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The Coexistence of D2D Communication under Heterogeneous Cellular Networks (HetNets)

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The Coexistence of D2D Communication under Heterogeneous Cellular Networks (HetNets)

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*To the soul of my mother (May Allah grant her Jannah Al Firdous),
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Abstract

Device-to-Device (D2D) communication is a promising technique for supporting the stringent requirements of the fifth-generation cellular network (5G). This new technique has garnered significant attention in cellular network standards for proximity communication as a means to improve cellular spectrum utilization, to decrease user equipment energy consumption, and to reduce end-to-end delay. This dissertation reports an investigation of D2D communication coexistence under 5G heterogeneous cellular network (HetNets) in terms of spectrum allocation and energy efficiency. The work reported herein describes a low-complexity D2D resource allocation algorithm for downlink (DL) resource reuse that can be leveraged to improve network throughput. Notably, cross-tier interference was considered when establishing D2D communication (e.g., macro base station to D2D links; small base station to D2D links; and D2D communication to cellular links served by the macro and small base stations). An allocation algorithm was introduced to reduce interference from D2D to cellular when a single D2D link is sharing cellular resources. Performance of the proposed algorithm was evaluated and compared to various resource allocations. Simulation results demonstrated that the proposed algorithm improves overall system throughput. This allocation algorithm achieved a near optimal solution when compared with a brute force approach.

This dissertation also presents a novel framework for optimizing the energy efficiency of D2D communication coexistence with HetNets in DL transmission. This optimization problem was mathematically formulated in terms of mode selection, power control, and resources allocation (i.e., NP-hard problem). The optimization fraction problem was simplified based on network load and was solved using various optimization methods. An innovative dynamic mode selection based on Fuzzy

clustering was also introduced. Proposed scheme performance was evaluated and compared to the standard algorithm. Simulation validated the advantage of the proposed framework in terms of performance gain in both energy efficiency and the number of successfully connected D2D users. Moreover, energy efficiency of HetNets with D2D compatibility was improved.

Finally, this dissertation details a stochastic analytical model for an LTE scheduler with D2D communication. By assuming exponential distributions for users scheduling time, a throughput estimation model was developed using two-dimensional Continuous Time Markov chains (2D-CTMC) of birth-death type. The proposed model will predict the expected number of D2D operated in dedicated and reuse mode, as well as the systems long-term throughput.

List of Key Symbols and Acronyms

$3GPP$	Third generation partnership
$4G$	Fourth-generation cellular network
$5G$	Fifth-generation cellular network
AC	Admission control
BS	Base station
CSI	Channel state information
CN	Conventional network
CM	Cellular mode
$CUEs$	Cellular users
DM	Dedicated mode
$2D-CTMC$	Two-dimensional continuous-time Markov chains process
$D2D$	Device- to-device
DL	Downlink
EE	Energy efficiency
$eICIC$	Enhanced inter-cell interference coordination
EPC	Evolved packet core
eNB	Evolved Node B
GA	Genetic algorithm
GEE	Generalized energy efficiency
$HetNets$	Heterogeneous cellular networks
ID	User identity
ITS	Intelligent transportation systems
ICT	Information and communication technology
ISM	Industrial, scientific, and medical spectrum
LTE	Long term evolution
$LTE-A$	Long term evaluation advance
MME	Mobility management entity
$MIMO$	Multi-input multi-output
$OFDMA$	Orthogonal frequency division multiple access
PC	Power control
PL	Pathloss
$ProSe$	Proximity service
QoS	Quality of service
RB	Resource block
RA	Resource allocation
RS	Reuse mode
$RSRP$	Reference signal received power
$SINR$	Signal to interference-plus-noise ratio

SNR	Signal to noise ratio
$SORP$	Sum of ratios
SE	Spectrum efficiency
SPS	Semi persistent scheduling
SMS	Sequential max search
TDS	Time domain schedulers
TTI	Transmission time interval
UE	User Equipment
UL	Uplink
$V2V$	Vehicle-to-vehicle
$VANET$	Vehicular ad hoc networks
VLC	Visible light communication

CHAPTER 1

Introduction

1.1 Motivation

Widespread use of smart devices and mobile applications continues to significantly increase the amount of mobile data traffic at a colossal rate. According to Ciscos latest report [1], total generated mobile data traffic is predicted to be 77 exabytes per month by 2022 (See Figure 1.1), nearly a sevenfold increase over 2017. By 2020, the expected number of connected devices will reach 50 billion. Over the next 10 years, data traffic will increase by 1000x [4,5]. Clearly, the current network simply cannot meet the incoming user requirements. Although it offers good quality-of service (QoS) in isolated areas, it cannot meet capacity demands for users in close proximity (e.g., stadiums, shopping malls, and the like [6]. Moreover, the increasing demand on our current mobile communications industry comes at the cost of a sizable carbon footprint. For example, in 2007 the information and communication technology (ICT) sector represented about 2% of global CO_2, and the overall ICT footprint will nearly double between 2007 and 2020 [7].

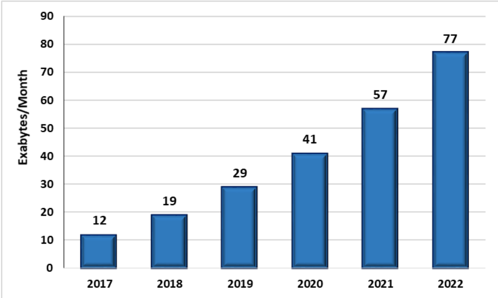


Fig. 1.1: Global mobile data traffic predication [1]

In addition to such issues that plague the current network, the incredible growth in usage causes insufficient spectrum resources and boost in power consumption. The impending fifth-generation cellular network (5G) has been envisioned to accommodate the high data volume of subscribers and to address the aforementioned challenges. Indeed, 5G networks are intended to provide 1000x larger mobile data volume per area, to offer 10x to 100x higher user data rate, and to serve 10x to 100x more connected devices than current cellular systems [6, 8]. With regard to power consumption, academics and industry professionals agree that 5G must fulfill these aggressive requirements at a power consumption that is similar-to or lower-than those available in the current network (e.g., 4G) [8]. $5G'^{s}$ heterogeneous architecture is composed of small cells that overlay macro cells. The technology is supported by new and enhanced technologies (e.g., massive MIMO, mm Waves, full duplex, Visible light communication (VLC), and device-to-device communication [D2D]). Moreover, one aim of 5G is shifting from an architecture-based (e.g. involving base stations) to a device-centric approach (e.g. ability to establish and exchange information between nodes) [9]. D2D technology supports the device-centric approach, which can be defined as direct communication between users in close proximity without traversing the base station (BS). D2D communication has been proposed as a new technology of Long-Term Evolution-Advance (LTE-A) release 12 [10]. It is one of the most promising components for targeting extreme cellular network requirements.

1.2 D2D Communication Technology

In cellular networks , the connection between user equipment (UE) necessitates the use of BSs. For example, UE sends its data to BS using uplink (UL) resources, and then the BS redirects the data to a corresponding receiver using downlink (DL) resources. D2D communication refers to a radio technology that allows devices to directly exchange data without use of a BS [11].

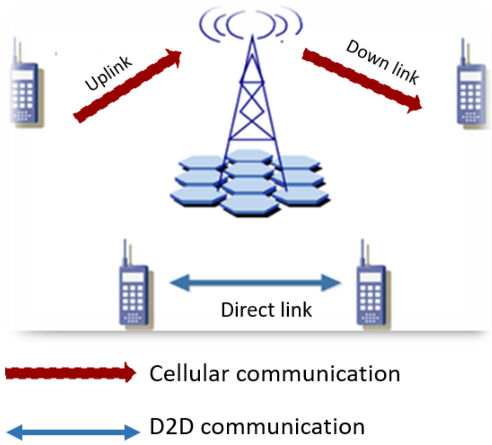


Fig. 1.2: Schematic representation of cellular and D2D communication

The Third Generation Partnership (3GPP) group has investigated Proximity Service (ProSe) communication under the control of cellular networks. 3GPP group divided ProSe communication into two-part proximity discovery and direct communication, D2D communication [12, 13]. With regard to modification of Long-

Term Evolution (LTE) architecture, required changes in LTE entities support ProSe communication and have been presented for both UEs and core network in [14]. In particular, the Evolved Packet Core (EPC) has a new function, namely ProSe Function, which was proposed and added to enable ProSe communication. The ProSe Function authorizes and configures UE for discovery and direct communication, as well as generates the identity (ID) for UEs from Home Subscriber Server (HSS) after authorization. The ProSe application server is added at the network side and connects to the PreSe application executed in the UE side [14]. Details of the conceptual framework for integrating D2D communication under LTE network is discussed in [15, 16]. In this work, authors presented the concepts of peer discovery, mode selection, user scheduling, and resources allocation for D2D communication.

1.2.1 *Configuration of D2D Communication*

D2D communication can be configured in three ways [17]

1. **Network controlled D2D communication**. In this scenario, the BS fully controls D2D communication (e.g. control signal, resources management, and discovering/establishing the connection) and cellular users. The centralized control results in efficient interference management and resource allocation. However, this configuration also causes high signaling overhead, wherein the number of D2D becomes large, and spectral efficiency (SE) is reduced [17].

2. **Autonomous D2D communication**. This scenario is similar to cognitive radio in which BS has no control over D2D users. Instead, D2D users

leverage empty holes in the spectrum and sense a surrounding environment for obtaining channel state information (CSI), interference, and cellular user information. Although this method can successfully avoid signaling overhead and time delay, communication security can be a potential issue. This configuration also causes unstable communication due to lack of control [17].

3. **Network assisted D2D communication**. In this scenario, the BS supports D2D communication by controlling the signal and discovering/establishing the connection. Then, D2D users communicate in a self-organizing way, which reduces signal overhead. This configuration has merits described in the first two approaches [17].

1.2.2 *Classification of D2D Communication*

D2D communication can be classified based on the spectrum on which direct communication occurs, namely **Inband** D2D communication and **Outband** D2D communication [2, 17, 18]. A schematic view of how D2D users can access the spectrum is illustrated in Fig. 1.3.

1. **Inband Communication**.

   D2D communication uses cellular network licensed spectrum. Based on spectrum sharing methods, inband D2D communication is further divided into overlay and underlay. In overlay inband, D2D and cellular users are assigned orthogonal resources (e.g., time/frequency). Hence, cross-tier interference between cellular and D2D users is eliminated. However, this method is insufficient in terms of spectrum efficiency (SE). In underlay inband, D2D and cellular users share time/frequency resources. Therefore, co-channel in-

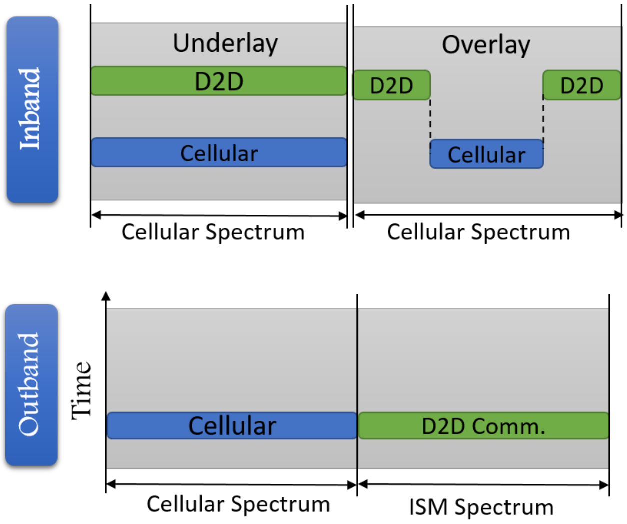


Fig. 1.3: Schematic representation of overlay, underlay inband, and outband D2D [2].

terference requires interference management techniques. Also, this method increases SE [2, 13, 18].

2. **Outband Communication.**

   D2D communication exploits the unlicensed industrial, scientific, and medical (ISM) band spectrum. Although outband communication eliminates interference between cellular and D2D users, it requires an extra radio interface. Hence, this type of communication adapts to other wireless technologies transmitting in the unlicensed band (e.g., Wi-Fi, ZigBee, or Bluetooth). Outband communication is further divided into controlled and autonomous communication [2, 13, 18].

1.2.3 *Advantage of D2D Communication*

D2D communication provides several advantages to the cellular network and promises different types of gain. These can be enumerated, as follows. First, user equipment is communicated via direct link experiences with low power consumption, high data rate, and low latency (i.e., proximity gain). Second, network SE can be highly enhanced by simultaneous use of resources by cellular, as well as, D2D users (i.e., increasing the number of transmitting bits in a given bandwidth [reuse gain]). Third, network energy efficiency (EE) can be improved by squeezing more data (i.e., spectrum reuse) with less energy per bit. Fourth, D2D can extend cellular network coverage without additional infrastructure cost. For example, users with poor coverage located at the cell edge can communicate directly to a nearby user (e.g. acting as relay) via direct communication. Relay then connects to BS via cellular link. Finally, D2D communication allows data offloading from BSs [2, 6, 18, 19].

1.2.4 *Challenges in D2D Communication*

Despite these advantages, D2D communication introduces technical challenges for network design including the following [13, 17, 18, 20]:

- **Peer discovery and synchronization.**
  Peer discovery and synchronization are prerequisite steps to establish D2D communication. These are realized in joint fashion. During the discovery phase, UEs try to discover potential candidate UEs located within a specified proximity to establish direct communication. Then, synchronization among UEs is leveraged for efficient use of the available spectrum and of the UE energy [18, 20, 21]. In general, there are two approaches of peer discovery for D2D communication: direct and network-assisted discovery. In direct discovery, UEs periodically broadcast discovery beacon signals. Hence, UEs

located nearby can identify their presence and determine whether setting up D2D communication is warranted; however, since there is no synchronization between nodes, and receiver nodes continue to listen for beacon signals all time, this results in a UE battery drain and an increase in energy consumption. Also, this approach is distributed and does not involve BS in the discovery process. Thus, illegal users (e.g., those not part of D2D links) can announce or listen to information to/or from D2D pairs. Another shortcoming of this approach is uncontrolled use of the licensed band. However, this approach reduces signaling overhead at the cost of possible resource collisions [13, 17]. In network-assisted discovery, UEs inform the BS about their intention to communicate, and then send beacon signals. BS exchanges some messages, including identity and link information between two UEs for initiating a D2D link. This approach is centralized, and UEs listen only when instructed by the BS. The result is less energy consumption; however, this method comes at the cost of larger overhead, and limitations in privacy and scalability [11, 20, 22].

- **Mode selection**

  Mode selection can be described as the process of determining whether the D2D pair should communicate in D2D mode or if a cellular mode (CM) should be used. This process can further choose whether the D2D link is allowed to reuse resources with the cellular links (i.e., underlay) or not (i.e., overlay). Mode selection can be performed either statically before the D2D connection is established (e.g., at the timescale of connection setup/release) or dynamically per time slot. This is an important decision because sometimes direct link quality could be worse than cellular link quality. Design issues related to mode selection can be described as follows. First, at what timescale should mode selection be performed and, subsequently, what measurement control signals are required, noting that timescale cannot be too coarse. To avoid signal overhead, measurements and required control signaling should be kept at a minimum. Second, which measurements (e.g., Signal-to-Noise ratio (SNR), pathloss, distance) should be used to decide the mode of the users [13, 18, 23]?

- **Interference management.**

  Interference between cellular and D2D communication is the most critical issue in underlaying D2D communication. Resource allocation and power control techniques can significantly mitigate interference and maximize network performance, and they typically occur simultaneously with mode selection. This issue is quite challenging; therefore, proper allocation of resources is necessary to maintain required users QoS. When D2D deploys under a cellular network, two types of interference can occur co-tier and cross-tier. Co-tier interference occurs between D2D pairs sharing the same resource blocks. Cross-tier interference occurs between cellular users of different tiers and D2D users when resource blocks of cellular users are reused by D2D pairs. Various interference management techniques were proposed for D2D communication under conventional cellular network for both UL and DL spectrum reuse. When D2D communication coexists with heterogeneous cellular networks (i.e., HetNets), interference management techniques become more complicated, as they take into consideration the dense deployments of small cells. Notably, the interference mitigation problem of HetNets with D2D communication is still an open area for investigation [2, 13, 18, 23].

1.2.5 *Application Scenarios of D2D Communication*

Various scenarios require exchange of data between close nodes (e.g., cars, UEs, and sensors, among others). 3GPP defines three main use cases for D2D communication: 1) public safety, 2) network offloading, and 3) commercial/social services [12]. Additional potential D2D use cases have since been introduced in the literature, as illustrated in Fig. 1.4.

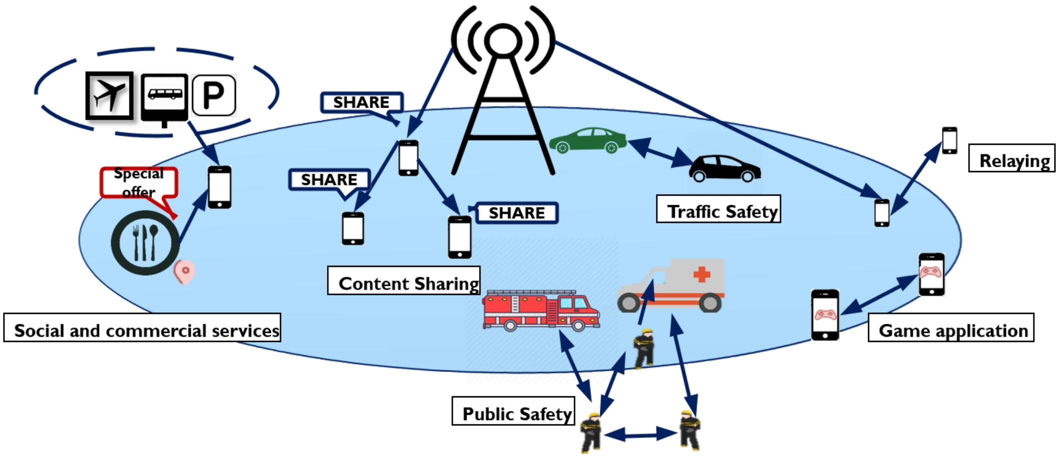


Fig. 1.4: Representative use cases of D2D communication in cellular networks [3].

