cellular and D2D model as given in [15, 22], which represent a micro-urban environment. Unless otherwise stated, Table 5.1 summarizes the main parameters used in our simulations.

Table 5.1 - Simulation Parameters

Simulation Parameters
Total Bandwidth = 10 MHz (Uplink)
Bandwidth of sub-channel = 180 KHz
No = -174 dBm/Hz
Carrier Frequency = 2 GHz
Cell Radius = 500 m
$PL_{D2D} = 40 \cdot \log_{10}(d) + 30 \cdot \log_{10}(1000 \cdot f_c) + 79$ (d in m, fc in GHz) [15]
$PL_{eNB} = 36.7 \cdot \log_{10}(d) + 26 \cdot \log_{10}(f_c / 5) + 40.9$ (d in m, f_c in GHz) [22]
Probability(User=D2D)=Probability(User=Cellular)=50%
Log-normal shadowing for Cellular users with standard deviation = 8 dB [22]
Log-normal shadowing for D2D users with standard deviation = 9 dB [22]
Rayleigh fading (exponential power distribution)
Number of users deployed per partition = NMAX
Number of frequencies per cell = 50
Minimum Power Received = -100 dBm

B. Single-Hop and Two-Hop Scenarios

For the main simulation, the variable is the number of users per cell, ranging from 7 to 105 (sparse to dense conditions). D2D users are paired with any other D2D device (could be from another partition) depending on the maximum distance allowed between them (in this simulation the distance is set to 150m). The simulation was repeated 500 times for each NMAX value to guarantee reliable results. We simulate the initial case when we have only one-hop communications, in addition to the case when two-hop communications is enabled to show the gains achieved. Figure 5.1 shows the throughput achieved as a function of the number of users in the cell, applying Algorithms 1 and 2.

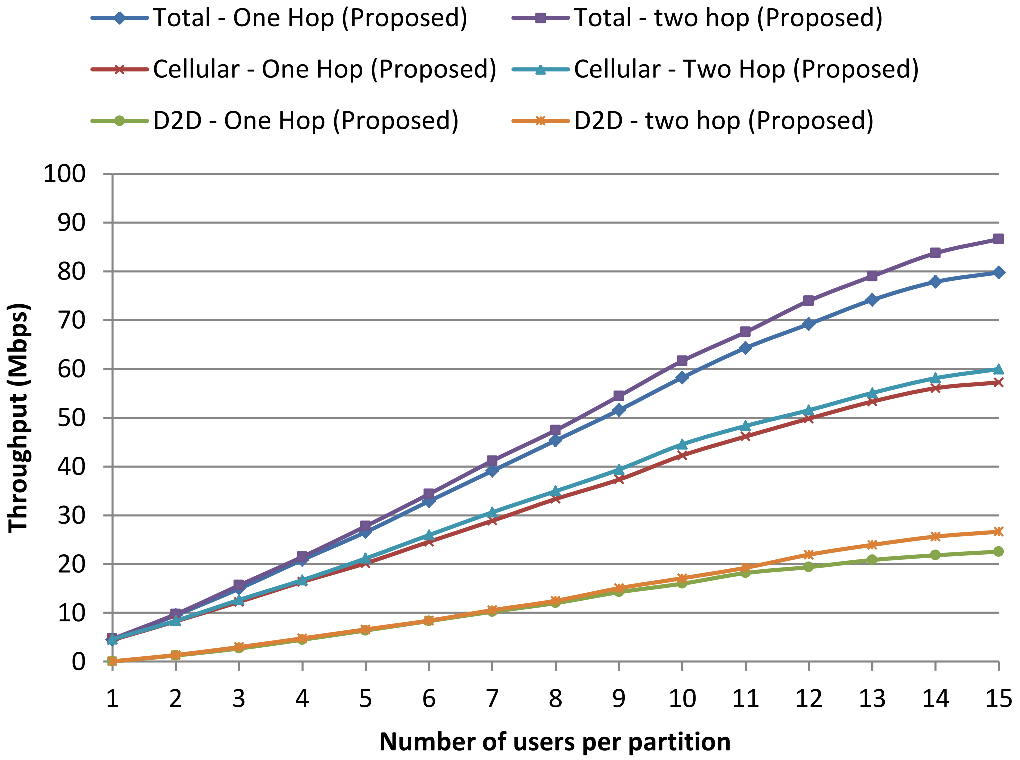

Figure 5.1 - Throughput as function of number of users

From the graph, we first notice that in our system the D2D throughput is almost half that of the cellular since users are randomly chosen to be cellular or D2D, and for each D2D device we have another one, hence the number of D2D links is around half that of the cellular users. The throughput keeps increasing with the number of users since more users will be able to use the available spectrum (whether D2D or Cellular) until we almost have a saturation at the end (NMAX=15) corresponding to 105 users in the cell, since we no longer have any bands available for the users to use while guaranteeing low degradation. Additionally, the two-hop case shows better results than the one-hop case, particularly in the high loaded cells due to the increased probability of finding suitable idle users that can act as relays, since introducing two-hop communications will mean less distance between D2D and the cellular users and hence less interference which implies more throughput. For instance when the number of users in the cell is 105, the D2D throughput is equal to 26.6 Mbps in the two hop case, while it is equal to 22.5 in the one hop case, an improvement of about 18%. In the cellular case we see an improvement of about 5% (from 57.2 Mbps to 59.9 Mbps), for an improvement of about 8.5% in the total throughput (from 79.8 Mbps to 86.6 Mbps).

For the same simulation settings, we plot the spectral efficiency as a function of the number of users (Figure 5.2). The aim of this plot is to show first that we can achieve higher spectral efficiency in the presence of D2D and second, to show the effect of having two-hop communications on both the spectral efficiency and the cellular users' link quality. Finally, we compare the results with those in [17].