- **Public safety**

  The 3GPP standard proposed D2D communication for supporting emergency services and for meeting public service requirements [12] [1]. LTE serves as an attractive solution for safety organizations (e.g., police, fire, and rescue services) that are required to intervene in the event of network damage or failure. Network failure may be the result of a natural disaster (e.g., earthquake, tornado, and hurricane) or high congestion due to extreme

[1]In the United States, LTE has been selected by the FCC as the technology [24–26] for the Public Safety Network

traffic load in crowded events (e.g., World Cup, Olympics). Safety organizations can rely on D2D technology to communicate information for short link communication between first responders.

- **Commercial and Social Services**

  D2D communication can support social networking in preference of fixed wireless infrastructure for communicating community information. Not only can it reduce resource usage and alleviate network load, it can also be used for a) local promotions or advertisement from stores and restaurants located within close proximity to users [13] and b) for broadcast information about public transportation services (e.g., train schedules in a subway station or flight updates in airports). Mobile multi-player gaming can also leverage D2D communication for social purposes. Direct link communication could offer advantages for game application in terms of high rate, battery consumption, and low latency.

- **Cellular offloading**

  D2D communication can also be a key component for offloading network traffic. Cellular communication between UEs served by the eNB can switch to direct mode, thus improving spectrum utilization due to proximity gain and increasing total data rates offered to the network [27].

- **Vehicular networks**

  Vehicular networks can be based on vehicle-to-vehicle (V2V) communication, which is basically another application of D2D communication where nodes are vehicles with unique features. This features make V2V different from other typical D2D communication. D2D communication can also be used to meet strict delay and reliability requirements for Intelligent Transportation Systems (ITS). D2D communication can be implemented into collision avoidance systems by communicating road conditions (e.g., accident and road work locations) from vehicle to vehicle [28, 29].

- Content Multi-casting

  Content multi-casting via D2D communication works in such a way that a user with high channel quality is responsible for retransmitting received data from BS to users with weak channel quality. Data retransmission is accomplished through D2D links [30].

1.3 Research Objectives

Q1) The paradigm of D2D communication is known to improve user and network centric throughput in homogeneous networks having macro cells only. Can D2D improve throughput in HetNets environment as well when small cells re-use same spectrum as macro cells?

Q2) If D2D communication is evident for meeting high throughput requirements in future heterogeneous networks, how can enhance energy efficiency as well in D2D communication powered HetNets?

Q3) Can LTE scheduler with D2D communication quantify using stochastic analytical model?

1.4 Contributions

Given these promising advantages, the integration of D2D communication in 5G cellular networks has become an attractive area for research and development. This dissertation quantifies the performance of HetNets with D2D capability in DL reuse by means of mode selection, power control, and resource allocation.

The contributions of this work can be summarized as follows:

- Development of a novel resource allocation algorithm, namely sequential search, for D2D users aimed at maximizing overall throughput of HetNets with D2D communication. This algorithm accounts for cross-tier interference between Macro/small/D2D tiers, is validated through extensive simulations, and then compared to different allocation algorithms (e.g., Random, Hungarian assignment).

- Introduction of a comprehensive framework for D2D under HetNets in DL reuse. The aim is maximizing overall D2D EE through a) D2D user selection, b) dynamic mode selection performed every Transmission Time Interval (TTI), c) resource allocation, and d) power control.

- Development and analysis of a mathematical framework based on two- dimensional continuous Markov chain for LTE scheduler with D2D communication. This new model computes the number of D2D users in underlay (Reuse) and overlay (Dedicated) modes every TTI and estimates throughput based on steady state probabilities. The model can be used as a benchmark for accessing network throughput for 5G network.

The balance of this dissertation is organized as follows. Chapter 2 presents the literature review and state-of the-art work in D2D communication under DL reuse. Chapter 3 introduces a sequential max search (SMS) allocation algorithm. Chapter 4 presents a detailed frame work for energy-efficient D2D communication. Chapter 5 presents the mathematical model for throughput estimation. Finally, chapter 6 discusses the conclusions and future work.

1.5 Dissemination and Publications

Work on this dissertation has offered the opportunity for a number of dissemination activities and resulted in the following presentations and peer-reviewed (accepted, pending) articles.

1. Algedir and H. H. Refai, ”Adaptive D2D resources allocation underlaying (2-tier) heterogeneous cellular networks,” 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Montreal, QC, 2017, pp. 1-6. 2017. [31]

2. A. Algedir and H. H. Refai, ”A User Association and Energy Efficiency Analysis of D2D Communication under HetNets,” 2018 14th International Wireless Communications and Mobile Computing Conference (IWCMC), Limassol, 2018, pp. 1184-1190. [32]

3. A. Algedir and H. H. Refai, ” Energy-Efficient D2D Communication under Downlink HetNets,” 2019 IEEE Wireless Communications and Networking Conference (WCMC), Marrakech, Morocco , 2019. [33]

4. A. Algedir and H. H. Refai, "Analytical Model for LTE downlink scheduler with D2D Communication for Throughput Estimation", 2019 IEEE Global Communications Workshop (under review) .
5. A. Algedir and H. H. Refai "Energy-Efficient Approach for D2D communication under HetNets in Downlink Reuse", IEEE Access, 2019 (under review)

CHAPTER 2

Literature Reviews

2.1 Introduction

2.1 Introduction This chapter provides an overview of earlier work related to DL spectrum reuse. Many investigations have concentrated on designing and developing algorithms for studying D2D under cellular networks. Researchers have utilized several approaches (e.g., optimization theory, game theory, and graph theory) to optimize various aspects of network performance (e.g., SE, EE, latency) in the presence of D2D communication. Most existing work related to either UL reuse [34–41] or DL reuse [42–48] has investigated D2D under conventional cellular networks (CN) where only macro cell BS and D2D were considered.

DL reuse scheme is more complicated than UL reuse scheme due to high interference generated by the BSs to D2D users, which limited D2D performance. As well as, base station power control is a challenging task. In DL reuse, D2D user interference depends exclusively on user location and BSs transmission power. Thus, improving D2D performance can be accomplished by controlling BS transmission power and performing an intelligent dynamic mode selection for D2D users. Designing both power and resource allocation can mitigate interference to cellular users (CUEs) and enhance network performance. Hence, joint mode selection, resource allocation, and power control are required to exploit the performance of D2D under HetNets. The work for D2D underlay cellular network can be organized via power control, resource allocation, and joint power and resources allocation optimization (See Table .2.1).

Ref.	Distance	No.D2D/RB	CN / HetNets	MS	RA	PA	Solution Domain	Remarks
[42]	20m	One pair	CN		√	√	Matching algorithms	Maximize D2D throughput
[43]	20 m	One pair	CN			√	Game theory	Maximize system and D2D throughput
[44]	-	One pair	CN	√	√	√	Heuristic algorithm	Minimize DL transmission power
[45]	20m	-	CN		√		Optimization	Maximize overall and D2D rate
[46]	25m	Multiple pairs	CN		√		Game theory	Maximize system sum rate
[47]	5m	Multiple pairs	CN		√		Game theory	Maximize system sum rate
[48]	-	One pair	CN		√	√	Auction theory	Maximize system sum rate of D2D and small cell users
[49]	25m	-	CN		√		Iterative algorithm	Maximize overall rate of network
[50]	-	-	CN		√		Han-Kobayashi based derivative	Maximize the sum rate
[51]	20m	One pair	CN		√	√	Optimization	Maximize D2D sum rate
[52]	-	Multiple pairs	CN		√		Iterative algorithm	Maximize D2D sum rate
[53]	20m	Multiple pairs	CN	√	√		Graph interference model	Maximize overall throughput
[54]	20m	Multiple pairs	CN		√	√	Optimization	Maximize sum rate of the D2D
[55]	50m	One pair	CN		√	√	Convex optimization	Maximize D2D Energy efficiency
[56]	10-100m	One pair	CN		√	√	Convex optimization	Maximize D2D Energy efficiency
[57]	15m	One pair	CN			√	Analytic solution	Maximize System capacity
[58]	20-120m	Multiple pairs	CN		√			Maximize resources efficiency (RE) and Energy efficiency of D2D
[59]	-	One pair	HetNets			√	Optimization	Maximizes EE of HetNets,D2D,and relays
[60]	25m	One pair	HetNets		√	√	Game theory	Maximize D2D Energy efficiency
[61]	20-140m	One pair	HetNets	√	√	√	Optimization	Maximize overall throughput
[62]	-	One pair	CN		√		greedy heuristic	Maximize Network throughput
[63]	15	One pair	CN		√		weighted bipartite matching Hungarian algorithm	Maximize Network throughput

Table 2.1: Summarized literature review of D2D in DL reuse

2.2 D2D Communication in DL reuse

2.2.1 *Power Control (PC)*

Controlling transmission power is yet another approach for improving EE in HetNets. For this solution, PC algorithms must be implemented to restrict interference among various network tiers and to reduce overall power consumption.

An interference management algorithm has been proposed for D2D during both UL and DL sharing [42]. Initially, authors performed D2D admission control and power allocation to prohibit harmful interference for CUEs, and then D2D channel assignment was designated to maximize throughput. In [43], the authors proposed an adaptive and cooperative reinforcement algorithm for D2D user power allocation to maximize CN throughput. Results showed improved performance for both CN and D2D throughput when compared with distributed reinforcement learning and random power allocation. An optimization problem was formulated in [44] to minimize DL transmission power, subject to rate and power constraints. First, a heuristic algorithm was used to select transmission mode for CUEs in either a cellular or direct manner, and then sub-carrier allocation was performed. Optimal power allocation of D2D over multiple resource blocks (RBs) was presented [45] to maximize D2D rate and overall rate. Researchers considered assigning multiple RBs from different CUEs for each D2D pair under the assumption of orthogonal RB assignments among D2D pairs. The asymptotic power solution for sum-rate maximization was obtained using convex optimization. The solution showed rate improvement in both UL and DL sharing for a 20 m D2D radius.

2.2.2 *Resources Allocation (RA)*

Efficient D2D resource allocation plays a crucial role in reducing CUEs interference levels in DL reuse.

In [62], the authors proposed a greedy heuristic algorithm utilizing channel gain information for both UL and DL spectrum reuse, which improved network performance in terms of cell and D2D throughput. Authors in [46, 47] applied game theory for D2D RA to optimize system sum rate of users. In particular, a sequential, second price auction was introduced as allocation method [46], and an allocation scheme based on a reverse iterative combinatorial auction was later proposed [47]. Both solutions allowed multiple D2D to share a single cellular resource. Notably, allocation scheme performance was evaluated at a separation distance of 25m [46] and 5m [47].

An auction-based distributed algorithm was proposed [48] to implement resources and power allocation for small cell and D2D users in HetNets. A distributed algorithm performed the resource and power allocation for both users while limiting interference to macro cell users under a predefined threshold. In [49], the interference limited area control and partial frequency reuse methods were first implemented to restrict mutual interference under a certain threshold. Then, D2D user resources were selected to improve the overall rate of the CN. Researchers used the Han-Kobayashi rate splitting scheme [50] for resource sharing in a two-link D2D underlay CN; however, a guard distance for BS was considered for reducing interference to D2D.

2.2.3 *Joint Resources and Power Allocation*

The joint resource and power allocation optimization problem has been studied with an aim to improve throughput and EE [51–56]. An iterative resource and power algorithm was proposed [52] to maximize the D2D sum rate subject to rate requirements for CUEs. In [53], the authors modeled interference relationships among various CUEs and D2D links using an interference graph with unique attributes. Based on this interference model, a power and resources algorithm was presented for maximizing CN throughput. Joint resource and power allocation were studied in [54]. Imperfect Channel State Information (CSI) was included in both the objective function and the constraints. Researchers formulated a nominal optimization problem to improve the sum rate of the D2D system while guaranteeing QoS for CUEs.

D2D EE was investigated using joint resources and power allocation while guaranteeing minimum QoS requirements [55, 56]. Researchers have also analyzed the fractional optimization of EE using different approaches, including Dinkebach [64] and Charnes-Cooper transform [65]. After simplifying the EE function and decoupling the numerator and denominator, convex optimization methods were applied to achieve a near optimal solution. The resources efficiency (RE) and EE problem for a multiuser DL orthogonal frequency division multiple access (OFDMA) network was formulated to maximize system EE in [58]. The authors performed RE optimization to obtain optimal power and RA for BS users. Next, D2D users utilized the remaining free channel for communicating in overlay mode, where multiple D2D shared an RB. It is important to note that this research did not account for interference from BS to D2D. In [66], investigators maximized D2D link EE through joint power control and resource allocation with QoS constraints for CUEs in multiple hop D2D communication.

2.2.4 *D2D Communication under HetNets*

Although ongoing research efforts address D2D in DL reuse, D2D underlaying HetNets has yet to be comprehensively studied (See Table .2.1) [2, 23]. An early inquiry of the EE maximization of HetNets supported D2D communication and relay was investigated in [59]. EE optimization was formulated as function in power and user cell association. In this work, the fraction concave problem was converted to concave optimization using Charnes-Cooper transformation. An outer approximation algorithm (OAA) was then applied to determine optimal power and association of the users to maximize overall EE. Notably, researchers assumed an interference-free network. A joint resource and power allocation framework was proposed in [60] to enhance D2D EE under three-tier HetNets macro/femto/D2D networks. The authors decomposed the optimization problem into resource and power allocation problems and solved them independently using a non-cooperative game. This work, however, did not consider the power control of BSs.

The most relevant study for this dissertation work was presented in [61]. Researchers introduced a centralized decision-making framework at the macro base station MB to maximize overall throughput of HetNets underlaying D2D. The framework performed mode selection (i.e., CM, reuse mode , or dedicated mode), resource allocation for CM and DM mode, as well as, PC in RS mode. An adaptive distance mode selection that considered separation distance between D2D pair and interference from MB was suggested. Notably, the researchers assumed a guard zone around MB to protect D2D users. They also assumed that the sum of signal-to-interference-plus-noise ratio ($SINR$) is quasi-convex to support convexity analysis in reuse mode. The vertex search approach was applied for power allocation. However, this solution is impractical, because complexity increases exponentially as the number of transmitters increases.

D2D EE maximization under HetNets (e.g., interference limited network) has not been investigated. Maximizing EE in terms of number of varying powers is a challenging task because EE fraction function is neither concave nor convex. Hence, standard convex optimization theory can not be directly employed. Prior works have addressed EE optimization via PC in limited interference scenarios only to find suboptimal methods with various trade-offs between global optimization and complexity. Researchers proposed a framework [67, 68] based on the fraction programming and sequential optimization for maximizing Generalized Energy Efficiency (GEE) in terms of PC. The proposed framework converged to a suboptimal solution with affordable complexity. The work in [67] is considered a massive MIMO network scenario. More recently, global EE maximization was achieved via an approach based on fractional programming and monotonic optimization [68]. The complexity of the proposed method exponentially increased as a function of the number of communicating links. The authors investigated two case studies: multi-antenna LTE network and the massive MIMO network.

2.3 D2D Mode Selection (MS)

MS entails determining whether users should exploit BSs in cellular mode or establish a direct link when communicating in either dedicated mode (DM) or reuse mode (RS). Two critical issues should be considered for MS design: choice of the performance metric and time scale. The later determines how often the communication mode should be updated. Generally, mode selection can be either dynamic or static, per time scale. Dynamic mode selection can be performed at different time scales, adapting the networks and wireless channel changes at the cost of increasing computation and communication overhead [69]. Static mode selection is permanent over time, meaning that D2D users cannot switch their mode or adapt to channel changes (e.g., distance-based mode selection).

Mode selection (e.g., cellular or direct) was designated for D2D users in [70–74]. In [70], static mode selection was considered based on threshold distance. In [71, 72], researchers investigated dynamic mode selection and resource allocation aimed at minimizing the delay under dropping probability constraints with bursty traffic arrival. The theoretical analysis of D2D mode selection with user mobility was explored in [73, 74]. Received signal strength (RSS) of the D2D link and cellular DL were considered in [73] as a metric for MS, while RSS for both UL and DL were considered in [74] to define the user mode.

Other investigations considered three modes, namely CM, DM, and RS, for each user. In [75], the authors studied static mode switching for maximizing EE during UL reuse. Game theory was applied for mode selection in [76, 77]. Specifically, a dynamic Stackelberg game framework was proposed for joint mode selection and spectrum allocation in [76]. In [77], the authors proposed a solution based on a coalitional game among D2D links for selecting mode (e.g., CM, DM, and RS) to ensure total transmission power was minimized.

CHAPTER 3

Sequential Max Search Resources Allocation

3.1 Abstract

The interference mitigation and resources allocation in HetNets enabled D2D communication is a cumbersome and challenging task, as an extra tier of interference is introduced as a consequence of spectrum sharing by D2D communication. In this chapter, the D2D resources allocation problem under HetNets was formulated to maximize the throughput. This optimization problem has been proven as an NP-hard problem [42]. Hence, a novel algorithm, namely Sequential Max Search (SMS), is proposed to minimize interference from D2D users to cellular users and to maximizes overall network throughput. It is a less computationally, demanding approach. Results demonstrated that SMS achieved a sub-optimal solution compared to brute force Algorithms. However, a significant space search reduction was earned.

3.2 System Model and Problem Formulation

3.2.1 *System Model*

Consider a single-cell cellular network with one centrally located macro base station (MB) and one randomly placed small base station (SB) in the cell on a DL period, as illustrated in Fig. 3.1. Both base stations use the same frequency band that causes inter-cell interference [1]. Cellular users are uniformly distributed and associated with base stations based on maximum reference received strength signal ($RSRP$)(e.g., users will associate to the base station from which it receives the maximum power in DL). Active users under MB are denoted by $U^M = \{1, ..., m\}$, and active users under the SB are denoted by $U^S = \{1, ..., s\}$. Moreover, $D2D$ pairs distributed in network and denoted by $U^D = \{1, ..., d\}$, where D2D transmitters ($D2D_{tx}$) are randomly distributed, and D2D receivers ($D2D_{rx}$) are distributed in a disk of radius (R) around their predetermined transmitter. Number of available resource blocks (RBs) are $K = \{1, ..., k\}$. Where bandwidth of a RB is w_B. For the sake of simplicity, in each tier a cellular user is assumed to occupy only one RB, and only one $D2D$ pair can share this RB with preassigned cellular user. Finally, base stations and $D2D_{tx}$ transmission powers are assumed fixed.