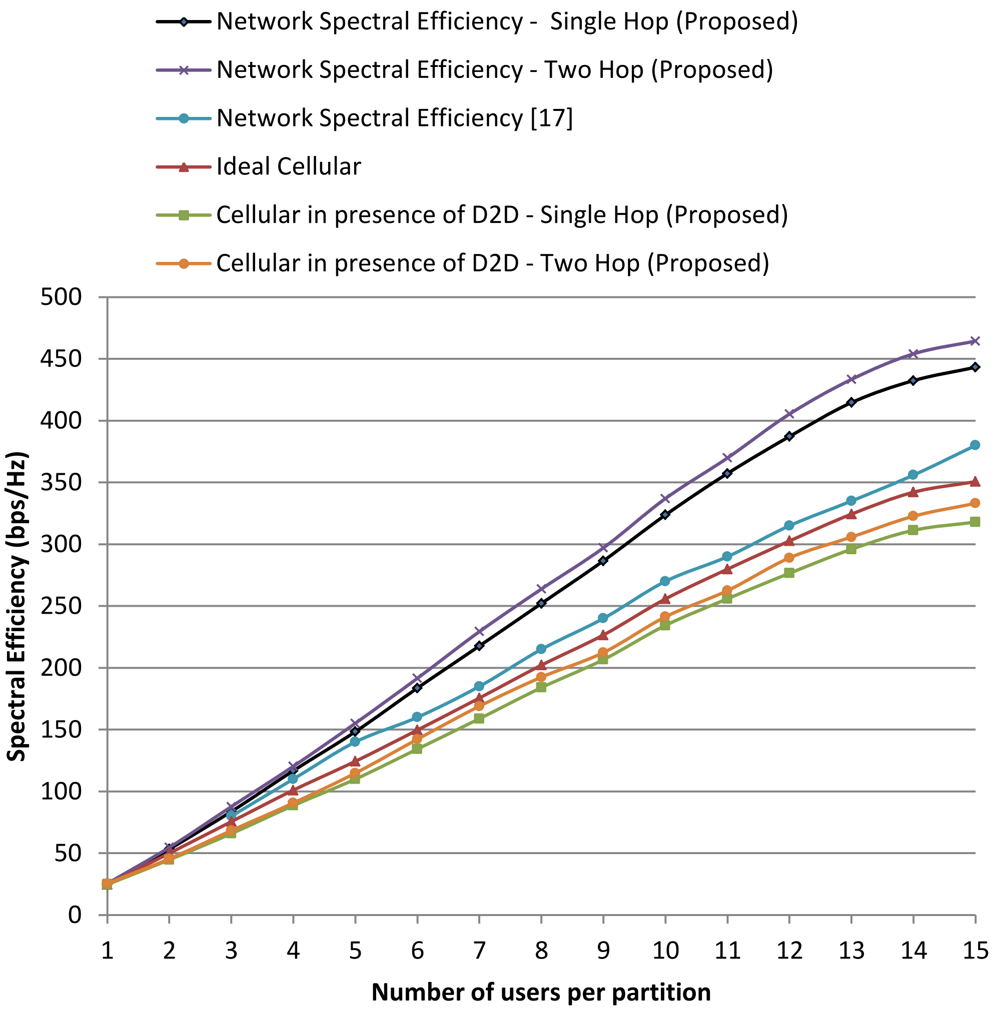

Figure 5.2 - Spectral Efficiency as a function of number of users

As we can see for the single-hop case (Figure 5.2), we have an increase in spectral efficiency with the increase in the number of users until around NMAX=15, where all the bands are exhausted (black curve). Also we note that the green curve (cellular efficiency in presence of single-hop D2D) is slightly below the red curve (ideal cellular spectral efficiency without D2D) since the addition of D2D will cause slight interference to the cellular link which we tried to minimize in our algorithm and the degradation is small, from 350 bps/Hz to 317 bps/Hz which is around 33 bps/Hz (9.5%) as shown from the red and green curves. Then, we repeated the simulation, but this time we introduced two-hop communications. The network spectral efficiency is greater than that of the single-hop case by around 25 bps/Hz, from 440 bps/Hz to 465 bps/Hz (6%), as shown in the purple and black curves, which is expected since the lower distance between the pairs will mean less interference and hence more throughput (purple curve). Additionally, we notice that the cellular link degradation is quite small, around 5%, (350 bps/Hz to 333 bps/Hz) as shown in the orange curve compared with green curve. So the degradation has decreased from 9.5% to 5%. This is expected since the lower distance limitation means that the D2D users will be farther than cellular users compared to the single-hop case.

To compare with [17], we examine each of the points separately. For instance, when NMAX=5, we have 35 users per cell, so approximately 17 D2D users and hence around 8 D2D pairs. At that point, our system shows a spectral efficiency of around 150 bps/Hz while that in [17] is around 130 bps/Hz, an improvement of 15%. When NMAX=10, we have 70 users per cell, so approximately 35 D2D users and around 17 D2D pairs. At that point, our system shows a spectral efficiency of around 320 bps/Hz while that in [17] is around 250 bps/Hz, an improvement of 28%. Therefore, we see an improvement in all cases.

Next, and for a fair comparison with the given reference, we set the simulation parameters as that of [15] particularly the number of available frequencies is reduced. We vary NMAX between 1 and 9, and run the simulation 500 times for each value of NMAX. The results are shown in Figure 5.3.

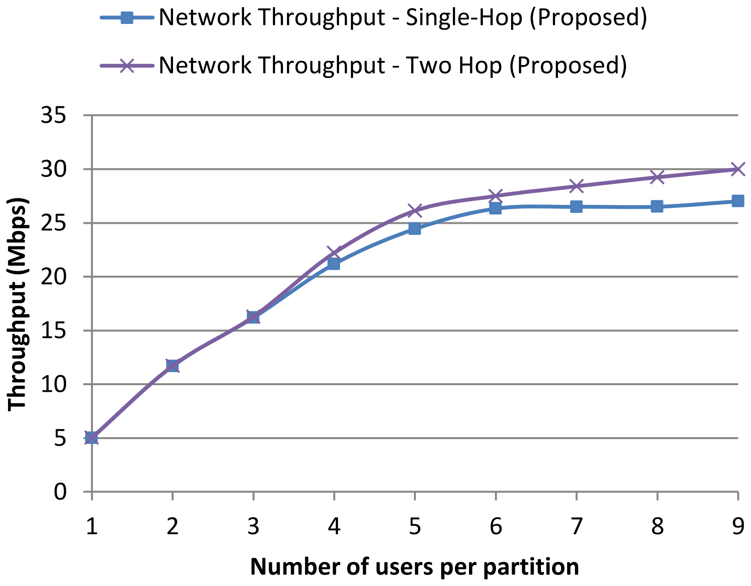

Figure 5.3 - Throughput as a function of number of users

The results in [15] show a maximum achievable rate of 18 Mbps, whereas in our system we obtain a throughput of around 26 Mbps (single hop) and 30 Mbps (two hop), an improvement of 44% to 66%. In [15] the capacities are obtained while having a high number of D2D senders (93) and 70 cellular users (so the comparison happens at saturation point). Note that we have saturation at relatively low number of users due to the restriction on the number of available bands.

For the following simulation we set the number of users to 98 (NMAX = 14). The simulation is run 500 times to guarantee reliable statistics. We plot the SINR CDF of the D2D links from our simulation (both single and two-hop scenarios) and compare with [15]. This is to study the probability of having D2D link rates above a specific SINR threshold value. The results are presented in Figure 5.4.

From the graph, we notice that our system presents higher SINR values with a very large probability. At 0 dB, our system shows a CDF of around 0.018 (single-hop) and 0.01 (two-hop), while that in [15] is around 0.01. At 10 dB SINR, our system shows a CDF of only 0.058 (single-hop) and 0.034 (two-hop) while that in [15] shows 0.6 which is significantly worse. The two-hop case outperforms the single-hop case due to the lower levels of interference.

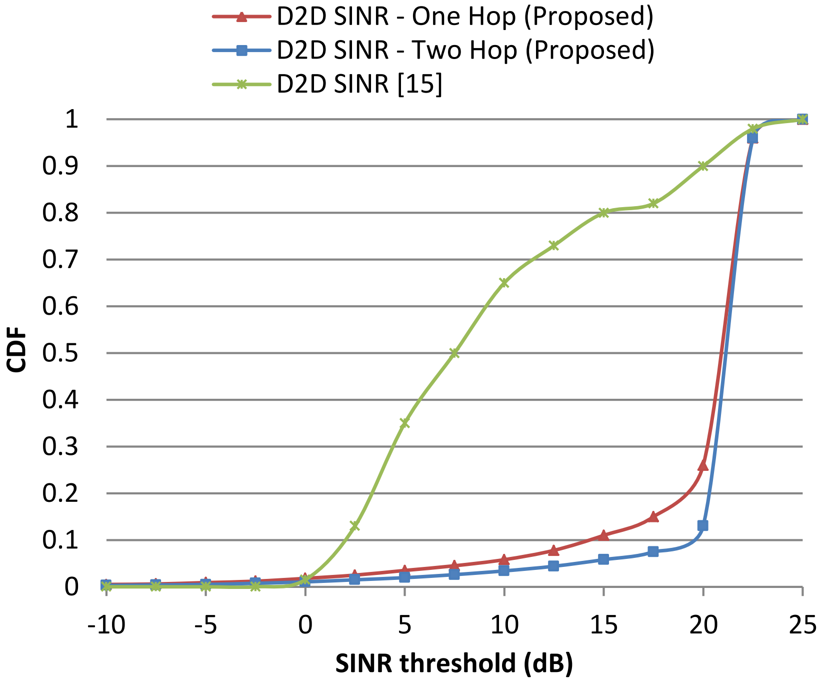

Figure 5.4 - D2D SINR

We also plot the SINR CDF of the cellular links from our simulation and compare with [15]. The results are shown in Figure 10. From the graph, we notice that our system presents higher SINR values with a very large probability. At 0 dB our system shows a CDF of around 0.028 (single-hop) and 0.01 (two-hop) while that in [15] is 0.2. At 10 dB SINR, our system shows a CDF of only 0.079 (single-hop) and 0.033 (two-hop) while that in [6] shows 0.86 which is significantly worse.

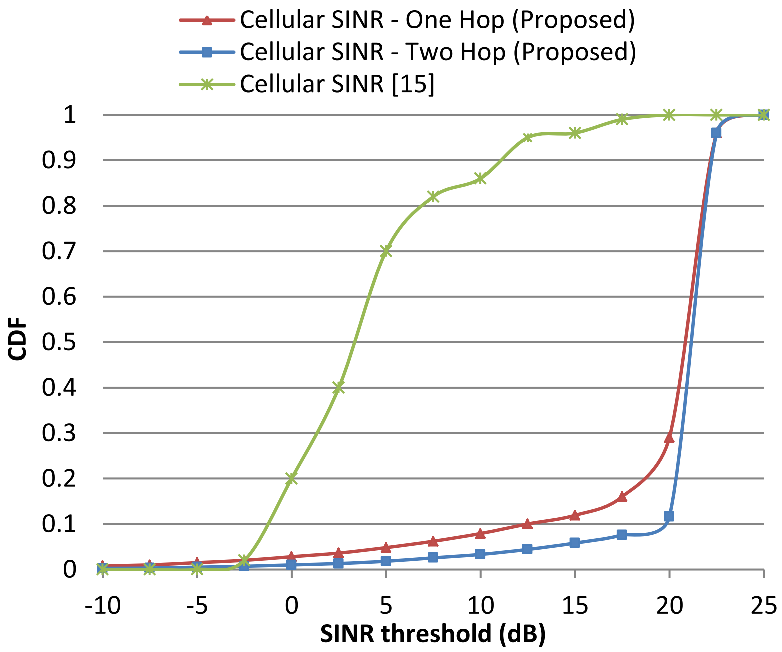

Figure 5.5 - Cellular SINR

For the same simulation settings of [17], Figure 5.6 shows the outage probability of the D2D links as a function of the minimum required SINR. The graph shows that we have an outage of 1.8% at 0 dB and 5.6% at an SINR value of 10 dB for the single-hop case, while in the two-hop case we have and outage of 1.1% and 3.3% at 0 dB and 10 dB, respectively. Comparing with the scheme in [17], we notice the best proposed scheme has an outage probability of about 2% at an SINR of 0 dB and around an outage of 9% at an SINR of 10 dB, an improvement of 10% to 33%, respectively for single-hop and 45% to 62% for the two-hop case. Simulations in [19] showed an outage of 9.04% at 5 dB threshold and 18.13% at 10 dB SINR threshold which is significantly worse than our results.