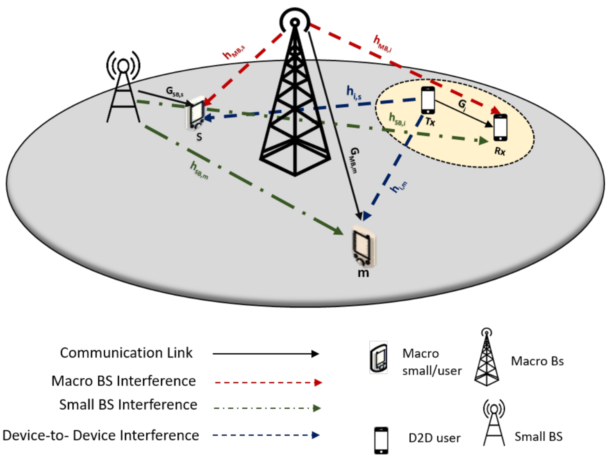


Fig. 3.1: System model of in-band D2D communications underlaying HetNets

[1]the assumption of this work that eICIC have implemented by base stations to mitigate the inter-cell interference. our goal to mitigate interference from D2D users to cellular users

3.2.2 *Problem Formulation*

Based on LTE-A structure, system bandwidth is divided into k physical resources block. Resources are allocated to users in units of RBs. In the frequency domain, each RB occupies 180 KHz and is divided into 12 adjacent subcarriers spaced 15 KHz apart while occupying a one time slot (0.5 ms) in time domain.

In this work, cellular communications are prioritized, thus, active U^M and U^S are assumed preassigned to RBs prior to the start of D2D communication [2]. $\mathbf{Y_M^K}$ and $\mathbf{Y_{SB}^K}$ are binary matrices indicating resource allocation for MB and SB users respectively $\forall \quad k \in K$.

$\mathbf{X_D^K}$ indicates U^d pairs resource allocation matrix, where $x_i^k = 1$ indicates that $k^{th} RB$ is assigned to i^{th} pair. Otherwise, $x_i^k = 0 \ \forall \quad k \in K$.

Co-channel interference is considered between users under different tiers $\{U^M, U^S\}$, $\{U^M, U^D\}$, and $\{U^S, U^D\}$. Consequently, the $SINR$ of $\{m, s, d\}$ users under macro, small, and D2D tier sharing the k^{th} RB is calculated by equations (3.1) through (3.3).

$$\gamma_m^k = \frac{P_{MB} G_{MB,m}^k}{N_0 + \sum_{j=1}^{d} x_j^k h_{j,m}^k p_j + Y_{SB}^k h_{SB,m}^k P_{SB}} \tag{3.1}$$

$$\gamma_s^k = \frac{P_{SB} G_{SB_j,s}^k}{N_0 + \sum_{j=1}^{d} x_j^k h_{j,s}^k p_j + Y_M^k h_{MB,s}^k P_{MB}} \tag{3.2}$$

$$\gamma_i^k = \frac{x_i^k p_i G_i^k}{N_0 + Y_M^k h_{MB,i}^k P_{MB} + Y_{SB}^k h_{SB,i}^k P_{SB}} \tag{3.3}$$

Where $\{G_{MB,m}^k, G_{SB,s}^k, G_i^k\}$ represents the channel gain between MB and m^{th} user, SB and s^{th} user, and $D2D_{tx}$ and $D2D_{rx}$ of the i^{th} pair, respectively.

[2] Cellular users allocation is not considered in this work.

The $\{h_{MB,i}, h_{MB,s}\}$ is the channel gain between MB and $\{D2D_{rx},\ s^{th}\}$ users, respectively, and $\{h_{SB,i}, h_{SB,m}\}$ is channel gain between SB and $\{D2D_{rx}\ ,\ m^{th}\}$ user, respectively. The $\{h_{i,m}, h_{i,s}\}$ is channel gain between $D2D_{tx}$ and $\{m, s\}$ users, respectively. Channel gains of communication and interference signals include pathloss and log-normal shadowing models. Users throughput is calculated based on Shannon Theorem using equations (3.4a) through (3.4c).

$$T_m^k = w_B \log_2 (1 + \gamma_m^k) \tag{3.4a}$$

$$T_s^k = w_B \log_2 (1 + \gamma_s^k) \tag{3.4b}$$

$$T_d^k = w_B \log_2 (1 + \gamma_i^k) \tag{3.4c}$$

The objective is maximizing system throughput by maximizing throughput of all allocated users at each RB, as well as satisfying various rate requirements for users in U^m, U^s, U^D.

Equation (3.5) represents the mathematical form of D2D resource allocation under HetNets. Since optimization variables are binary and the objective function is not convex, optimization problem (3.5) defined as Mixed Integer Nonlinear Program (MINLP) which is NP-hard, therefore, it is difficult to get analytical optimal solutions [42].

$$\max_{\mathbf{X_D^K}} \sum_{k=1}^{k} (\mathbf{T_{U^M}}(\mathbf{X_D^K}) + \mathbf{T_{U^S}}(\mathbf{X_D^K}) + \mathbf{T_{U^D}}(\mathbf{X_D^K})) \tag{3.5}$$

Subject to

$$
\begin{aligned}
&C1 : x_i^k \in \{0,1\} \quad \forall \quad i \in U^D, k \in K \\
&C2 : \sum_{k=1}^{k} x_i^k \leq 1 \quad \forall \quad i \in U^D \\
&C3 : \sum_{i=1}^{d} x_i^k \leq 1 \quad \forall \quad k \in K \\
&C4 : w_B \log 2(1 + \frac{P_{MB} G_{MB,m}^k}{N_0 + \sum_{j=1}^{d} x_j^k h_{j,m}^k p_j + Y_{SB}^k h_{SB,m}^k P_{SB}}) \geq R_{min,m}^k \quad \forall \quad m \in U^M \\
&C5 : w_B \log 2(1 + \frac{P_{SB} G_{SB,s}^k}{N_0 + \sum_{j=1}^{d} x_j^k h_{j,s}^k p_j + Y_M^k h_{MB,s}^k P_{MB}} \geq R_{min,s}^k \quad \forall \quad s \in U^S \\
&C6 : w_B \log 2(1 + \frac{x_i^k p_i G_i^k}{N_0 + Y_M^k h_{MB,i}^k P_{MB} + Y_{SB}^k h_{SB,i}^k P_{SB}} \geq R_{min}^k \quad \forall \quad i \in U^D
\end{aligned}
$$

Constraint C2 indicates only one RB is assigned to each D2D pair. Constraint C3 indicates RB cannot be used by more than one D2D pair. Constraints C4 and C5 represent various QoS requirements of U^M and U^S users ,respectively. Constraint C6 ensures minimum QoS for U^D pairs.

3.2.3 *Sequential Max Search Algorithm*

The problem of radio resources allocation is MINLP problem and is notoriously difficult to solve in the LTE-A scheduling within of period of TTI (1 msec). A low complexity algorithm was developed to achieve maximum system throughput by maximizing throughput at each RB. The proposed algorithm consists of three steps, as detailed below.

1. **Set Maximum Interference Threshold**

   Users under MB and SB demand different QoS rate requirements, therefore, maximum allowed interference threshold for users at $k^{th}RB$ is calculated by solving the constraints ($C4$) and ($C5$) as given in equations (3.6a) and (3.6b). Then, the maximum interference I_{TH}^{k} allowed by D2D pairs to reuse k^{th} RB is set by equation (3.7).

$$I_{m,k}^{max} = \frac{P_{MB} G_{MB,m}^{k}}{2^{R_{min,m}^{k}} - 1} - (O.I)_k \quad \forall \quad m \in U^M \tag{3.6a}$$

$$I_{s,k}^{max} = \frac{P_{SB} G_{SB,s}^{k}}{2^{R_{min,s}^{k}} - 1} - (O.I)_k \quad \forall \quad s \in U^S \tag{3.6b}$$

$$I_{TH}^{k} = \min\left\{ I_{m,k}^{max}, I_{s,k}^{max} \right\} \quad \forall \quad k \in K \tag{3.7}$$

where $(O.I)_k$ is an accumulated interference in $k^{th} RB$ before assigning $D2D$ pairs. In this work, $(O.I)_k$ represents the interference received by the cellular user from the unassociated BS (inter-cell interference).

2. **Identify Optimal Resource Blocks Candidate**

The interference caused by D2D pairs to set of the users at each RB was computed, which equals the received power from $D2D_{tx}$ to users using the $k^{th} RB$, as explained in equations (3.8a) and (3.8b).

$$I_{i,m}^{k} = h_{i,m}^{k} p_i \quad \forall \quad i \in U^D, m \in U^M \tag{3.8a}$$

$$I_{i,s}^{k} = h_{i,m}^{k} p_i \quad \forall \quad i \in U^D, s \in U^S \tag{3.8b}$$

$\psi_{RBs}(i)$ is an initial set of candidate RBs for each $i \in U^D$. Set $\psi_{RBs}(i)$ contains RBs that can be share without violating constraints C4 and C5. It is found by comparing interference computed by equations (3.8a) and (3.8b) with the maximum threshold I_{k}^{TH} defined in (3.7).

Next, an optimal candidate set $\psi_{RBs}^{*}(i)$ for $i \in U^D$ by finding RBs that satisfy the local minimum condition for each pair.

$$\psi^*_{RBs}(i) = \arg\min_k \quad I_i(\psi_{RBs}) \tag{3.9}$$

3. **Allocate Resources Blocks**.

Improve overall network throughput by maximizing achieved throughput at each RB in the presence of U^D pairs. Achieved throughput was computed for all users allocated in the best candidate set $\psi^*_{RB}(i)$ for each D2D pair.

$$\mathbf{T}(\psi^*_{\mathbf{RBs}}) = \mathbf{T}_{\mathbf{U^M}}(\psi^*_{\mathbf{RBs}}) + \mathbf{T}_{\mathbf{U^S}}(\psi^*_{\mathbf{RBs}}) + \mathbf{T_i}(\psi^*_{\mathbf{RBs}}) \quad \forall \quad \mathbf{i} \in \mathbf{U^D} \tag{3.10}$$

Given throughput matrix $[\mathbf{T}(\psi^*_{\mathbf{RBs}})]$ where its elements are composed of total throughput from all users sharing the set of candidates resources (ψ^*_{RBs}). Sequential search is performed to match a D2D pair to an RB once at the time given the priority to D2D pair that achieved maximum gain in each RB.

$$\mathbf{x_i^k} = \max_{\{\mathbf{k},\mathbf{i}\} \in \{\mathbf{RB}^*, \mathbf{U^D}\}} \quad [\mathbf{T}(\psi^*_{\mathbf{RBs}})] \tag{3.11}$$

Algorithm 1 Sequential Max Search Algorithm

Input: users sets $U^M; U^S; U^D$; $Y_M^K; Y_S^k; T_{U^M}^k; T_{U^S}^k$

Output: Network Throughput $\mathbf{T}$, Allocation matrix $\mathbf{X_D^K}$

Step1: Compute maximum threshold I_{TH}^k

while $k \leq k$ **do**

  Compute $I_{m,k}^{max}; I_{s,k}^{max}$ equation (3.6a)-(3.6b)

end while

Step2: Find optimal set of RBs ψ_{RBs}^*

for $i \leftarrow 1, d$ **do**

  for $k \leftarrow 1, k$ **do**

    $\psi_{RBs}(i) = \emptyset$

    Compute $I_{i,m}^k$, $I_{i,s}^k$

    if $I_{i,m}^k \leq I_{TH}^k$ and $I_{i,s}^k \leq I_{TH}^k$ **then**

      $\psi_{RBs}(i) = \psi_{RBs}(i) \cup k$

    end if

  end for

  Compute ψ_{RBs}^* as in equation (3.9).

end for

Compute $T(\psi_{RBs}^*)$ as in equation (3.10)

Step3: Allocate D2D users

for *count* $\leftarrow 1, d$ **do**

  Return $\{k^*, i^*\} = \arg\max_{i,j} T[(\psi_{RBs}^*)]$

  Set $\mathbf{x_i^{*k} = 1}$

  update $\{RB^*\} = \{RB^*\} \setminus k^* \quad \forall, d \in U^D$

  update $\{D\} = \{D\} \setminus i*$

end for

Compute overall system Throughput (3.5).

3.2.4 *Brute Force Search*

MINLP problems can be computationally solved, and the global optimal solutions can be determined by applying exhaustive searching methods (e.g., brute force). Although the implementation of brute force is simple and will always find a solution if one exists, its cost is proportional to the number of candidate solutions. One way to speed up a brute-force algorithm is to reduce the search space. In this work, the search space was reduced by considering only the optimal set ψ^*_{RBs} of RBs found in SMS for each pair. Then, a brute-force search was applied to determine an optimal allocation solution. The brute-force search algorithm explored all candidates. Subsequently, the solution that yielded maximum value was regarded as the final optimal solution. Output should be calculated for each candidate that could potentially offer a solution to problem (3.5). The algorithm is stopped after testing a specified number of candidates.

Algorithm 2 Brute Force Search

Input: $\psi^*_{RBs}(i) \quad \forall \quad i \in U^D$
Output: T , $\mathbf{X_D^{*K}}$

```
1: ν ⟵ list possible candidate solutions to (3.5) c ← first candidate solution for
   (3.5) .
2: while c ≠ ν do
3:     Compute equation (3.5) at c
4:     if c feasible solution  then
5:         save (T, c)
6: c ← next candidate solution
7:     end if
8: end while
```

3.3 Simulation Results

In this section, D2D communication performance underlaying two-tier cellular networks is evaluated. A single-cell scenario is considered where D2D pairs are placed randomly within the cell coverage. Macro BS is fully occupied, and the small cell BS is partially occupied. Simulation Monte-Carlo is performed to evaluate the performance of algorithm. Different pathloss models are applied for D2D and CUEs users according to [78]. Simulation parameters and their values are listed in Table 3.1. The performance of SMS algorithm is compared to different resource allocation (e.g. ,Random, Hungarian assignment [79]) algorithms.

- **Random Allocation**. Random allocation is used for D2D pairs.
- **Brute Force Search**. Brute force search is applied to find the optimal allocation for each D2D pair as explained in algorithm (2).

3.3.1 *Impact of the D2D Pairs Number*

Fig. 3.2 shows the relationship between system throughput and the number of D2D pairs. D2D communication showed an improvement of HetNets throughput. It can be observed that the throughput gain increases when the number of D2D users increases. The maximum gain obtained with 35 pairs then performance slowly declines due to co-channel interference. Throughput obtained using SMS allocation was very close to throughput obtained using brute-force. As well as, SMS results always outperforms random or Hungarian allocation.

Parameter	Value
Carrier frequency	2.0 GHz
Macro cell radius	500 m
Number of cellular users	200
System bandwidth	10 MHz
Number of resources block	50 RBs
MB PL	$PL(dB) = 128.1 + 37.6 \log_{10}(d[km])$
SB PL	$PL(dB) = 140.7 + 37.6 \log_{10}(d[km])$
D2D PL	$PL(dB) = 148 + 40 \log_{10}(d[km])$
MB power	43 dBm
SB power	33 dBm
D2D-Tx Power	20 dBm
D2D-distance	10-80 m
No. of D2D	10-40 pairs
Shadowing U^m, U^s	$\mu = 0$,$std = 8db$
Min.of.rate U^m, U^s	24-500 kbps
Min.of.rate U^D	24 kbps
Noise spectral density	-174 dBm/Hz

Table 3.1: Simulation parameters

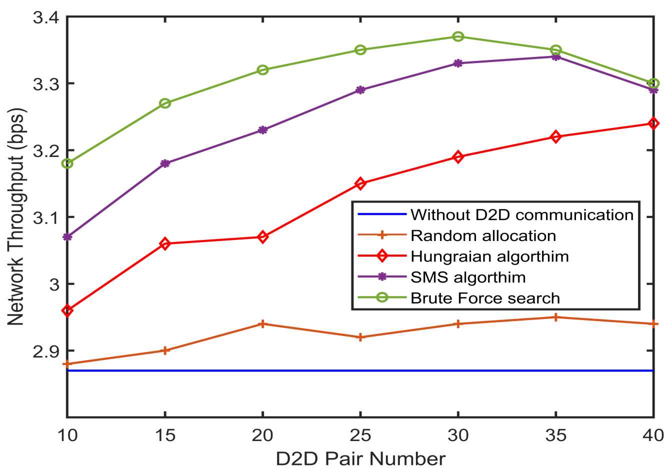


Fig. 3.2: D2D pairs number versus system throughput

3.3.2 *Impact of the D2D Radius*

Average D2D throughput versus separation distance (distance between $D2D_{tx}$ and $D2D_{rx}$) is plotted in Fig. 3.3. As the separation distance increases, the throughput gain reduces consequently. Brute force and SMS allocations follow the same trend, and they were achieving a gain in HetNets throughput up to 80 m while the performance of HetNets with D2D communication degraded using random and Hungarian allocation at 35m and 55m, respectively.

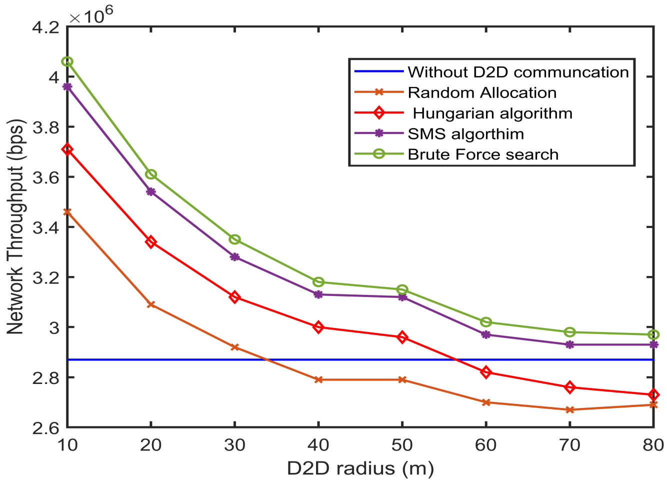


Fig. 3.3: D2D pairs radius versus system throughput

3.3.3 *SINR for D2D and Cellular Users*

Fig. 3.4 gives the SINR distribution of D2D and CUEs. D2D $SINR$ is degraded as the radius of D2D communication increases. Although D2D users were exposed to a high interference (no power control applied to BSs) from SB and MB, SINR of D2D pairs separation distance less than 40 m was better than $SINR$ of SB users. The interference from D2D users using SMS allocation does not significantly affect the $SINR$ the users of MB and SB.