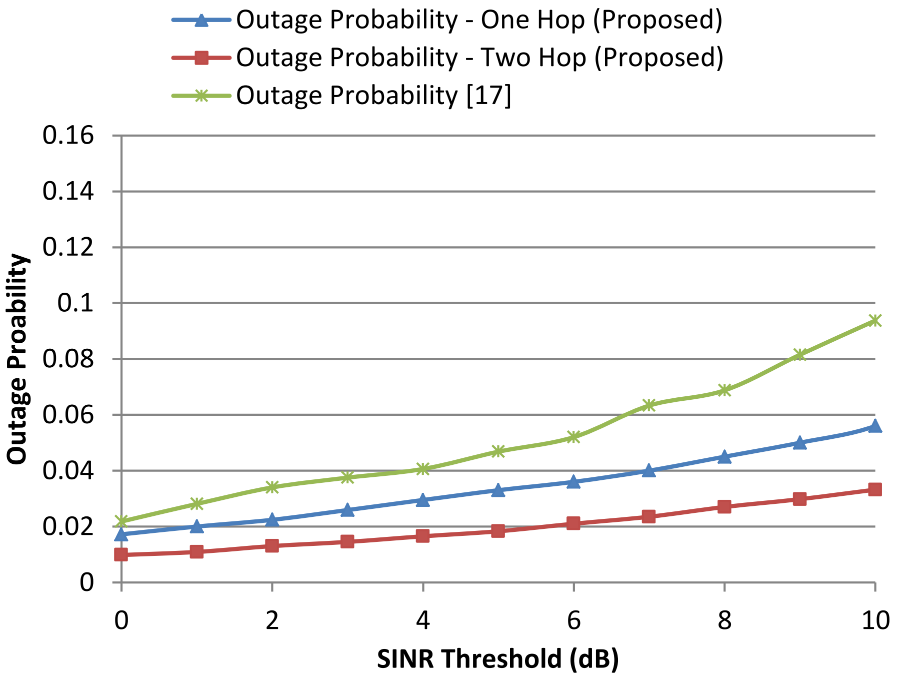

Figure 5.6 - D2D Outage Probability as a function of SINR

Next, we plot the number of D2D pairs as a function of the minimum required SINR. We run the simulation 500 times for reliable statistics. We provide results for both single hop and two hop scenarios to show the improvements achieved. The results are presented in Figure 5.7.

From the graph, we notice that the two-hop outperforms the single hop case which is expected as explained above. The average number of D2D pairs having a minimum SINR of 0 dB is 18.3 for the single hop and 18.7 in the two-hop case, an improvement of 2.3%. While the average number of D2D pairs having a minimum SINR of 20 dB is 14.5 for the single hop and 16.9 in the two-hop case, an improvement of 16%.

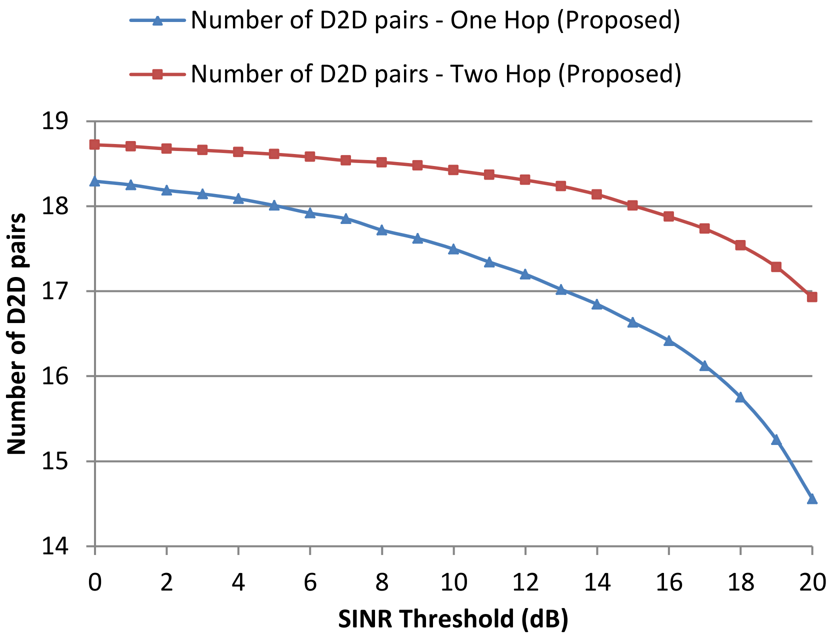

Figure 5.7 - Number of D2D pairs as a function of SINR

Figure 5.8 illustrates the CDF of the system throughput. We notice that the lowest values in our system occur at around 62.5 Mbps and the highest around 85 Mbps (CDF=1). While the model proposed in [16] starts increasing at around 42.5 Mbps and saturates at the same point as our model. This means that our system achieves higher throughputs with higher probabilities than the one proposed in [16]. For example at a CDF of 0.5, out system achieves a throughput of 77 Mbps for the single hop case, and 83 Mbps for the two hop case, while that in [16] achieves a throughput of 65 Mbps. Hence we have an improvement of 18% to 27%. As explained earlier, the two hop case always outperforms the single hop case.

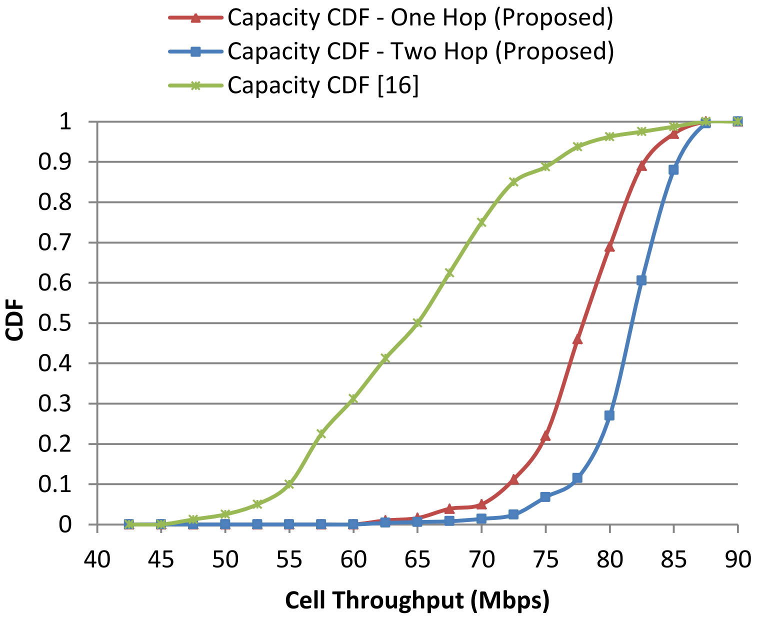

Figure 5.8 - Capacity CDF

In the following simulation, we change the simulation settings so that D2D users are dropped within a specific distance range to compare with [18]. We use single-hop only due to the small distances and we vary the distance range between 30 and 65 meters. The results are shown in Figure 5.9.

As noticed, we have a decrease in spectral efficiency with the increase in distance due to the larger amount of interference generated by the cellular UEs. Compared to [18] our results show a huge improvement. For instance at a distance limitation of 30m, our model achieves a spectral efficiency of 375 bps/Hz while that in [18] achieves 330 bps/Hz, an improvement of 13.6%. At a distance limitation of 65m, our model achieves a spectral efficiency of 355 bps/Hz while that in [18] achieves 275 bps/Hz, an improvement of 17%.

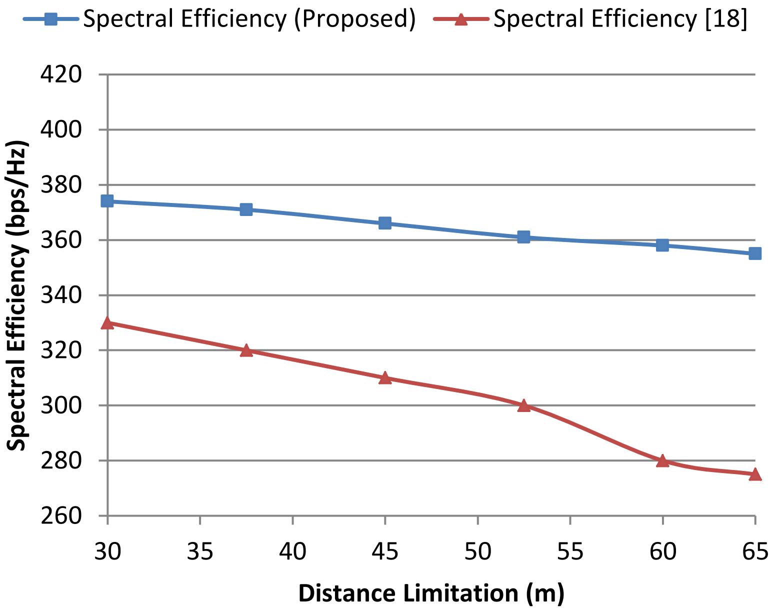

Figure 5.9 - Spectral Efficiency as a function of D2D distance

Finally, we perform a simulation to study how the throughput varies as a function of the number of available bands. We increase the traffic in the cell and set the number of users to 350 (NMAX=50) to show the effectiveness of the increased number of bands. The simulation is run 100 times for each NMAX to guarantee reliable results. We compare our results to the results obtained in [20] as shown in Figure 5.10. As noticed, our system shows substantial gains relative to [20]. When the number of frequencies is 60, our system shows a throughput of 99 Mbps (single hop), 109 (two hop) while that in [20] shows 70 Mbps, hence an improvement of around 42% and 55% respectively. When the number is 140, the gain increases to 64% (single-hop) and 75% (two-hop).

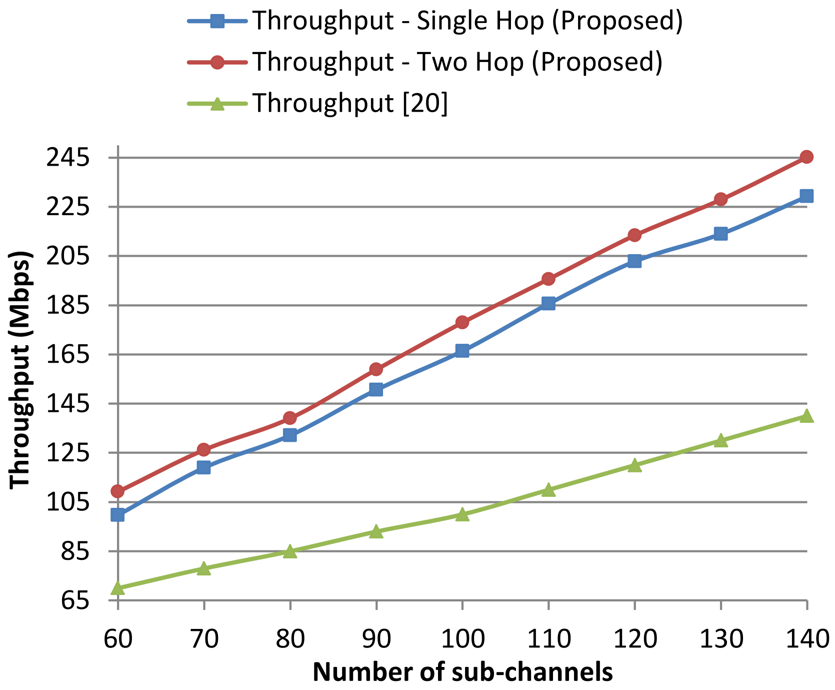

Figure 5.10 - Throughput as a function of number of bands

C. Clustering Scenarios

As stated in Chapter IV, we will simulate three case scenarios that can be summarized as follows:

1- Choosing a random cluster head and a random resource from the opposite partitions of the cell. (Basic Model)

2- Choosing a random cluster head and an optimized resource according to (6) from the opposite partitions. (Random CH & Optimal Resource Model)

3- Choosing the cluster head to be optimal according to (7) along with a resource with low average interference level. (Optimal CH and Resource Model)

In the first simulation, we vary the number of users in the cell from 7 to 105 and forming D2D clusters of variable sizes from a minimum of 2 (normal D2D case) to a maximum of 15 users. We plot the throughput and the spectral efficiency as a function of the number of users.