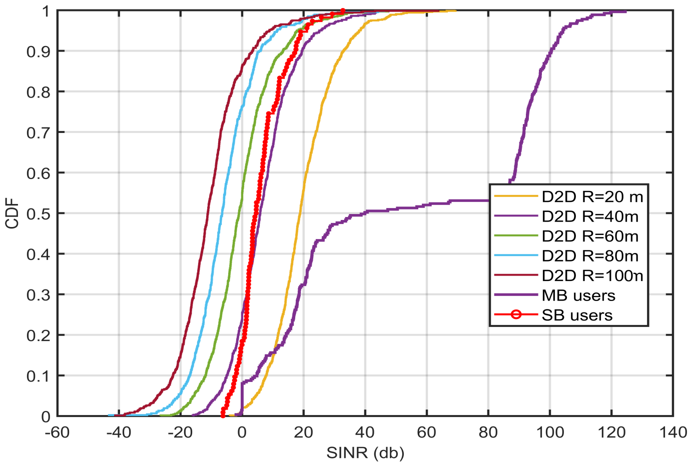


Fig. 3.4: SINR distribution of CUEs and D2D users with different radius (R)

3.3.4 Computational Complexity Analysis

Computational complexity of the proposed resources allocation algorithm (SMS) was compared with the brute force approach. SMS complexity is linear with the number of D2D users. Overall running time of SMS algorithm is $O(N) = (NK + N + K) \simeq (NK)$ where N is the number of D2D links and K is the number of RBs. On the other hand, a global solution can be found using brute force search. Total number of candidate solutions will be $(K)^N$, and complexity will be $O(K)^N$. Table 3.2 gives the execution time of the SMS alogrthim and brute force using space reduction based on SMS candidate resources. The results are computed based on the laptop with the following specifications: (Intel core ^{TM}i7 @2.4 GHz, RAM 8.00GB).

No. D2D pairs	SMS-Time	brute force-Time
10	0.2110 s	2.6978 s
15	0.2375 s	5.1870 s
20	0.2469 s	8.3149 s
25	0.2485 s	11.5248 s
30	0.2714 s	16.5007 s
35	0.3019 s	43.3232 s
40	0.3435 s	52.9122 s

Table 3.2: The average execution time results

3.4 Conclusion

This chapter considered the problem of D2D resource allocation under a two-tier cellular network to mitigate the interference from D2D communication to cellular users . QoS requirements of both cellular and D2D links were considered. To obtain a sub-optimal solution, a resources allocation algorithm for D2D pairs, namely Sequential Max Search (SMS), was proposed. The SMS scheme does not require modification in LTE-A structure. Numerical results verified that SMS enhances system throughput without causing significant loss to cellular users. Moreover, search space for D2D pairs was reduced, and brute-force search was applied to find an optimal solution of D2D resources allocation problem.

CHAPTER 4

Energy-Efficient D2D Communication

4.1 Abstract

Recently, EE has become an essential requirement for designing future wireless communications [69, 80, 81]. Many earlier studies have investigated EE optimization of a CN with D2D communication. Studies of EE fall into two main branches. The first aims at power consumption minimization by designing interference coordination or power control schemes. The second maximizes system SE by devising appropriate resource allocation policies among users. However, limited user power and co-channel interference make designing an energy efficient D2D communication under HetNets a difficult task. In this chapter, a comprehensive framework was proposed that assigns the communication mode, transmission power, and resources allocation for D2D to maximize the EE while maintaining QoS requirements on cellular and D2D links. The optimization problem is formulated as the sum of an individual EE fraction nonlinear function, which is, in general, NP-hard. Based on network traffic, efficient (and for some scenarios, optimal) solutions were developed to maximize EE of D2D communication, as well as, overall EE of HetNets.

4.2 Contribution

As previously mentioned in Chapter 2- and to the best of our knowledge, D2D EE in terms of mode selection, resource, and power allocation in DL reuse under HetNets has not been studied (See Table .2.1). A review of the literature suggests that most existing research considers only a short separation distance, in spite of the fact that D2D is targeted for use at a separation distance of up to 500m [14]. Moreover, some studies assume a guard distance to reduce harmful interference caused by BSs. The following points were considered in this work.

1. The main contribution is introducing a detailed framework for D2D under multi-tier heterogeneous networks in DL reuse. The objective is maximizing overall D2D EE through a) D2D user selection, b) dynamic mode selection per TTI, c) D2D resource allocation (RA), and d) power control (PC). A diagram of the proposed framework is depicted in Fig. 4.1.

2. The worst case scenario for D2D in DL reuse was studied. Unlike [61], our scheme does not consider guard zones around BSs for limiting severe interference. D2D user selection based on Reference Signal Received Power ($RSRP$) values does not restrict separation distance of D2D transmitter ($D2D_{tx}$) and D2D receiver ($D2D_{rx}$).

3. The EE optimization problem is formulated in terms of mode selection, RA, and PC. This problem is an NP-hard problem and is difficult to solve. Hence, the optimization problem is simplified based on network load and solved using various optimization methods.

4. In a low load network, EE maximization is performed by minimizing D2D

user transmission power while maintaining minimum rate requirements. The fraction optimization function can be simplified and solved using a Dinkelbach-like algorithm.

5. In a medium load network,a novel mode selection was proposed based on unsupervised learning fuzzy clustering. Unlike previous mode selection approaches that considered one attribute (e.g., pathloss or SNR) for determining user mode, clustering-based mode selection allowed to combine $RSRP$ and $SINR$ attributes. D2D users are clustered into dedicated and reuse users clusters with different membership coefficients to each cluster. EE maximization is implemented by applying appropriate algorithms for each group of users.

6. In a high load network, D2D users operate in RS mode so that EE maximization is completed in two-step RA and PC. First, Sequential Max Search (SMS) algorithm is used to allocate D2D resources, and then genetic algorithm (GA) is applied to maximize EE via PC in interference limited network.

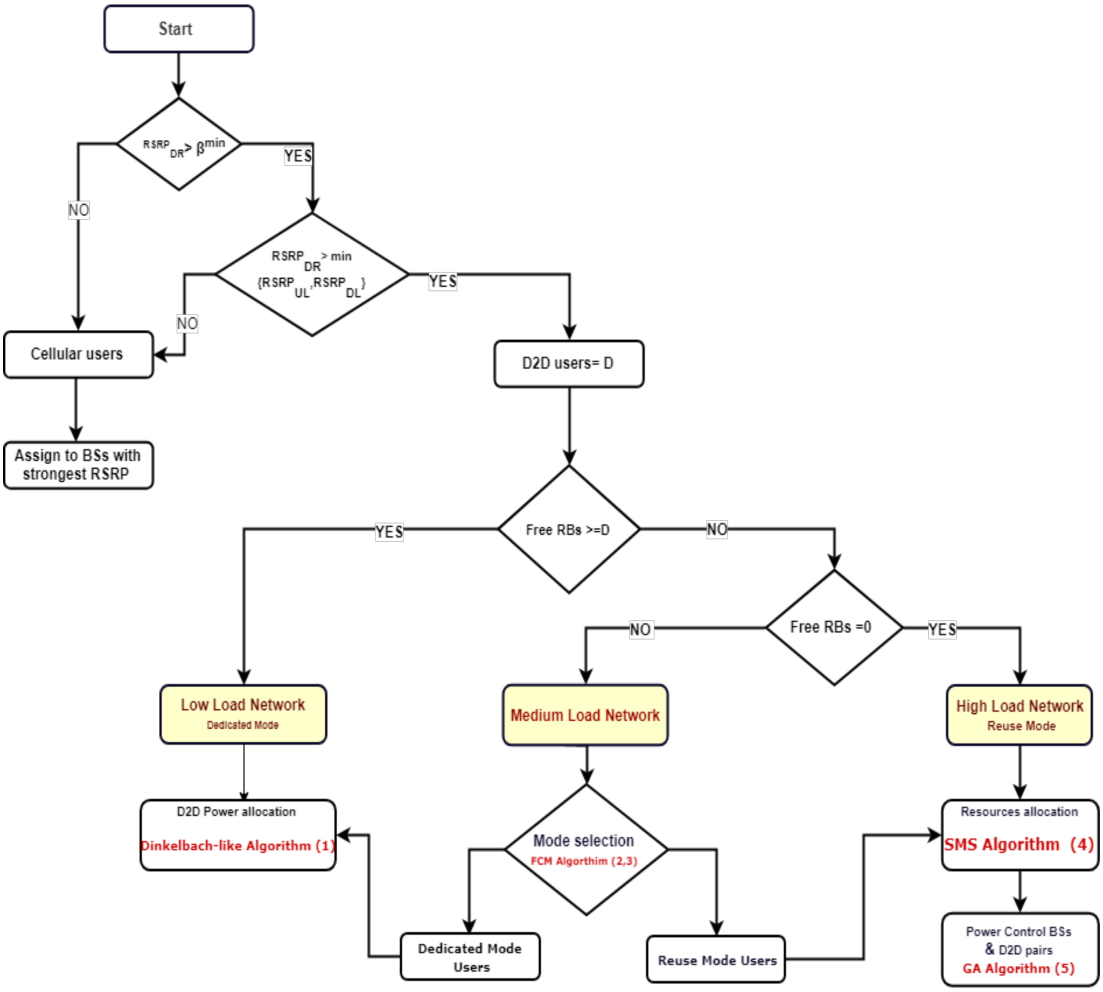


Fig. 4.1: Flowchart of proposed framework of D2D communication in DL reuse.

4.3 System Model and Problem Formulation

4.3.1 *System Model*

The multi-tier heterogeneous cellular network supporting D2D communication in DM and RS modes is shown in Fig. 4.3. An OFDMA downlink of a frequency reuse-1 was considered, wherein bandwidth is divided into k physical resource blocks (RBs) with bandwidth w_B. The set of DL RBs is $K = \{1, 2, ...k\}$. The network consists of a MB located at the center and a set of small BSs SB_j $j = \{1, 2, ..., N\}$ distributed within the MB coverage area. All BSs and transmitters were equipped with omnidirectional antennas. $\widetilde{U}$ pairs of transmitters and receivers are uniformly distributed inside the coverage area. During DL, users are associated with either the MB or an SB_j and marked as CUEs (e.g.,based on maximum $RSRP$), or connected directly to the associated receiver through direct link as D2D users. D2D pair selection approach is shown in Fig. 4.2. Selection is based on UL, DL $RSRP$, and the minimum association $RSRP$ of D2D link (β^{min}), as defined in [82]. A pair must satisfy the following two conditions to use direct link:

1. Transmitter to receiver ($RSRP_{Dr}$) is greater than the minimum association $RSRP$ ($RSRP_{Dr} \geq \beta^{min}$).

2. $RSRP_{Dr}$ is higher than minimum $RSRP_{UL}$ and $RSRP_{DL}$. More specifically, $RSRP_{Dr} \geq \min\{RSRP_{DL}, RSRP_{UL}\}$.

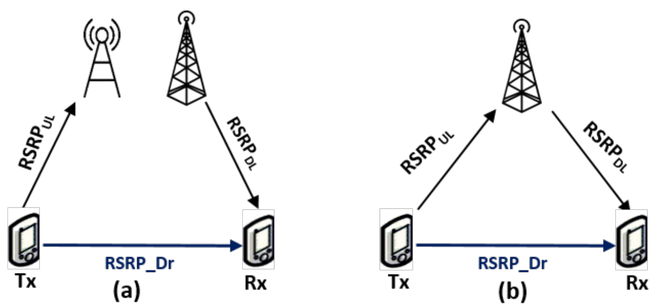


Fig. 4.2: (a) $\{Tx, Rx\}$ associated with different base stations. (b) $\{Tx, Rx\}$ associated with the same base stations.

Total network users are denoted by $U = M \cup S \cup D$, where $M = \{1, 2..., m\}$ the set of users served by MB tier in DL, and $S = \{1, 2, ..., s\}$ the set of users served by SB_j tiers in DL. D2D users are denoted by $D = \{1, 2, ..., d\}$.

For simplicity, allocation matrices $\mathbf{Y_M^K}, \mathbf{Y_{SB_j}^K}$ for MB users and SB_j users are assumed to be determined by the base stations. The Y_D^K matrix represents D2D user allocation in RS mode. Also, one RB is assumed to be assigned exclusively to no more than one user in each tier, and only one D2D pair can share an RB with preassigned CUEs. Co-channel interference is considered among different network tiers $\{MB_{tier}, SB_{tier}\}$, $\{MB_{tier}, D2D_{tier}\}$, and $\{SB_{tier}, D2D_{tier}\}$.

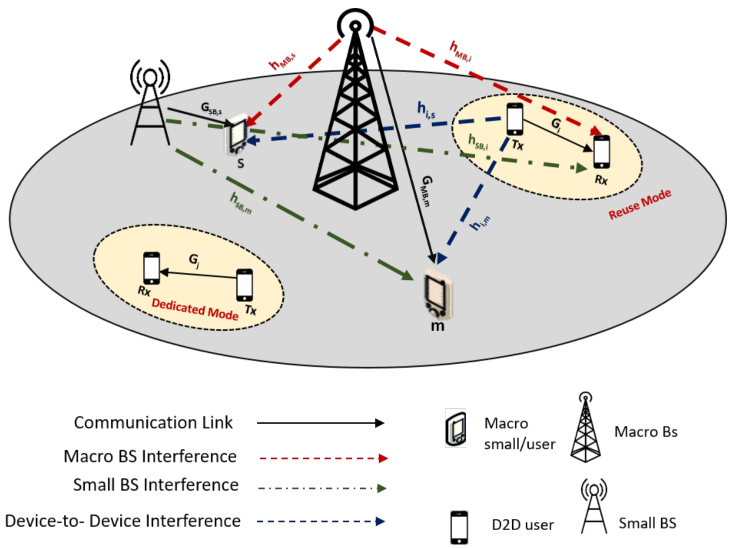


Fig. 4.3: D2D communication under HetNet model.
Solid lines indicate communication link. Dashed lines indicate interference link

4.3.2 *D2D Communication Mode*

1. Dedicated Mode (DM).

   In DM mode, orthogonal resources assign to D2D users so no co-channel interference occurs. Consequently, user ***Signal-to-Noise ratio*** (SNR) and

Table 4.1: Annotations used throughout this chapter

Symbol	Definition
MB	Macro base station
SB_j	Set of small base station
K	Set of RBs
U	Set of users communicating in DL
M, S	Set of users under MB and SB_j in DL
D	Set of D2D users
$RSRP_{DL}$	Received power at receive from the associated BS
$RSRP_{UL}$	Received power at BS from transmitter
$RSRP_{Dr}$	Received power at receiver from its associated transmitter
$D2D_{tx}$	D2D transmitter
$D2D_{rx}$	D2D receiver
p_i	$D2D_{tx}$ power at k^{th} RB
P_{MB}, P_{SB_j}	Marco and small stations transmission power
$G^k_{MB,m}$	Channel gain from MB to m^{th} user at k^{th} RB
$G^k_{SB_{j,s}}$	Channel gain from SB_j to s^{th} user at k^{th} RB
G^k_i	channel gain from $D2D_{tx}$ to $D2D_{rx}$ pair i
$h_{MB,i}, h_{MB,s}$	Channel gain from MB to $D2D_{rx}$ and s^{th} user under SB_{tier}
$h_{SB_{j,i}}, h_{SB_{j,m}}$	Channel gain from SB_j to $D2D_{rx}$ and m^{th} user under MB
$h_{i,m}, h_{i,s}$	Interference from $D2D_{tx}$ of the i^{th} pair to the users m, s under MB, SB_j
DUE_{DM}	Set of D2D users in dedicated mode
DUE_{RS}	Set of D2D users in reuse mode
$\psi^*_{RBs}(i)$	Set of RBs candidates for i^{th} D2D pair

throughput (T_i^{dm}) in DM mode are expressed by

$$\gamma_i^{dm} = \frac{p_i G_i^k}{N_0} \tag{4.1a}$$

$$T_i^{dm} = w_B \log_2 (1 + \gamma_i^{dm}) \tag{4.1b}$$

Where p_i is power of $D2D_{tx}$ of pair i^{th} and G_i^k channel gain between $D2D_{tx}$ and $D2D_{rx}$ communicating in k^{th} RB .

2. Reuse Mode (RS).

In RS mode, D2D users share the CUEs channel, which results in a complicated interference situation for users in each tier, as shown in Fig. 4.3. Frequency reuse one is considered between MB and SB_j cells. Consequently, users in each tier receive co-channel interference from the other two tiers. The SINR of the users $\{m, s, i\}$ under macro, small, and D2D tier communicating in the same RB k^{th} is given by.

$$\gamma_m^k = \frac{P_{MB} G_{MB,m}^k}{N_0 + \sum_{j=1}^{d} y_j^k h_{j,m}^k p_j + \sum_{j=1}^{N} Y_{SB_j}^k h_{SB_{j,m}}^k P_{SB_j}} \tag{4.2}$$

$$\gamma_s^k = \frac{P_{SB_j} G_{SB_j,s}^k}{N_0 + \sum_{j=1}^{d} y_j^k h_{j,s}^k p_j + Y_M^k h_{MB,s}^k P_{MB}} \tag{4.3}$$

$$\gamma_i^k = \frac{y_i^k p_i G_i^k}{N_0 + Y_M^k h_{MB,i}^k P_{MB} + \sum_{j=1}^{N} Y_{SB_j}^k h_{SB_{j,i}}^k P_{SB_j}} \tag{4.4}$$

where $\{G_{MB,m}^k, G_{SB_j,s}^k, G_i^k\}$ represents the channel gain between MB and m^{th} user, SB_j and s^{th} user, and $D2D_{tx}$ and $D2D_{rx}$ of the i^{th} pair, respectively.