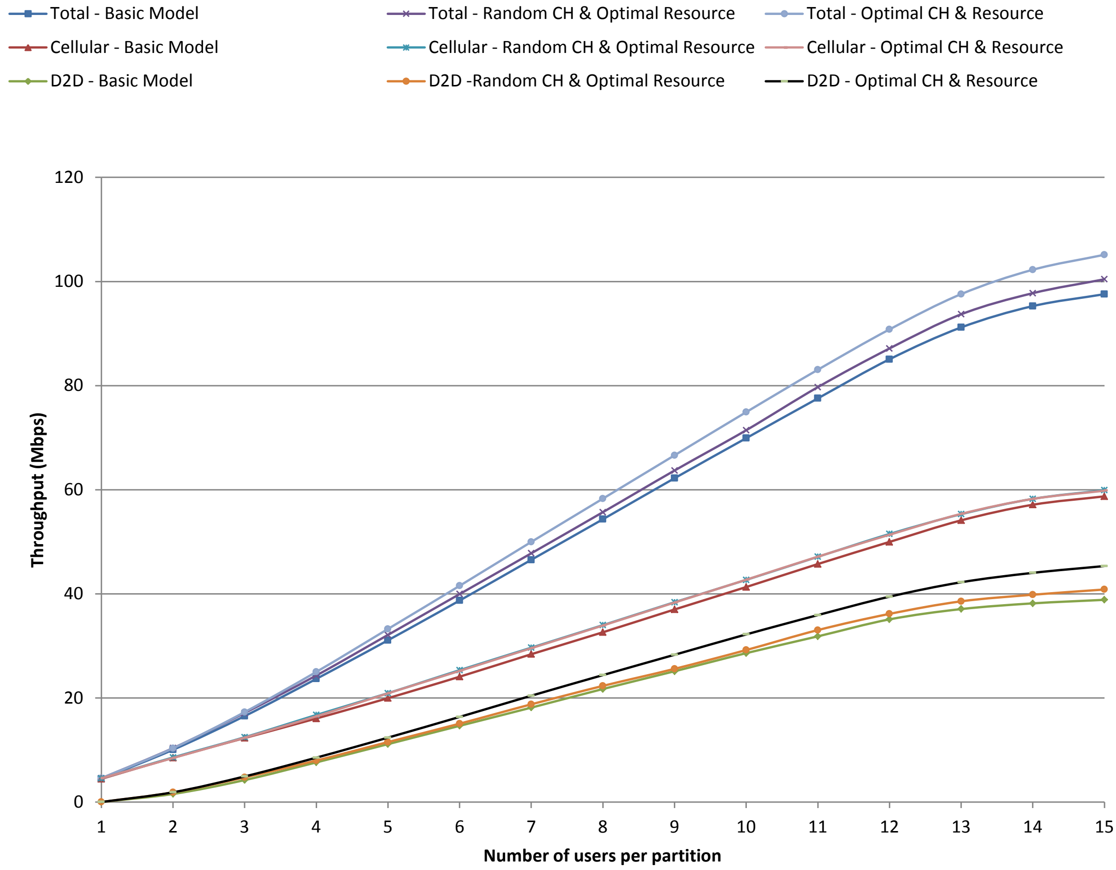

Figure 5.11 - Cell Throughput in Clustering Scenarios

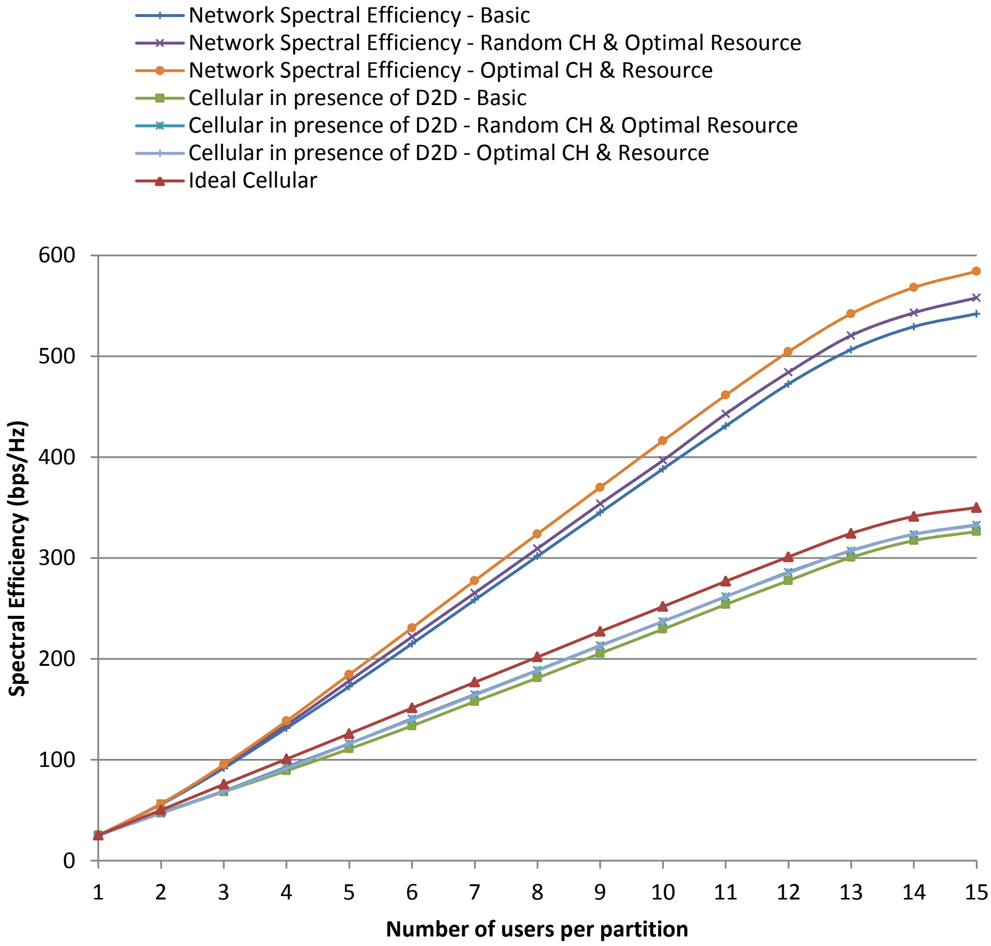

Figure 5.12 - Spectral Efficiency in Clustering Scenarios

As noticed from the curves, the differences become larger with the increase in the number of users. The throughput and spectral efficiency achieved in case scenario 1 (Basic Model) is less than that of the other 2 cases since the cluster head and resource are not optimum and hence cluster heads might be far away from some of the users (no LOS component) which leads to higher interference levels and consequently less throughput. Cases 3 (Optimal Cluster Head & Resource) outperforms case 2 (Random Cluster Head and Optimal Resource), with the difference showing in high load scenarios since the number of users per cluster will increase and hence optimizing the cluster head will become very important to manage the interference. Also finding a better cluster head will lead to less degradation to the quality of the existing cellular links (as shown by the blue and green curves in figure 5.12). In case 3, choosing the optimal cluster head depends on the channel quality between the head and the D2D receivers, so optimizing according to this criteria will show good gains. It is important to note that achieving these improvements will require a higher level if complexity.

In the second simulation, we fix the number of users to 105 (high load) in the cell and study the outage probability and capacity CDF in the 3 case scenarios. The simulation was run 20000 times to obtain reliable graphs. The results are presented in figures 5.13 and 5.14.

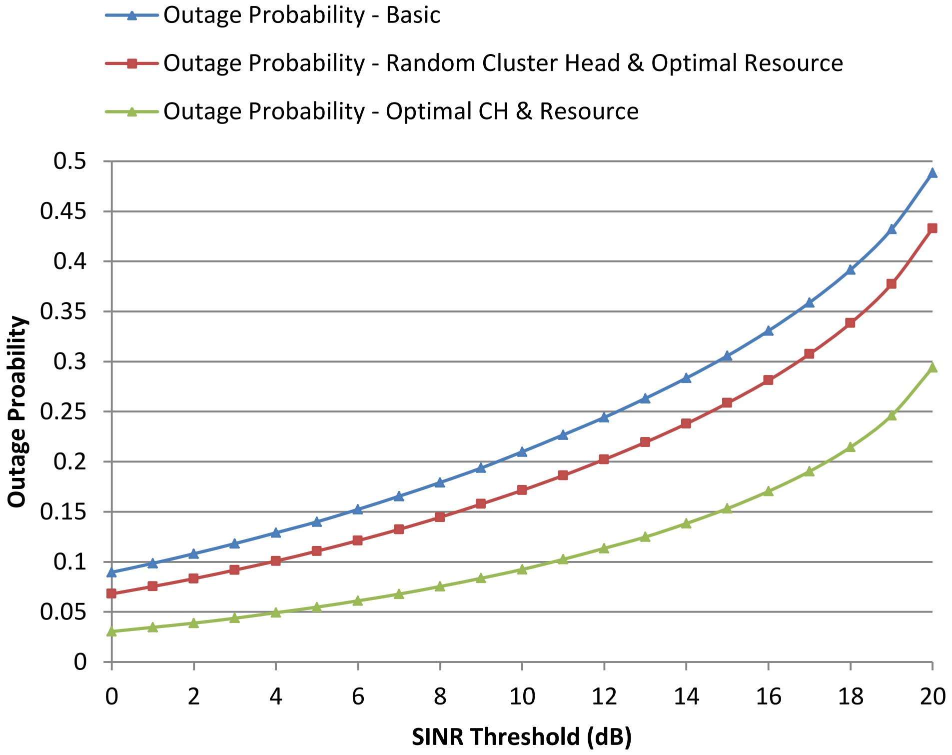

Figure 5.13 - Cluster Outage Probability

The results in figure 5.13 show the huge gains achieved by finding the optimal cluster head and resource. In the normal case the outage varies from almost 9% at 0 dB to 21% at 10 dB and finally 48% at 20 dB. In case 2, the outage varies from 7% at 0 dB 17% at 10 dB and finally to 43% at 20 dB. While in case 3, the outage varies from 3% to 9% to 29% at 0, 10 and 20 dB respectively. The results verify the need to optimize for both the cluster head and the resource.

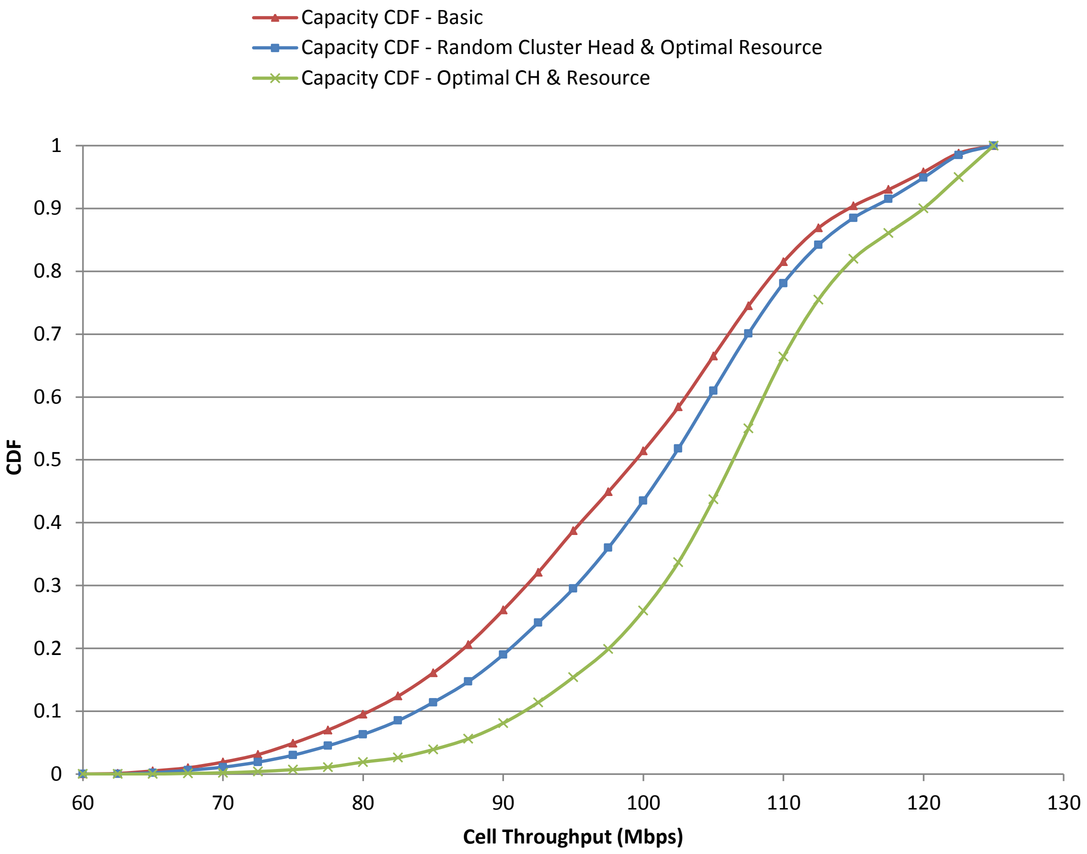

Figure 5.14 - Clustering Capacity CDF

The graphs show the improvement achieved by introducing the better solutions. The CDF shows that in case 3 we achieve higher throughputs with higher probabilities than those of cases 1 and 2. For instance, at a CDF of 0.5, the basic model shows a throughput of around 100 Mbps, while that of the random cluster head with optimal resource shows 102 Mbps, and finally the optimal cluster head and resource shows a throughput of 107 Mbps.

We have thus showed the various gains achieved by two different optimization schemes. Optimizing for cluster head, in particular, shows very good gains on the D2D link qualities.

CHAPTER VI

CONCLUSION AND FUTURE WORK

In this thesis, a resource allocation algorithm for single and two hop D2D communications has been proposed in multiple cell scenarios that exploits the locations and channel qualities of users has been proposed. A clustering algorithm was also proposed along with the optimal selection of various parameters. The algorithms can share frequencies between cellular and D2D users depending on network and channel conditions. The effectiveness of the algorithm has been analyzed through simulations. It has been shown that the proposed algorithm is capable of achieving higher throughput, spectral efficiency, SINR, and a lower outage probability than existing schemes. In particular, the two-hop algorithm achieves better results at the expense of requiring a higher complexity.

Future work includes a study on the incentives for users to act either as relays or cluster heads, a study about the battery life of devices and modifications to the algorithm accordingly, a study on mode selection is also an important issue, e.g. deciding whether a user should be in cellular, D2D, or clustering mode, and finally, a study on resource allocation when there is partial or no network coverage.

BIBLIOGRAPHY

[1] "Ericsson Mobility Report: Global 4G/LTE divide will be wide in 2019," June 3,2014. [Online]. Available http://www.ericsson.com/news/1790097. [Accessed: Apr. 15, 2015].

[2] Small Cell Forum. (2012). Small Cells whats the big idea? Femtocells are expanding beyond the home. Feb 2012.

[3] J. Marinho and E. Monteiro, "Cognitive Radio: Survey on Communications Protocols, Spectrum Issues, and Future Research Directions," *Wireless Networks*, vol. 18, no. 2, 2012, 147-164.