The $\{h_{MB,i}, h_{MB,s}\}$ is the channel gain between MB and $\{D2D_{rx}, s^{th}\}$ users, respectively; and $\{h_{SB_{j,i}}, h_{SB_{j,m}}\}$ is channel gain between SB_j and $\{D2D_{rx}, m^{th}\}$ users, respectively. The $\{h_{i,m}, h_{i,s}\}$ is channel gain between $D2D_{tx}$ and $\{m, s\}$ users, respectively. Channel gains of communication and interference signals include pathloss and log-normal shadowing models. Based on the $SINR$ given by (4.4), the achieved throughput of the i^{th} pair in the RS mode is expressed

$$T_i^{Rs} = w_B \log_2 (1 + \gamma_i^k). \tag{4.5}$$

4.3.3 *Problem Formulation*

The aim is to maximize D2D EE by mode selection DM or RS, as well as power and resources allocation while guaranteeing user rate requirements in the network. Theoretically, EE is defined as the ratio of user achieved throughput to power consumption. D2D user throughput was determined in each mode as in (4.1b) and (4.5). Power consumption was composed of average circuit power p_0 plus power transmitted over air interface on link p_i. Therefore, EE achieved by i^{th} pair in DM and RS modes is written as (η_i^{dm}) and (η_i^{dm}), respectively. Mathematically, the EE optimization in terms of joint mode selection, power allocation, and resources allocation is formulated as (4.6) and (4.6a).

$$\Omega = \max_{\left\{Z^{dm}, Z^{Rs}, Y_D^K, P_D, P_{MB}, P_{SB}\right\}} \sum_{i=1}^{d} \left(Z_i^{dm}\eta_i^{dm} + Z_i^{Rs}\eta_i^{Rs}\right) \tag{4.6}$$

$$\Omega = \max_{\left\{Z^{dm}, Z^{Rs}, Y_D^K, P_D, P_{MB}, P_{SB}\right\}} \sum_{i=1}^{d} (Z_i^{dm} \frac{w_B \log_2 (1 + \frac{p_i G_i^k}{N_0})}{p_i + p_0} + Z_i^{Rs} \frac{w_B \log_2 (1 + \frac{y_i^k p_i G_i^k}{N_0 + Y_M^k h_{MB,i}^k P_{MB} + \sum_{j=1}^{N} Y_{SB_j}^k h_{SB_{j,i}}^k P_{SB_j}})}{p_i + p_0}) \tag{4.6a}$$

Subject to

$$Z_i^{dm}, Z_i^{Rs}, y_i^k \in \{0,1\} \forall \quad i \in D, k \in K \tag{4.6b}$$

$$Z_i^{dm} + Z_i^{Rs} \leqslant 1 \quad \forall \quad i \in D \tag{4.6c}$$

$$\sum_{k=1}^{k} y_i^k = 1 \quad \forall \quad k \in K \tag{4.6d}$$

$$\sum_{i=1}^{d} y_i^k = 1 \quad \forall \quad i \in D \tag{4.6e}$$

$$0 \leq p_i \leq p_i^{max} \quad \forall i \in D \tag{4.6f}$$

$$p_{MB}^{min} \leq p_{MB} \leq p_{MB}^{max} \tag{4.6g}$$

$$p_{SB_j}^{min} \leq p_{SB_j} \leq p_{SB_j}^{max} \quad \forall \quad j \in j \tag{4.6i}$$

$$log_2(1+\gamma_i) \geq R_i^{min} \quad \forall \quad i \in D \tag{4.6j}$$

$$log_2(1+\gamma_m) \geq R_m^{min} \quad \forall \quad m \in M \tag{4.6k}$$

$$log_2(1+\gamma_s) \geq R_s^{min} \quad \forall \quad s \in S \tag{4.6l}$$

Denote $\{Z^{dm}, Z^{Rs}\}$ as mode selection indication vectors of $(d \times 1)$ dimension, where indicator $Z_i^{dm} = 1$, given that i^{th} pair operates in DM; otherwise, $Z_i^{dm} = 0$. $Z_i^{Rs} = 1$, given that D2D pair i^{th} works in RS; otherwise, $Z_i^{Rs} = 0$. D2D user resources allocation was considered in RS mode. Denote Y_D^K $(d \times K)$ allocation matrix, whose element $y_i^k \in \{0,1\} \quad \forall k \in K, i \in D$ indicates whether k^{th} RB is or is not allocated to i^{th} D2D pair. Denote $P_D = \{p_1, ...p_d\}$ as D2D users transmitting a power vector. BSs power was controlled in RS mode. Let variable P_{MB} and vector $P_{SB} = \{P_{SB_1}, ...P_{SB_N}\}$ serve as transmission power of MB and BS_j, respectively.

With regard to the above conditions, constraint (4.6c) indicates a D2D pair will choose no more than one mode DM or RS. Constraint (4.6d) indicates only one

RB will be assigned to each D2D pair. Constraint (4.6e) indicates an RB cannot be used by more than one D2D pair. Constraints (4.6f) to (4.6i) represent the upper and lower bound of $D2D_{tx}$ and BSs transmission power. Constraints (4.6j) to (4.6l) denote minimum rate requirements of users. The optimization problem (4.6) is the sum of fraction optimization functions and a mixture of binary and continuous variables, making it an NP-hard problem that requires exponential computation efforts to obtain an optimal solution. To address this problem, the optimization problem was simplified based on network load. In each TTI, the number of free resources in both MB and SB_j tiers is represented by RB_{free}, and various algorithms are utilized for maximizing EE. Three load scenarios are considered:

1. **Low Load Network**: number of available resources RB_{free} is greater than the number of D2D users.

2. **Medium Load Network**: number of available resources RB_{free} is less than D2D users.

3. **Full Load Network**: all channels are occupied by CUEs and RB_{free} equals zero.

4.4 Framework for D2D Communication Based on the Network Load

4.4.1 *EE Maximization in Low Load Network*

Under a light load network, RBs are sufficient for D2D users to operate in DM mode [1]. Selection variable $Z_i^{dm} = 1$ for $\forall i \in D$. Therefore, optimization problem (4.6) is reduced into (4.7). EE maximization is achieved by optimizing D2D user transmit power and considering D2D user rate requirement and maximum allowed transmission power.

$$\max_{P_D} \quad \sum_{i=1}^{d} \frac{w_B log_2(1+\frac{p_i G_i^k}{N_0})}{p_i + p_0} \tag{4.7}$$

$$log_2(1+\frac{p_i G_i^k}{N_0}) \geq R_i^{min} \quad \forall \quad i \in D \tag{4.7a}$$

$$0 \leq p_i \leq p_i^{max} \quad \forall \quad i \in D \tag{4.7b}$$

Equation (4.7) is the sum of ratio functions (SoRPs). A Dinkelbach-like algorithm was proposed for solving SoRPs in [83], as the algorithm converts the sum of ratio functions into a sequence of parametric function. Given that the numerator non negative and concave function in p_i for $\forall i \in D$ and that the denominator is positive and an affine function, as well as, constraints R_i are concave function in $p_i \quad \forall i \in D$. The fraction problem (4.7) was reformulated into the sum of a parametric problem (4.8). Function $\eta_i^{dm}(\lambda_i)$ is the sum of quasiconcave functions and continuous strictly monotonic decreased in λ_i with unique root [83]. The

[1] D2D resources allocation in low load scenario is implemented by MB

optimal solution P_D^* of fraction problem (4.7) is equivalent to finding the root λ_i of the parametric function $(\eta^{dm}(\lambda_i))$. Dinkelbach-like algorithm implementation is given in algorithm(3). An interior-point method is applied to solve the problem $(\eta^{dm}(\lambda_i))$ and find the optimal power that maximizes the eq (4.7). Algorithm (3) shows that in each iteration (line 2), the optimization function (4.8) was solved for a given parameter vector $\{\lambda_i\}_{i=1}^d$ to the point at which the value of parametric function was less than the tolerance.

$$\eta^{dm}(\lambda_i) = \max_{P_D} \sum_{i=1}^{d} \{w_B log_2(1+\gamma^{dm}(p_i)) - \lambda_i(p_i + p_0)\} \tag{4.8}$$

$$S.t \quad (4.7a) \quad and \quad (4.7b)$$

Algorithm 3 EE Optimization in Low Load Network

Initialize : $\epsilon = 10^{-6}$; $n = 0$; $\{\lambda_i^n\}_{i=1}^d = 0$

Input:

P_D^{LU},P_D^{UP}: Solution space.

P_D^0: Initial Solution point

$D = D$: in low load network.

$D = DUE_{Dm}$ in medium load network.

Output: η^{dm}, $P_D^* = [p_1, ...p_D]$

1: **while** $\eta^{dm}(\{\lambda_i^n\}_{i=1}^d) \geq \epsilon$ **do**
2: Solve optimization problem (4.8) using interior point algorithm and find (P_D^{n*}).
3: $P_D^{n*} = \arg\max\{\sum_{i=1}^d w_B log_2(1+\gamma^{dm}(p_i)) - \lambda_i^n(p_i+p_0)\}$
4: Find the value of equation (4.8) at $\eta^{dm}(\{\lambda_i^n\}_{i=1}^d$, $P_D^{n*})$
5: **update** $\lambda_i^{(n+1)} = \frac{w_B log_2(1+\gamma^{dm}(p_i^*))}{p_i^*+p_0} \quad \forall i = \{1, ..., d\}$
6: $n = n + 1$.
7: **end while**

Return $\eta^{dm} = \eta^{dm}(\{\lambda_i^n\}_{i=1}^d)$, $P_D^* = [p_1, ...p_d]$

4.4.2 *EE Maximization in Medium Load Network*

Under a medium load, the number of D2D users is greater than the number of free resources RB_{free}. Hence, some D2D users work in DM, while others remain in RS mode. The optimization problem is expressed as the primary one in (4.6) with the constraints from (4.6b) to (4.6l) carried out in the following way.

$$\max_{\{Z^{dm}, Z^{Rs}, Y_D^K, P_D, P_{MB}, P_{SB}\}} \sum_{i=1}^{d} Z_i^{dm} \eta_i^{dm} + \sum_{i=1}^{d} Z_i^{Rs} \eta_i^{Rs} \tag{4.9}$$

$$S.t \quad (4.6\text{b}) \quad To \quad (4.6\text{l})$$

To solve equation (4.9), mode selection approach is developed based on Fuzzy C-Means clustering (FCM). In FCM algorithm, each object (D2D pair) is not uniquely assigned to a single cluster. Instead, a fuzzy membership matrix $\mathbf{U}\left[\{\mathbf{u_{ij}}\}\right]$ is used, where u_{ij} represents membership coefficient of the i^{th} D2D pair to the j^{th} cluster. The membership coefficient u_{ij} has the following properties.

- $u_{ij} \quad \forall i = 1, 2, ...d, \quad j = 1, 2$
- $\sum_{j=1}^{2} u_{ij} = 1$
- $0 < \sum_{i=1}^{d} u_{ij} < d$,where d number of data points(D2D pairs).

FCM algorithm seeks to minimize the following objective function, J_m, made up of cluster memberships and distance.

$$J_m = \sum_{i=1}^{d} \sum_{j=1}^{2} u_{ij}^m \parallel y_i - c_j \parallel \tag{4.10}$$

where y_i defines the feature vector for i^{th} D2D pair, and cj the cluster centroid.

FCM algorithm clustered D2D users into DM and RS clusters. For each D2D pair, two parameters (features) are considered input for the FCM algorithm $y_i = \{RSRP_{Dr}, \gamma_i^{Rs}\}$. The first feature $RSRP_{Dr}$ is received power at $D2D_{rx}$, which takes into account large scale fading (i.e., pathloss and shadowing). The second feature γ_i^{Rs} is the SINR of D2D pairs in reuse mode. γ_i^{Rs} accounts for the worst case interference scenario caused by MB and SB_j tiers. Outcomes of the FCM algorithm (4) divided D2D users into two clusters —DM user cluster (DUE_{DM}) and RS user cluster (DUE_{RS}). Moreover, each D2D pair is associated to the two clusters with membership coefficient u_{ij}. Given the number of the available resources RB_{Free} and membership matrix $\mathbf{U}\left[\{\mathbf{u_{ij}}\}\right]$ of the D2D users are known in every TTI, algorithm (5) was used to select users either in DM and RS modes. Given that network load decreases, the number of free RBs increases. Users in RS cluster with high DM membership coefficient will be transformed into DM mode. However, if the network becomes heavily loaded with users and a greater number of CUEs get scheduled, a D2D dedicated mode user with high RS membership coefficient will be forced into RS mode.

The pseudo code of the proposed mode selection algorithm is written in algorithm (4) and algorithm (5) with post processing of isolated points. After identifying mode selection indicator vectors $\{Z^{dm}, Z^{Rs}\}$ for D2D pairs, algorithm (3) was applied to a set DUE_{DM} for EE optimization. EE maximization for set DUE_{RS} was executed by performing algorithm (6) for RA followed by algorithm (7) for PC.

Algorithm 4 FCM clustering in Medium Load Network

Initialize: ϵ: Threshold value ; $m = 2$: Weight exponent

Input:

$Y = [y_1, y_2, ..., y_d]$: D2D feature matrix

$D = \{1, 2, ...d\}$:Set of D2D users

Output:

C : Centroid matrix ; U : Membership matrix;

DUE_{DM}: Set of users in DM cluster;

DUE_{RS}: Set of users in RS cluster.

1: Randomly initialize the fuzzy partition max $U^{(0)} = [u_{ij}]$

2: **repeat**

3: Calculate the cluster center with U^k

4: $c_j = \frac{\sum_{i=1}^{d} u_{ij}^k y_i}{\sum_{i=1}^{d} u_{ij}^m}$

5: Calculate dissimilarity between data points and centroid.

6: $d_{ij} = \|y_i - c_j\|^2$

7: Update the membership matrix U^{k+1}

8: $\frac{1}{\sum_{i=1}^{c} (\frac{d_{ij}}{d_{kj}})^{\frac{2}{m-1}}}$

9: Check for isolated point

10: Post Processioning isolated points and go to (4)

11: **until** $\max_{ij} \|u_{ij}^{k+1} - u_{ij}^k\| \leq \epsilon$

4.4.3 *EE Maximization in High Load Network*

When the network is fully loaded and all RBs are allocated to CUEs under different tiers, D2D users are forced to work in RS mode. Therefore, mode selection indicators $Z_i^{dm} = 0$, $\forall i \in D$ and $Z_i^{Rs} = 1$, $\forall i \in D$, the optimization problem can be written as (4.11).

$$\max_{\{Y_D^K, P_D, P_{MB}, P_{SB}\}} \sum_{i=1}^{d} \frac{w_B log_2(1 + \frac{y_i^k p_i G_i^k}{N_0 + Y_M^k h_{MB,i}^k P_{MB} + \sum_{j=1}^{N} Y_{SB_j}^k h_{SB_j,i}^k PSB_j})}{p_i + p_0} \tag{4.11}$$

Subject to

Algorithm 5 Dynamic Mode Selection

Input:

DUE_{DM}: Set of users in DM mode, DUE_{RS}Set of users in RS mode
N_{DM}: Number of D2D users in DM cluster
U : Membership matrix from algorithm (4)
RB_{free} : Number of Free RBs

Output:

Z^{dm}: Z^{Rs} DM and Rs mode selection vectors

Construct U_{dm} vector, whose element is membership's coefficient in DM mode.
Construct U_{Rs} vector, whose element is membership's degree in RS mode.
if $RB_{free} \geq N_{DM}$ **then**
    Sort $DUE_{DM}; DUE_{RS}$ Based on U_{dm} in descending order.
    $m = RB_{free} - N_{DM}$
    Update $DUE_{DM} = DUE_{DM} \cup \{DUE_{RS}\}_1^m$
    Set $\{Z_i^{dm} = 1\} \quad \forall i \in DUE_{DM}$
    Update $DUE_{RS} = DUE_{RS} \backslash \{DUE_{RS}\}_1^m$
    Set $\{Z_i^{Rs} = 1\} \quad \forall i \in DUE_{RS}$
else
    Sort $DUE_{DM}; DUE_{RS}$ Based on U_{Rs} in descending order.
    $m = N_{DM} - RB_{free}$
    Update $DUE_{Rs} = DUE_{Rs} \cup \{DUE_{DM}\}_1^m$
    Set $\{Z_i^{Rs} = 1\} \quad \forall i \in DUE_{Rs}$
    Update $DUE_{DM} = DUE_{DM} \backslash \{DUE_{DM}\}_1^m$
    Set $\{Z_i^{dm} = 1\} \quad \forall i \in DUE_{DM}$
end if

$$y_i^k \in \quad \{0,1\} \quad \forall \quad i \in D \quad \forall k \in K \tag{4.11a}$$

$$\sum_{k=1}^{k} y_i^k = 1 \quad \forall \quad k \in K \tag{4.11b}$$

$$\sum_{i=1}^{d} y_i^k = 1 \quad \forall \quad i \in D \tag{4.11c}$$

$$0 \leq p_i \leq p_i^{max} \quad \forall \quad i \in D \tag{4.11d}$$

$$P_{MB}^{min} \leq P_{MB} \leq P_{MB}^{max} \tag{4.11e}$$

$$P_{SB_j}^{min} \leq P_{SB_j} \leq P_{SB_j}^{max} \quad \forall \quad j \in SBj \tag{4.11f}$$

$$log_2(1 + \frac{y_i^k p_i G_i^k}{N_0 + Y_M^k h_{MB,i}^k P_{MP} + \sum_{j=1}^{N} Y_{SB_j}^k h_{SB_{j,i}}^k P_{SB_j}}) \geq R_i^{min} \quad \forall i \in D \tag{4.11g}$$

$$log_2(1 + \frac{P_{MB} G_{MB,m}^k}{N_0 + \sum_{j=1}^{d} y_j^k h_{j,m}^k p_j + \sum_{j=1}^{N} Y_{SB_j}^k h_{SB_{j,m}} P_{SB_j}}) \geq R_m^{min} \quad \forall m \in M \tag{4.11h}$$

$$log_2(1 + \frac{P_{SB_j} G_{SB_j,s}^k}{N_0 + \sum_{j=1}^{d} y_j^k h_{j,s}^k p_j + Y_M^k h_{MB,s}^k P_{MB}}) \geq R_s^{min} \quad \forall s \in S \tag{4.11i}$$

By setting $Z_i^{Rs} = 1$, $\forall i \in D$, the problem becomes a joint RA and PC optimization. equation (4.11) remains an NP-hard problem, given that the objective function is fractional and non-convex, and the optimization variables are integer and continuous variables. The problem is solved by two steps. First, D2D user resource allocation uses SMS algorithm. Then, power control is performed using a genetic algorithm.

1. **Sequential Max Search Resources Allocation**

   The SMS RA was proposed [31] to enhance overall throughput of HetNets while guaranteeing the QoS of users under the SB and MB. Power of $\{MB, SB_j, D2D_{TX}\}$ is assumed fixed. Primary steps for the SMS algorithm are listed below, and pseudo code of the SMS algorithm is given in algorithm (6).