[4] Z.-J. Yang, J.-C. Huang, C.-T. Chou, H.-Y. Hsieh, C.-W. Hsu, P.-C. Yeh, and C.-C. A. Hsu, "Peer Discovery for Device-to-Device (D2D) Communication in LTE-A Networks," *Proceedings of IEEE Globecom*, 2013.

[5] 3GPP, "3GPP TSG SA: Feasibility Study for Proximity Services (ProSe) (Release 12)," 3GPP, Tech. Rep. TR 22.803, Aug. 2012.

[6] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Miklos and Z. Turanyi, "Design aspects of network assisted device-to-device communications," *IEEE Commun. Mag.*, vol. 50, no.3, pp. 170–177, Mar.2012.

[7] K. Doppler, M. Rinne, C.Wijting, C. B. Ribeiro, and K. Hugl, "Device-to device communication as an underlay to LTE-advanced networks," *IEEE Commun. Mag.*, vol. 47, no. 12, pp. 42–49, Dec. 2009.

[8] K. Doppler and M. Xiao, Eds., "Innovative Concepts in Peer-to-Peer and Network Coding," WINNER+/CELTIC Deliverable CELTIC/CP5-026 D1.3, 2008.

[9] K. W. Choi and H. Zhu, "Device-to-device discovery for proximity-based service in LTE-advanced system," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 1, pp. 55-66, Jan. 2015.

[10] M. Corson, R. Laroia, J. Li, V. Park, T. Richardson, and G. Tsirtsis, "Toward Proximity-Aware Internetworking," *Wireless Communications, IEEE*, vol. 17, no. 6, pp. 26–33, December 2010.

[11] J. Li, X. Wu, and R. Laroia, OFDMA Mobile Broadband Communications: A Systems Approach. Cambridge, U.K.: Cambridge Univ. Press, 2013.

[12] P. Mach, Z. Becvar, and T. Vanek, “In-Band Device-to-Device Communication in OFDMA Cellular Networks: A Survey and Challenges,” *IEEE Communications Surveys & Tutorials,* June 2015.

[13] S. Mumtaz and J. Rodriguez, Eds., Smart Device to Smart Device Communication. Zürich, Switzerland: Springer-Verlag, 2014.

[14] R. Ghaffar and R. Knopp, "Fractional frequency reuse and interference suppression for ofdma networks," in *Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 2010 Proceedings of the 8th International Symposium on*, pp. 273-277, 2010.

[15] H. S. Chae, J. Gu, B.-G. Choi, and M. Chung, “Radio resource allocation scheme for device-to-device communication in cellular networks using fractional frequency reuse,” in *Proc. IEEE APCC*, Kuala Lumpur, Malaysia, pp. 58–62, Oct. 2011.

[16] S. Mumtaz, K. M. S. Huq, A. Radwan, J. Rodriguez, and R. L. Aguiar, “Energy efficient interference-aware resource allocation in LTE-D2D communication,” in *Proc. IEEE Int. Conf. on Commun. (ICC),* Sydney, Australia, pp. 282-287, June 2014.

[17] D. J. Son, H. Y. Chang, and D. I. Kim, "Resource allocation based On clustering for D2D communications in underlaying cellular networks", *Int. Conf. on Information and Communication Technology Convergence,* pp. 232-237, Oct. 2014.

[18] H. Meshgi, D. Zhao, and R. Zheng, “Joint channel and power allocation in underlay multicast device-to-device communications,” *IEEE Int. Conference on Communications,* pp. 2937-2942, Jun. 2015.

[19] C. Lee, S. M. Oh, and A. S. Park, "Interference avoidance resource allocation for D2D communication based on graph-coloring," *International Conference on Information and Communication Technology Convergence,* pp. 895-896, Oct. 2014.

[20] D. H. Lee, K. W. Choi, W. S. Jeon, and D. G. Jeong, “Resource allocation scheme for device-to-device communication for maximizing spatial reuse,” in *Proc. IEEE WCNC,* pp. 1–5, Apr. 2013.

[21] M. Zulhasnine, C. Huang, and A. Srinivasan, “Efficient resource allocation for device-to-device communication underlaying LTE network,” in *Proc. IEEE6th Int. Conf. Wireless Mobile Comput., Netw. Commun.,* pp. 368–375, Oct. 2010.

[22] ITU-R report M.2135, “Guidelines for evaluation of radio interface technologies for IMT-Advanced,” 2008.

[23] K. Doppler, M. Rinne, P. Janis, C. B. Ribeiro, and K. Hugl, “Device-to-Device Communications; Functional Prospects for LTE-Advanced Networks,” in *Proc. IEEE International Conference on Communications Workshops,* pp. 1-6, Jun. 2009.

[24] K. Doppler, M. Rinne, C.Wijting, C. B. Ribeiro, and K. Hugl, “Device-to-device communication as an underlay to LTE-Advanced networks,” *IEEE Commun. Mag.,* vol. 47, no. 12, pp. 42–49, Dec. 2009.

[25] C. H. Yu, K. Doppler, C. Ribeiro, and O. Tirkkonen, “Resource sharing optimization for device-to-device communication underlaying cellular networks,” *IEEE Trans. Wireless Commun*., vol. 10, no. 8, pp. 2752–2763, Aug. 2011.

[26] K. Doppler, C. H. Yu, C. B. Ribeiro, and P. Janis, “Mode selection for device-to-device communication underlaying an LTE-Advanced network,” in *Proc. IEEE WCNC,* pp. 1–6, Apr. 2010.

[27] T. Chen, G. Charbit, and S. Hakola, “Time Hopping for Device-To-Device Communication in LTE Cellular System,” *in Proc. IEEE Wireless Communications and Networking Conf. (WCNC),* pp.18-21, April 2010.

[28] X. Zhu, S. Wen, G. Cao, X. Zhang, and D. Yang, “QoS-based resource allocation scheme for Device-to-Device (D2D) radio underlaying cellular networks,” *2012 19th International Conference on Telecommunications (ICT),* pp 1-6, April 2012.

[29] B. Cho, K. Koufos, and R. Jantti, “Spectrum allocation and mode selection for overlay D2D using carrier sensing threshold” *International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM),* pp. 26-31, June 2014.

[30] P. Bao, G. Yu and R. Yin, “Novel frequency reusing scheme for interference mitigation in D2D uplink underlaying networks,” *2013 9th International Wireless Communications and Mobile Computing Conference (IWCMC),* 491-496, July 2013.

[31] P. Janis, C.-H. Yu, K. Doppler, C. Ribeiro, C. Wijting, K. Hugl, O. Tirkkonen, and V. Koivunen, “Device-to-Device communication underlaying cellular communication systems,” *International Journal on Communications, Networking and System Science*, vol. 2, no. 3, June 2009.