(a) Set Interference Threshold for CUEs.

Based on rate requirements of CUEs under MB and SB_j stations in each $k \in K$, interference threshold I_{TH}^k was computed by solving the rate-constraint equations (4.11h) and (4.11i). I_{TH}^k defines maximum allowed interference from D2D pairs for sharing k^{th} RB with allocated CUEs.

(b) Identify Optimal RBs Candidate Set.

For each $i \in D$, interference $(I_{i,A}^k)$ calculated for the set of CUEs A allocated at $k \in K$. If $(I_{i,A}^k < I_{TH}^k)$, the k^{th} RB is identified as RB candidate for i^{th} pair. Consequently, the set ψ_{RBs} contains RBs that can be used without violating constraints (4.11h) and (4.11i). To reduce the search space for each pair, the set $\psi_{RBs}^*(i)$ is defined for each pair.

$$\psi_{RBs}^*(i) = \arg\min_k \quad I_i(\psi_{RBs}) \tag{4.12}$$

(c) Allocate RB for D2D pairs.

Following step (2), each D2D pair would have access to a set of candidate RBs $(\psi_{RBs}^*(i))$. Also, an RB can be a candidate for more than one D2D pair. Hence, sequential search is performed to match a D2D pair to an RB. Given throughput matrix $[T(\psi_{RBs}^*)]$ where its elements are composed of total throughput from CUEs and D2D pairs at the set of candidates resources (ψ_{RBs}^*). The SMS allocates an RB to D2D pair that achieving the highest gain in the throughput compared to other D2D pairs. Thus, accumulated throughput is maximized in each RB.

2. **Genetic Algorithm Power Control**

The presence of interference powers (P_{MB}, P_{SB_j}) in SINR causes throughput of D2D link not be jointly concave in the interference powers. This prevents the use of fractional programming algorithms [84]. Graphic visualization of RS mode EE versus that of various interference levels is depicted in Fig. 4.4. Notably, the graph of function is non-smooth and contains many saddle and local maximum points, which result from the summation term in optimization function (4.11). Particularly, GA can overcome this and determine global maximum. Hence, the GA [85] algorithm is utilized for controlling BSs and D2D transmitters power. GA are population-based methods adapting its concepts from the field of biology. At each iteration of the GA algorithm, a new population of points based on an older iteration is generated. The function then assesses each point until a point in the population reaches an optimal solution. Since GA follows random initialization, it avoids local maximums and evolves instead toward global maximum by searching different areas within the search space. The pseudo code of GA algorithm is provided in (7).

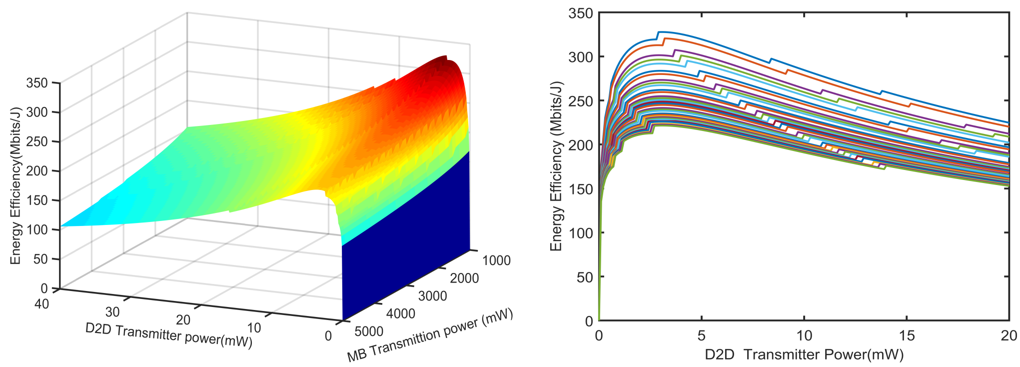


Fig. 4.4: D2D energy efficiency in RS mode.

Algorithm 6 SMS Algorithm for D2D Resources Allocation

Input:

M : Set of MB users; S :set of SB_j users

$L = D$: in high load network. $L = DUE_{RS}$: in medium load network;

$\mathbf{Y_M^K}$, $\mathbf{Y_{SB_j}^K}$: Allocation matrices for MB and SB_j users

Output:

$\mathbf{T_{D2D}}, \mathbf{T_{network}}, \mathbf{Y_D^K}$

Step1: Compute maximum threshold I_{TH}^k

while $k \leq K$ **do**

    Find $I_{m,k}^{max}; I_{s,k}^{max}$ from eq (4.11h) and(4.11i)

    $I_{TH}^k = \max\{I_{m,k}^{max}, I_{s,k}^{max}\}$

end while

Step2: Find optimal set of RBs ψ_{RBs}^*

for $i \leftarrow 1, L$ **do**

    while $k \leq K$ **do**

        $\psi_{RBs}(i) = \oslash$

        Compute $I_{i,m}^k$, $I_{i,s}^k$

        if $I_{i,m}^k \leq I_{TH}^k$ and $I_{i,s}^k \leq I_{TH}^k$ **then**

            $\psi_{RBs}(i) = \psi_{RBs}(i) \cup k$

        end if

    end while

    Compute $\psi_{RBs}^*(i) = \arg\min_k \quad I_i(\psi_{RBs})$

end for

Step3: Allocate D2D users

Compute total throughput in $T(\psi_{RBs}^*)$

for *count* $\leftarrow 1, L$ **do**

    return $[i, k] = \arg\max_{i,k} T(\psi_{RBs}^*)$

    Set $y_i^k = 1$

    update $\{\psi_{RBs}^*\} = \{\psi_{RBs}^*\} \setminus k \quad \forall i \in L$

    update $\{DUE_{RS}\} = \{DUE_{RS}\} \setminus i$

end for

Algorithm 7 Genetic Algorithm for Power Optimization RS

Input:

Y_D^K:D2D RA matrix algorithm (6).
Solution space **S**= $\{P_D^{LU}, P_{MB}^{LU}, P_{SB}^{LU}\}$,$\{P_D^{UP}, P_{MB}^{UP}, P_{SB}^{UP}\}$
G: Max Iterations
E: Key samples per iteration
M: Mutation ratio

Output:

Solution: $\mathbf{X} = \{PD^*, P_{MB}^*, P_{SB}^*\}$

```
Generate |P| sets from S randomly;
Generate values of Ω for each set in P
Save the sets in current solution space Pop;
for i = 1 to G do
    Number of elite members in Pop num_elite = E;
    select the best num_elite solutions in Pop and save them in Pop_1;
    Number of crossover solutions num_crossover = (|P| * num_elite)/2;
    for j = 1 to num_crossover do
        Randomly select 2 solutions X_A and X_B from Pop;
        Generate X_C and X_D by one-point crossover to X_A and X_B;
        Save X_C and X_D to Pop_2;
    end for
    for j = 1 to num_crossover do
        Select a solution X_j from Pop_2;
        Mutate each element of X_j at a rate M and generate new solution X́_j;
        if X́_j is non-feasible then State Update X́_j with a feasible solution by repairing X́_j;
        end if
        Update X_j with X́_j in Pop_2;
    end for
    Update Pop = Pop_1 + Pop_2;
end for
Return the best solution P*_D, P*_MB, P*_SB which gives the best value of η^{*Rs} in Pop;
```

4.5 Simulation Results and Analysis

Proposed framework performance was evaluated through simulation. A single cell with MB located at the center and two SBs located within MB coverage were considered. Primary parameters are found in Table 4.2. System bandwidth is 10MHz, and the channel corresponded to a resource block of 180KHz bandwidth in the 3GPP LTE system. The path loss (PL) model utilized in this study was based on 3GPP standard. Moreover, the proposed algorithms were compared with the following baseline algorithms.

Table 4.2: Simulation parameters

Parameter	Value
Carrier frequency	2.0 GHz
Macro cell radius	500 m
Number of CUEs	100
Number of RB	50 RBs
MB PL	$PL(dB) = 128.1 + 37.6\log_{10}(d[km])$
SB_j PL	$PL(dB) = 140.7 + 37.6\log_{10}(d[km])$
D2D PL	$PL(dB) = 148 + 40\log_{10}(d[km])$
$p_{MB}^{max}, p_{MB}^{min}$	40, 30 dBm
$p_{MB}^{max}, p_{SB}^{min}$	30, 26 dBm
P_d^{max}	23 dBm
D2D-distance	varied
Number of D2D	5-25 pairs
β^{min}	-107dBm
Shadowing M, S	$\mu = 0$,$std = 8db$
R_s^{min}, R_m^{min}	0.6-3 bps/Hz
R_i^{min}	0.3 bps/Hz
Noise power	-174 dBm/Hz
P_{MB}^0 ,P_{SB}^0	130,6.8 w
$\triangle_{MB}$,$\triangle_{SB}$	4.7 ,4
p_0	10 dBm

1. **Mode Selection Algorithm**

   - **Random mode selection**. In random mode selection each D2D pair randomly determines its mode with 0.5 probability.
   - **Static mode selection**. In static mode selection D2D pair chooses its mode based on predefined threshold distance d_{th}. As in [61], threshold sets $d_{th} = 50m$. If the distance between $D2D_{tx}$ and $D2D_{rx}$ is less than d_{th}, DM mode is selected; otherwise, RS mode is selected.

Power allocation was performed using algorithm (3) for DM mode users. RA and PC were implemented by algorithms (6) and (7), respectively, for RS mode users. D2D pair locations for two of simulated topologies are displayed in Fig. 4.5. D2D user selection based on $\{RSRP, \beta^{min}\}$ does not restrict separation distance to a specific distance. This variable separation distance demonstrates the practicality of D2D communication. Also, the guard distance surrounding BSs was not assumed in the proposed scheme which represents the worst case scenario for D2D users.

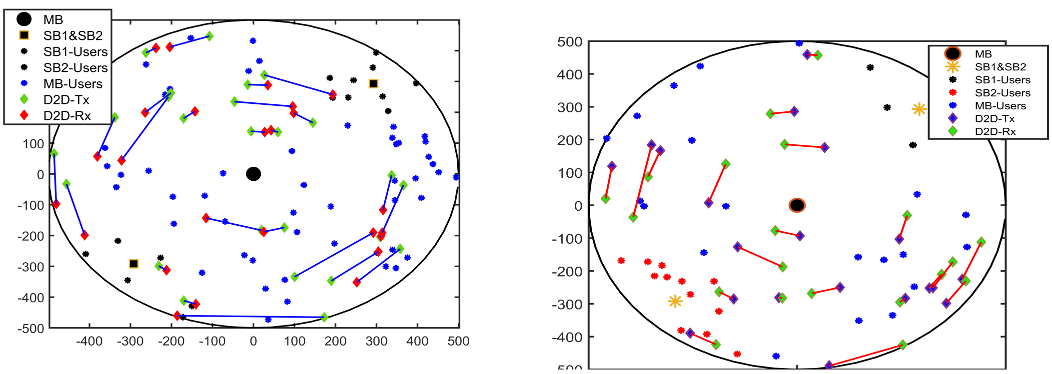


Fig. 4.5: Topology snapshot

4.5.1 *Histogram of D2D separation Distance*

A histogram of the separation distance of D2D users is displayed in Fig. 4.6. When DM mode was selected all users communicated and maintained QoS requirements. However, when RS mode was selected, maximum separation distance of connected D2D users decreased up to 160m due to significant interference caused by the spectrum sharing and the sizable separation distance.

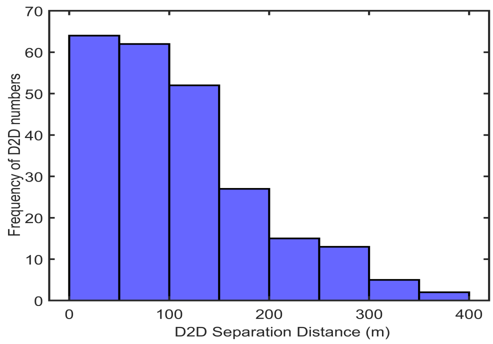


Fig. 4.6: Separation distance histogram

4.5.2 *D2D Throughput*

Although the primary focus of this study is EE, SMS allocation algorithm performance in the RS mode was also examined. The figure below illustrates overall D2D throughput versus the number of D2D pairs for three different allocation algorithms: 1) brute force (blue line), 2) SMS (red line), and 3) random (green line). Overall, SMS and brute force performed better than random allocation. SMS throughput achieved nearly the same results as brute force, albeit giving priority to users with high throughput and with less complexity.

Generally, throughput rate increases consistently as the number of D2D users increases. However, the rate of the increase varied based on distance separation between $D2D_{tx}$ and $D2D_{rx}$ (See Fig4.7).

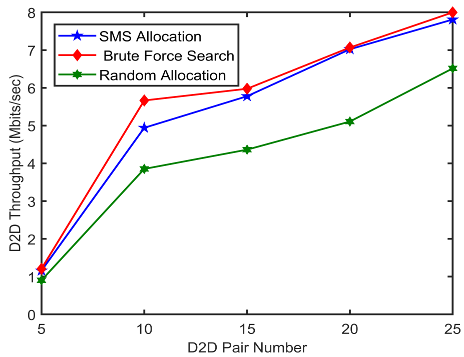
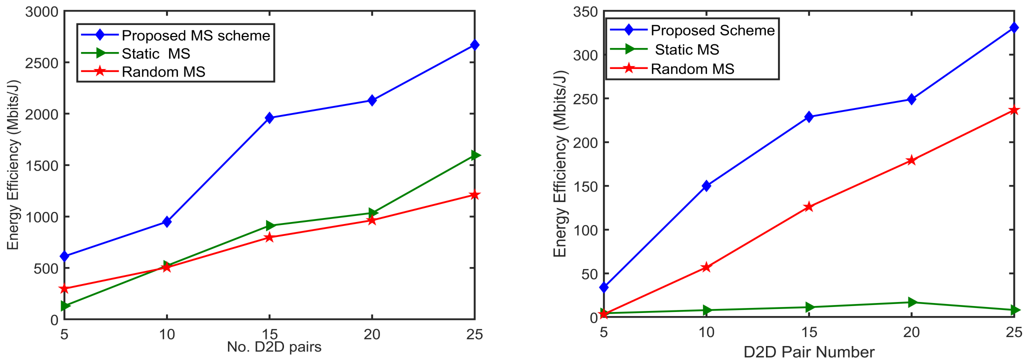


Fig. 4.7: D2D users throughput

4.5.3 *Low and High Network Load Energy Efficiency*

In this section, the EE in low and high load circumstances is investigated for a various number of D2D users. Fig. 4.8 a. details EE maximization results when applying algorithm (3) in low load. And Fig 4.8b. details EE maximization when applying algorithm (6) for RA and (7) for PC in a high load scenario. Results were averaged over multiple typologies for each D2D number. Fig.4.8. demonstrates that EE increases as the number of D2D users increases in both low and high load scenarios. At low load network, there is a significant difference in the level of EE obtained using the proposed scheme as opposed to the EE level obtained using the two mode selection schemes. The proposed scheme forced D2D users to operate in DM mode when free RBs were available. This results in an essential increase in EE. In fact, achieved EE is nearly two times EE obtained when using random and static mode selection.

In high load networks, and despite the fact that in the proposed scheme all D2D users operated in RS mode, D2D EE outperformed the other two mode selection schemes. This phenomenon was aided by the advantage the proposed scheme had of using dynamic mode selection. Notably, D2D users are not assigned to a permanent mode, as is the case in static mode selection. In static mode selection, users are unable to switch from DM to RS mode when orthogonal resources become unavailable, even if users are able to maintain QoS requirements in RS mode. Consequently, more users were blocked, and EE performance was significantly degraded.



(a) (b)

Fig. 4.8: D2D energy efficiency (a) Low load (b) High load

4.5.4 *Medium Load Network Result*

This section illustrates performance of the proposed dynamic mode selection scheme based on FCM membership coefficients. Number of D2D users was fixed at 25 pairs, and minimum rate requirement was 56kbps. Number of RBs occupied by CUEs was changed to represent variation in network load. Appropriate algorithms were chosen to perform EE maximization.

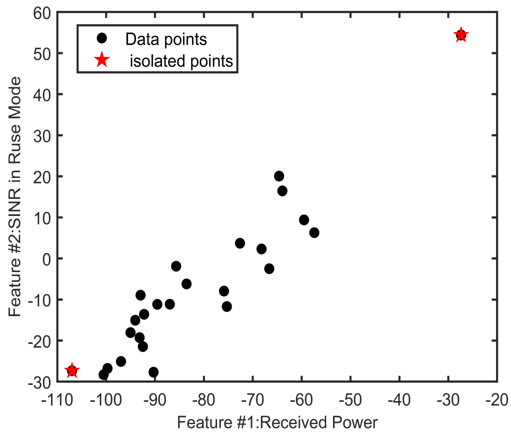


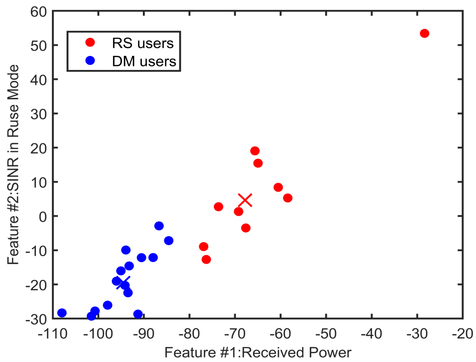
Fig. 4.9: Two dimensional feature space.

1. **Clustering Analysis**

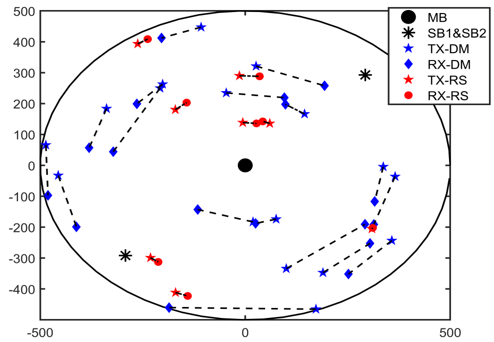
Fig. 4.9 illustrates the two-dimensional feature space of input attributes for a typology. One can see that some data points are sufficiently close to each other, while others are distant. The distant points (i.e., referred to as isolated points in algorithm [4]) influence cluster centroids and membership coefficients. Thus, they may not be as representative as they should be. To overcome the bias due to the isolated points, post-processing steps were implemented to correct cluster centroids, adjusting membership coefficients of D2D users. Isolated points were assigned to its cluster with membership equal to 1, and to the other cluster with membership equal to 0. Then, FCM algorithm was applied to the set of remaining users, which updated centroid for each cluster and membership coefficient of D2D users.

Fig. 4.10a. shows the results of FCM clustering algorithm (4) after post-processing the isolated points. Users grouped in the blue cluster are with low $RSRP$ and low SINR measurements and assigned DM mode, while the users grouped in the red cluster are high $RSRP$ and high SINR and assigned

RS mode. User location in each cluster of a topology is shown in Fig.4.10b. The FCM algorithm groups users with small separation distance in the RS cluster regardless of their location with respect to MB. Gain achieved using proximity of the pairs was shown to overcome high interference, assisting users to maintain the required QoS.



(a)



(b)

Fig. 4.10: Clustering analysis (a) D2D clusters (b) User Location

Algorithm (5) was applied for D2D mode selection at various load scenarios. Operation mode of each user was based on its membership coefficient to each cluster. Fig. 4.11 depicts the scenario of selecting users from RS cluster to DM mode when network load decreases and additional RBs became available. Fig. 4.12 illustrates switching users from DM cluster to RS mode when CUEs requested additional RBs.

2. **D2D Energy Efficiency versus Load**

This section demonstrates the advantage of switching user mode based on FCM membership coefficient for adapting to network load changes. The proposed scheme shows improvements over other selection modes for most network load conditions. It also maximizes the number of connected pairs

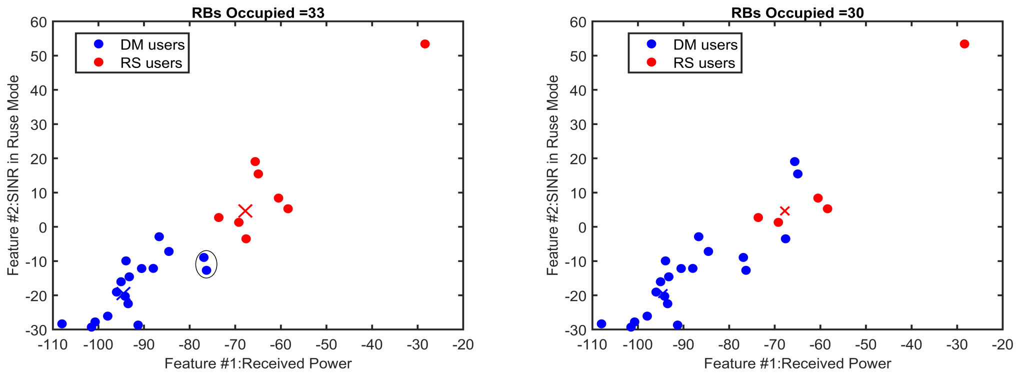


Fig. 4.11: Select users from RS cluster to DM Mode

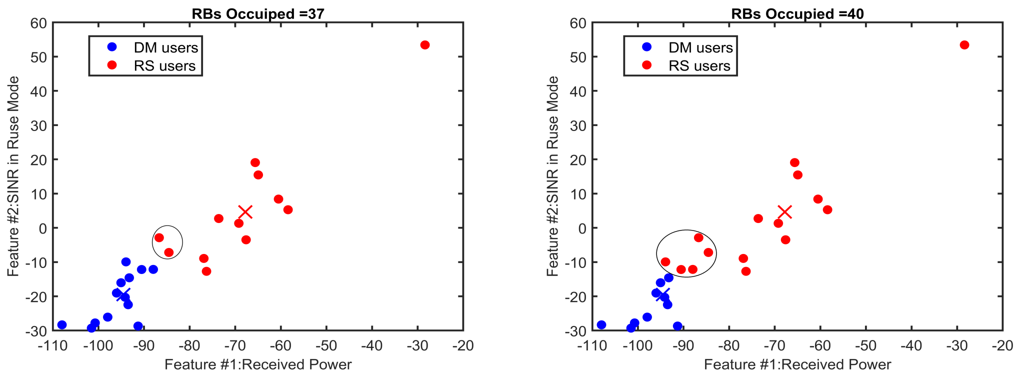


Fig. 4.12: Select users from DM cluster to RS Mode

(as fewer connections were blocked), as shown in Fig. 4.13. As more RBs are occupied and more DM users change to RS mode, results of static mode selection outperform the proposed scheme in a number of cases. High EE leverages static mode selection when users with separation distance less than 50m, as defined earlier, are chosen as DM mode. Notably, the proposed scheme assigned users with small separation distance to RS mode. Static mode selection outperformance comes at the expense of increasing the number of blocked D2D, as shown in Fig. 4.14. Random mode selection does not follow any trend and depends on DM and RS user selection for each case. Although the proposed scheme presents less EE values in some load cases, it maximizes the number of successful D2D communication in all load cases, as shown in Fig. 4.13 and Fig. 4.14 FCM membership coefficient as mode selection indicator, timely switches users from DM to RS while minimizing the number of blocked D2D.

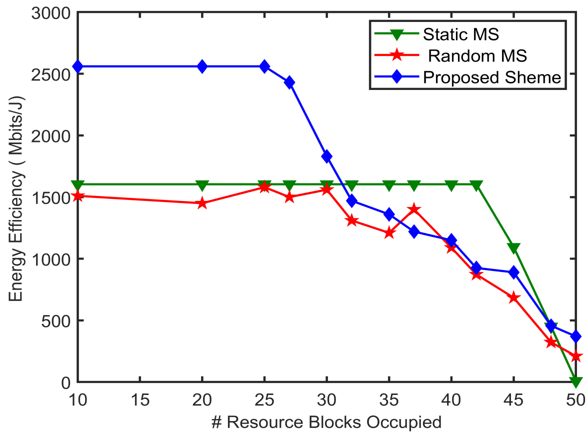


Fig. 4.13: Energy efficiency versus network load

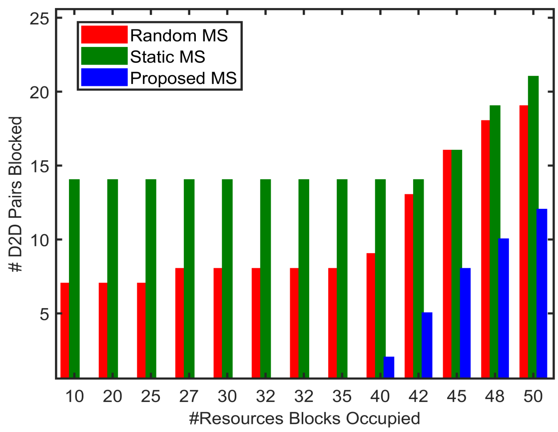


Fig. 4.14: D2D blocked versus load

3. **Power Consumption**

Fig. 4.15 illustrates power consumption and number of D2D users in DM and RS mode versus network load. Power consumption gradually increased as more users shifted from DM to RS mode. At the beginning, power increment rate was nearly constant since switched users belonged to an RS mode cluster with a large degree of membership and small separation distance. As network load increased, rate of power consumption increased, as well, since switched DM cluster users required more power due to increase separation distance. Finally, when switching users were blocked, power consumption decreased. Generally, average power consumption per pair was approximately 11.61 dBm in dedicated mode and 14.84 dBm in reuse mode

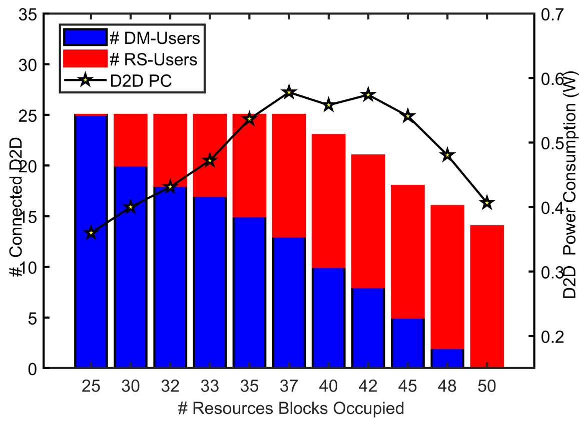


Fig. 4.15: D2D power consumption

4.5.5 Overall Energy Efficiency

Network EE is defined as the ratio of achieved throughput to total power consumption of HetNets. BSs power consumption model is given in [86]. The overall power consumed by HetNets with D2D communication is given by eq. (4.13).

$$P_{tot} = (P_{MB}^0 + \triangle_{MB} P_{MB}) + \sum_{i=1}^{N} (P_{SB}^0 + \triangle_{SB} P_{BS_j}) + \sum_{i=1}^{d} (p_i + p_0) \qquad (4.13)$$

Parameters $\triangle_{MB}$ and $\triangle_{SB}$ represent the slope of the load-dependent power consumption of MB and SB_j, respectively. Finally, P_{MB}^0 and P_{SB}^0 denote static power of MB and SB_j, respectively. HetNets EE with D2D capability was compared to HetNets EE without D2D capability. Fig. 4.16 shows that D2D improves HetNets EE. Given that the network load is light, there is a significant improvement in EE, since D2D users operate in DM mode. However, as network load increases, EE gain and losses are due to D2D mode switching to RS. As more users switch to RS mode, they are required to increase transmission power to accommodate the minimum required QoS. On the other hand, users may become blocked due to high interference and increased separation distance.

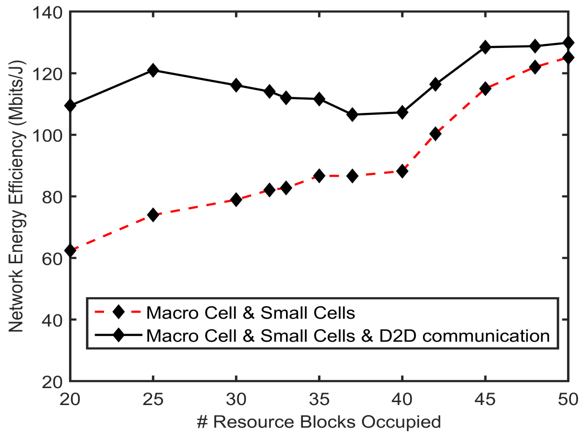


Fig. 4.16: Overall energy efficiency of HetNets

4.6 Computational Complexity Analysis of The Proposed Framework

- **SMS Algorithm**

  SMS algorithm complexity results from the need to calculate the optimal set of resources for each pair. Hence, D2D pair interference threshold should be compared to maximum interference threshold at each RB line 5-12 to yield a computational complexity of $O(KL)$. For line 17, a search method is applied to determine maximum values in a vector. The worst case scenario for finding the maximum in each iteration is $O(KL)$. Consequently, total computational complexity of SMS algorithm (6) is polynomial $O(KL+KL+K) \simeq O(KL)$, where L is the number of D2D users working in RS mode and K total number of resource blocks in system.

- **Dinkelbach Link Algorithm**

  In [84], Dinkelbach-link algorithm converged to the optimal solution at a linear rate. The algorithm converts the original fractional problem into a sequence of parametric functions so that algorithm complexity depends on solving the parametric function and finding its roots. In each iteration, Newton method was used to update the value of auxiliary variables λ_i. Then, optimal PD^* was obtained for a given λ_i using a convex optimization method; if $\eta^{dm}(\{\lambda_i^n\}_{i=1}^D) \leq \epsilon$, iteration is terminated and optimal PD^* is obtained. Otherwise, a new λ_i is calculated, followed by the next iteration. The time complexity for algorithm 3 was using different D2D numbers, and the running time increased at most linearly with the number of the D2D.

- **Mode Selection Algorithms**

  FCM complexity is given by $O(dC^2FI))$, where D is the number of data point (D2D pairs), C is number of cluster (2 clusters), and F is the dimension of the features space. In our proposed model 2-D is $\{RSRP_d, \gamma_i^{Rs}\}$, and I is the number of iterations required for FCM objective function to converge in [87].

- **Genetic Algorithm**

Time complexity of GA algorithms cannot be determined since it depends on many factors: population size, objective function complexity, and iteration number.

4.7 Conclusion

In this chapter, a comprehensive framework was developed for optimizing D2D communication EE in downlink by leveraging dynamic mode selection, power allocation, and resource allocation. The framework presents a novel dynamic mode selection based on a fuzzy clustering algorithm, which identified similarities between users based on two parameters, and then identified them as a DM or RS user. Dynamic mode selection can be extended to include additional features for adapting network changes and user mobility. Based on network load, algorithms were implemented to maximize EE via power and resources allocation. The proposed framework achieved higher energy efficiency when compared to baseline schemes, and maximized the number of connected D2D users. Moreover, results demonstrated that D2D deployment under HetNets improved network EE of downlink transmission.

CHAPTER 5

Analytical Model for LTE Downlink Scheduler with D2D Communication for Throughput Estimation

5.1 Abstract

Device-to-Device (D2D) communication is expected to be an essential component of the next generation cellular network. Although this promising technology has already demonstrated its ability to increase network throughput, the need for an accurate, fast-computing model of throughput estimation is essential. In this dissertation, an analytical model for LTE scheduler-supported D2D communication is presented. The model is based on two-dimensional Continues-Time Markov Chain and is utilized for estimating network throughput. A closed formula is obtained for determining the expected number of D2D users in dedicated and reuse modes. Two algorithms, Round Robin and Max signal-to-interference-plus-noise ratio, were used for estimating throughput. Analytical model results closely aligned with simulations and demonstrated that the analytical model is accurate and time efficient.

5.2 Introduction and Related Work

Our current cellular network architecture requires an update to support increasing demands of ever growing data volume and higher rate requirements. Device-to-device (D2D) communication is considered a possible contender, having been designed to support such impending demands. This technology allows information exchange for nearby users without generating traffic via base stations [11]. D2D users can leverage three modes of communication: 1) Cellular mode (CM), in which users communicate through base stations; 2) Dedicated mode (DM), in which users are assigned free channels; and 3) Reuse mode (RS), in which users share channels with cellular users during downlink or uplink transmission [10].

Throughput is defined as a key performance indicator (KPI) for cellular networks and can be improved by means of increasing bandwidth, maximizing number of users/resource block (RB), and/or enhancing user $SINR$. D2D communication increases network throughput in two ways: 1) allowing additional users to communicate in a given bandwidth and 2) achieving higher $SINR$ due to short range communication. In spite of potential advantages, the integration of D2D into cellular architecture has imposed changes in LTE system design. Since D2D users can be scheduled by either 1) allocating free RB (DM mode) or 2) sharing RBs with cellular users (RS mode), LTE scheduler serves as a primary entity requiring a redesign to account for D2D communication. In each TTI in LTE system, Evolved Node B (eNB) schedules users based on admission control (AC), as well as the number of RBs required to accommodate and maintain users' QoS. Then, a scheduling algorithm allocates radio resources to active users based on a specific metric (e.g, $SINR$, fairness). In LTE system, the smallest unit allocated to a scheduled user is one RB every TTI. In the time domain, an RB includes a one-time slot of 0.5 ms duration, and each slot consists of seven orthogonal frequency division multiplexing symbols, where two slots is one TTI (scheduling time). In the frequency domain, an RB can be characterized as 180 kHz bandwidth, divided into 12 consecutive sub-carriers with bandwidth of 15 kHz [88].

Simulation models require a significant amount of time to obtain credible results. Analytical models, on the other hand, can be used to study network behavior over a long period of time, making them increasingly more effective than simulation models for evaluating network performance. Continuous-Time Markov Chain (CTMC) has been utilized as one such analytical model for studying complex communication systems.

An analytical model for LTE has been developed to estimate cell throughput based on multidimensional CTMC [89]. In this research, the model studied the impact of time varying capacity on an AC algorithm, albeit a simple and unrealistic radio scheduler.

In [90], an analytical model based on two dimensional 2D-CTMC with dynamic scheduling and semi persistent scheduling (SPS) was proposed for LTE system. This model represented a number of active cellular users for voice and data traffic and was used to calculate the number of idle RBs in each TTI. The authors proposed reserving idle RBs in the LTE system to supporting vehicle safety services in vehicular ad hoc networks (VANET). Results demonstrated that the reliability of safety application improved by borrowing limited LTE bandwidth. Analytical models for LTE radio scheduler were proposed for single- and two-traffic classes in [91]. Models were based on CTMC and utilized various LTE Time Domain Schedulers (TDS).

D2D handover management was modeled in [92] using a two-stage open queuing network and multidimensional Markov Chain. The model was used to evaluate the handover performance (e.g., blocking and successful handover probabilities) of D2D pairs, whereas a Reference Point Group Mobility (RPGM) model was considered for D2D users.

In [93], a dynamic spectrum-access scheme for cellular and D2D communication based on the CTMC model with both queuing and non-queuing cases was proposed to improve overall capacity. The access scheme ensured that spectrum access for cellular and D2D users was coordinated via designing optimal spectrum access Probabilities for D2D and cellular users.

5.3 System and Analytical Model

5.3.1 *System Model*

In this work, a network with one base station (MB)was considered during downlink transmission. Cellular users and D2D users were served under eNB control. The set of DL RBs is indicated as $K = \{1, 2, ...k\}$. At each TTI, the scheduler allocated RBs to N users selected from active cellular and D2D users. D2D users are assigned free RBs when available. In the event that all RBs were allocated for cellular users, D2D users shared RBs with scheduled cellular users. Allocation of RBs is assumed to perform in a centralized manner, and controlled by eNB. For simplicity the following assumption is considered, one RB was allocated to each user for every TTI. This model can be generalized for a different number of RB assignments based on quality of services (QoS) requirements.

Based on Shannon Theory [94], throughput of D2D user assigned free RBs is defined as T_d^1 in DM mode and as T_d^2 in RS mode.

$$T_d^1 = w_B \log_2 \left(1 + \frac{P_d G_{dd}}{N_0}\right) \tag{5.1a}$$

$$T_d^2 = w_B \log_2 \left(1 + \frac{P_d G_{dd}}{P_0 G_{0d} + N_0}\right) \tag{5.1b}$$

Where G_{dd} is channel gain between D2D transmitter and D2D receiver; P_d represents power of D2D transmitter. G_{0d} is channel gain between MB and D2D receiver.

Cellular user throughput in DL is defined as T_c^1 given that cellular user does not share an RB with D2D user, and as T_c^2 given that the cellular user shares RB with D2D user.

$$T_c^1 = w_B \log_2 \left(1 + \frac{P_0 G_{0c}}{N_0}\right) \tag{5.2a}$$

$$T_c^2 = w_B \log_2 \left(1 + \frac{P_0 G_{0c}}{P_d G_{dc} + N_0}\right) \tag{5.2b}$$

P_0 defines BS power; and G_{dc} Channel gain between D2D transmitter and cellular user.

5.3.2 *Analytical Model*

Without loss of generality, the following assumptions were made.

1. Cellular and D2D user arrivals are a Poisson process with arrival rates (λ_c) and (λ_d), and with departure rates (μ_c) and(μ_d), respectively.

2. User inter-arrival times are independent and follow exponential distribution $exp(\frac{1}{\lambda_c})$ and $exp(\frac{1}{\lambda_d})$ for cellular and D2D users, respectively .

3. Scheduling times τ_c and τ_d for D2D and cellular users are independent exponential random variables with mean $(\frac{1}{\mu_c})$ and $(\frac{1}{\mu_d})$, respectively.

4. No two users could arrive or depart at exactly the same time. This assumption is justified for independent Poisson processes.

Based on these assumptions, total number of scheduled users at each TTI can be modeled by the stochastic process $X\left(t\right) = \left(X_D(t), Xc(t), t \geq 0\right)$ where $X_D(t)$ is the number of D2D users and $X_C(t)$ is the number of cellular users scheduled at time (t). The process $\{X(t), t \geq 0\}$ is a homogeneous 2D-CTMC of birth-death type with finite state space $S = \{(i, j)\,; 0 \leq i \leq k, 0 \leq j \leq k\}$. Thus, the 2D-CTMC model is composed of $(k+1)^2$ states.

Scheduler state is described by a 2D state (i, j), where i represents the number of scheduled D2D users and j represents the number of scheduled cellular users at time t. Transition from state (i, j) to state $(i+1, j)$ indicates that an additional D2D user was allocated an RB by the scheduler. Transition (i, j) to state $(i-1, j)$ indicates that its communication ended and no longer needed an RB. The state transition rate diagram of 2D-CTMC for LTE system of k RBs is shown in Fig.5.1, where arrival rates are state independent and departure rates are state dependent.

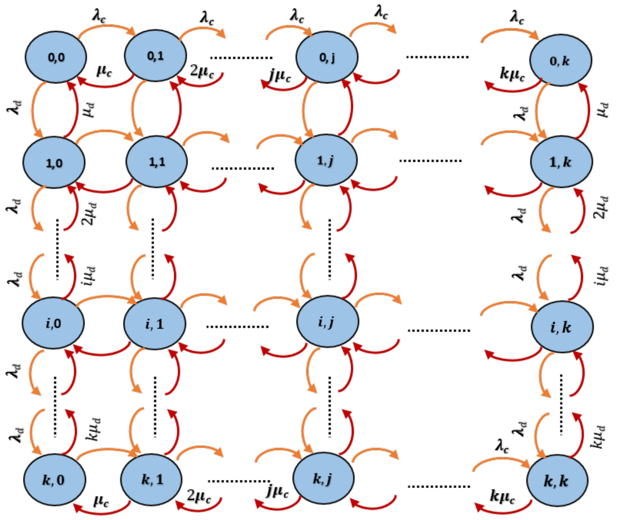


Fig. 5.1: State transition rate diagram of 2D-CTMC

5.4 Transient Analysis

The dynamic behavior of the 2D-CTMC model can be described by Kolmogorov differential equations, which are system of ordinary differential equations governing behaviors of probabilities Pij(t). Equation (5.3) provides the matrix notation of the Kolmogorov differential equations.

$$P^{'}(t) = P(t)Q \tag{5.3}$$

To provide context to the analysis presented in this section, 2D-CTMC states were labeled in S state space from 1 through $(k+1)^2$, where $1 \leq i \leq (k+1)^2$. Hence, the symbol i and j represent index of the state, not the number of the scheduled users.

Rate matrix $R = [r_{ij}]$ for 2D-CTMC can be found, wherein row elements are rate out from state i to other states j, and diagonal elements r_{ii} equal zero.

Consequently, infinitesimal generator matrix $Q = [q_{ij}]$ that represented 2D-CTMC model can be obtained, given element $q_{ij} = r_{ij}$ and its diagonal elements $q_{ii} = \sum_{j=1}^{(k+1)^2} rij$.

The system of differential equations (5.3) can be solved, and the transition matrix $P(t) = [P_{ij}(t)]$. $P_{ij}(t)$ defines transition probability from state i to j at time t, which can be obtained by equation (5.4) using the uniformization method [95]. Summation of infinite series is truncated to M terms, and accuracy error is calculated by ϵ= 0.00001 in the uniformization algorithm given in [95].

$$P(t) = e^{tQ} = \sum_{k=0}^{\infty} e^{-\beta t} \frac{\beta t^k}{k!} \widehat{P}^k \tag{5.4}$$

where $\beta = \max_i |q_{ii}|$ is a uniform rate parameter, and $\widehat{P}$ probability transition matrix is given as

$$\widehat{P} = I + \frac{Q}{\beta} \tag{5.5}$$

5.4.1 *LTE Scheduler Next State Predication and Throughput Estimation*

During TTI, scheduler remains in a single state. Hence, LTE scheduler next state predication can be found based on computing transition matrix $P(t)$ for a duration of one TTI (t=1msec) given initial state of scheduler S_0 at (t=0). Equation (5.6) is used to predicate the next state for L period of time.

$$S(t+1) = P(t) * S(t), \quad 0 \leq t \leq L \tag{5.6}$$

The next state of scheduler defines as the state with maximum transition probability from the current state. S(t) is a column vector of $(k+1)^2 \times 1$, whose elements are zeros expect for one element corresponding to the index of the next state that is set to one.

Based on the next state predication, estimation throughput for L duration can be computed as total bits transmitted per unit of time (e.g., one frame).

$$T_L = \frac{\sum_{t=1}^{L} \sum_{k=1}^{k} T_k^t}{L} \tag{5.7}$$

where T_k^t denotes throughput on k^{th} RB at time (t) and L denotes period of time. T_L represents achieved throughput by scheduled users during L period of time.

5.5 Steady State Distribution Analysis

Scheduler long term behavior can be explained by determining the steady state distribution of the 2D-CTMC model. Let $\pi(i,j) := P(X_D = i, X_C = j)$, defined as

$$\pi(i,i) = \lim_{t \to \infty} Pr(X(t) = (i,j)) \tag{5.8}$$

The balance equations of 2D-CTMC model shown in Fig 5.1 are found by equating the rates of flow into and out of each state. Balance equations for the proposed model are listed in(5.9a) - (5.9h). For notational convenience, the row vector of steady state probabilities can be written as:

$\pi = [\pi(0,0), \pi(1,0), ...\pi(i,j), ..., \pi(k,k)]$.

$$\mu_d\pi(1,0)+\mu_c\pi(0,1)=(\lambda_d+\lambda_c)\pi(0,0), i=0, j=0 \tag{5.9a}$$

$$\lambda_d\pi(i-1,0)+(i+1)\mu_d\pi(i+1,0)+\mu_c\pi(i,1)=(i\mu_d+\lambda_d+\lambda_c)\pi(i,0)$$
$$,0<i\leq k, j=0, \quad \lambda_d=0, \mu_d=0, i=k \tag{5.9b}$$

$$\lambda_c\pi(0,j-1)+\mu_d\pi(1,j)=(j\mu_c+\lambda_d)\pi(0,j), \quad i=0, j=k \tag{5.9c}$$

$$\lambda_d\pi(i-1,j)+\lambda_c\pi(i,j-1)=(i\mu_d+j\mu_c)\pi(k,k), \quad i=j=k \tag{5.9d}$$

$$\lambda_d\pi(i-1,j)+\lambda_c\pi(i,j-1)+(i+1)\mu_d\pi(i+1,j)=(j\mu_c+i\mu_d+\lambda_d)\pi(i,j)$$
$$, \quad 0<i<k, j=k \tag{5.9e}$$

$$\lambda_d\pi(i-1,j)+\lambda_c\pi(i,j-1)+(i+1)\mu_d\pi(i+1,j)+(j+1)\mu_c\pi(i,j+1)$$
$$=(\lambda_d+\lambda_c+j\mu_c+i\mu_d)\pi(i,j), \quad 0<i,j<k \tag{5.9f}$$

$$\lambda_c\pi(i,j-1)+(i+1)\mu_d\pi(i+1,j)+(j+1)\mu_c\pi(i,j+1) \tag{5.9g}$$
$$=(\lambda_d+\lambda_c+j\mu_c)\pi(i,j)$$
$$, \quad i=0, 0<j<k$$

$$\lambda_c\pi(i,j-1)+\lambda_d\pi(i-1,j)+(j+1)\mu_c\pi(i,j+1)$$
$$=(\lambda_c+i\mu_d+j\mu_c)\pi(i,j), \quad i=k, 0<j<k \tag{5.9h}$$

The normalization is provided by

$$\sum_{i=0}^{i=k}\sum_{j=0}^{j=k}\pi(i,j)=1 \tag{5.10}$$

The closed form solution of steady state probabilities can be obtained by solving the system of balance equations (5.9a)-(5.9h), using the recursive substitution method [96]. Thus, steady state probabilities of 2D-CTMC (i.e., the probabilities that there are $i+j$ users in LTE scheduler) can be computed using eq. (5.11a) to eq (5.11d), where $\rho^c = \frac{\lambda_c}{\mu_c}$ and $\rho^d = \frac{\lambda_d}{\mu_d}$. Additionally, the 2D-CTMC model is demonstrated by the SHARP software package [97], and steady state solution can be found using a numerical method.

$$\pi(0,0) = \frac{1}{1+\sum_{i=1}^{k}\frac{\rho_d^i}{i!}+\sum_{j=1}^{k}\frac{\rho_c^j}{j!}+\sum_{j=1}^{k}\sum_{i=1}^{k}\frac{\rho_d^i}{i!}\frac{\rho_c^j}{j!}} \tag{5.11a}$$

$$\pi(i,0) = \frac{\rho_d^i}{i!}\pi(0,0) \tag{5.11b}$$

$$\pi(0,j) = \frac{\rho_c^j}{j!}\pi(0,0) \tag{5.11c}$$

$$\pi(i,j) = \frac{\rho_d^i}{i!}\frac{\rho_c^j}{j!}\pi(0,0) \tag{5.11d}$$

5.5.1 *Performance Evaluation*

Once steady state probabilities vector π is determined, the network performance metric can be found. Overall long term throughput is given by (5.12).

$$T = \sum_{i=1}^{k}\sum_{j=1}^{k}\pi(i,j)\bar{T}(i,j) \tag{5.12}$$

where $\bar{T}(i,j)$ is the average throughput obtained by users in state $\pi(i,j)$.

An expected number of D2D users in LTE scheduler can be calculated by (5.13a). Average number of users operated in dedicated mode (DM) mode and reuse mode (RS) are determined using equations (5.13b) and (5.13c), respectively.

$$\bar{N}_D = \sum_{i=1}^{k} \sum_{j=1}^{k} i\pi(i,j) \tag{5.13a}$$

$$\bar{N}_{DM} = \sum_{i=0, i \leq \{k-j\}}^{k} i\pi(i,j) + \sum_{i > k-j}^{k} (k-j)\pi(i,j) \tag{5.13b}$$

$$\bar{N}_{RS} = \sum_{i \geq \{k-j\}}^{k} (i-(k-j))\pi(i,j) \tag{5.13c}$$

5.6 Numerical Results

A single cell of 1000 m radius and a macro BS located at the center was considered. Two hundred pair of D2D users and 200 cellular users were randomly distributed within the coverage of a macro cell. D2D transmitter power was set to 23 dBm. For simplicity, LTE system of 3 MHz bandwidth is considered, where bandwidth is divided into 6 RBs. When D2D users shared RBs with cellular users, the Hungarian assignment algorithm was implemented to match D2D users with their cellular counterparts. To maximize cellular user SINR, Hungarian assignment cost was formulated to minimize interference from D2D users to cellular users. Fig 5.2 illustrates the 2D-CTMC model of the scheduler. Blue indicates scheduler state, where D2D users are allocated free channels and operate in DM mode. Yellow indicates mixed states, where some of D2D users allocated free RBs and others shared RBs with cellular users. Green indicates full reuse state with RBs allocated to cellular users. Gray indicates the state in which cellular users are scheduled, given that no D2D users arrived.

Three values for $\lambda_c = \{2, 4, 6\}$ were considered to represent low, medium, and high cellular traffic, respectively. D2D arrival rate changed from $\lambda_d = 0$ users /TTI to $\lambda_d = 10$ users /TTI. Service rates μ_d and μ_c for D2D users and cellular are equal to one user/TTI for all cases.

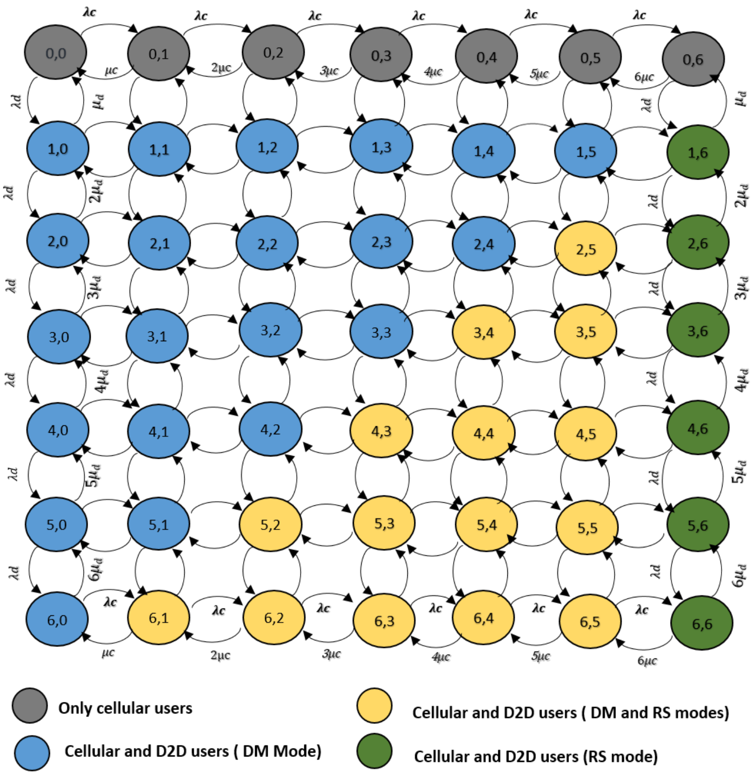
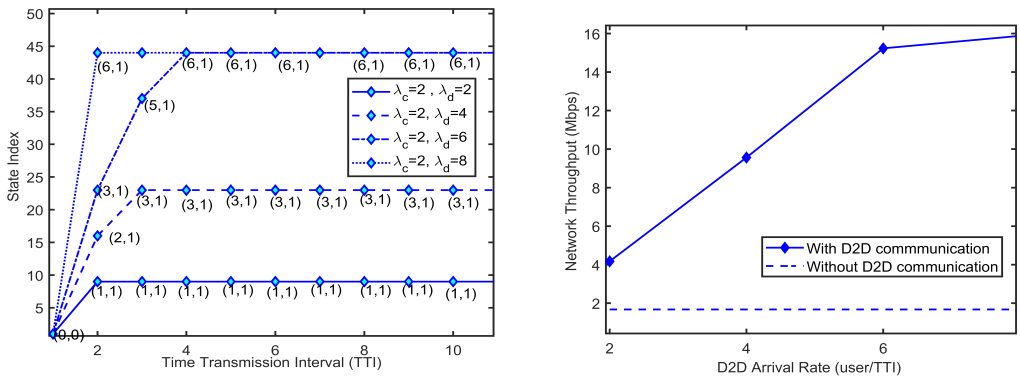


Fig. 5.2: State transition rate diagram of 2-D CTMC k=6RBs

5.6.1 *Scheduler Next State Prediction and Throughput Calculation*

The next scheduler state prediction for a duration of one frame ($L = 10 \quad msec$) is displayed in Figures 5.3a, 5.4a, and 5.5a for $\lambda_c = \{2, 4, 6\}$, respectively. P(t) was computed for one TTI (t=1 msec), and initial states of scheduler S(0) at ($t = 0$) was assumed $\pi(0, 0)$. Figures 5.3b, 5.4b, and 5.5b show throughput based on state predication for cellular arrival $\lambda_c = \{2, 4, 6\}$, respectively. In each case, throughput was averaged over one frame period. Throughput with D2D communication was compared to network throughput without D2D communication (dotted line) when arrival λ_d equals zero.

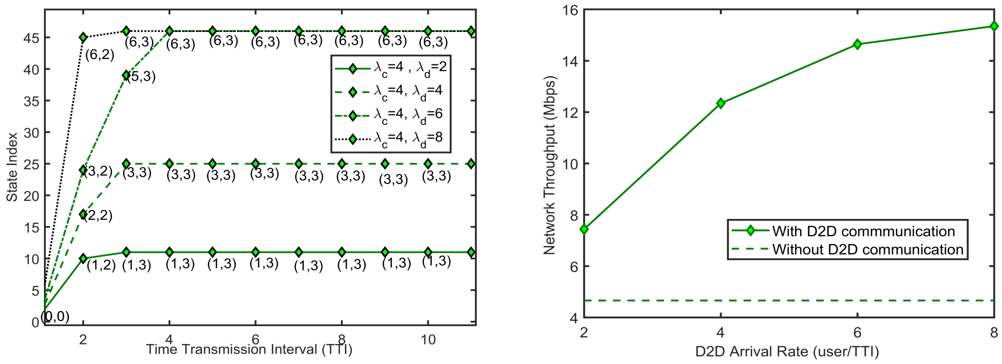
Significant throughput improvement was obtained when the cellular arrival rate was low. The rate contributed by cellular to throughput is low; therefore, adding D2D users (increasing λ_d) causes a large increase in throughput. Most RBs were not assigned to cellular users causing of increasing probability of DM (blue) states. Scheduler sojourn is typically blue, as shown in Fig. 5.3a. Incoming D2D users were assigned free channel and achieved high throughput as illustrated in Fig.5.3b.



(a) (b)

Fig. 5.3: (a) Next state predication (b) Throughput/Frame ($\lambda_c = 2$)

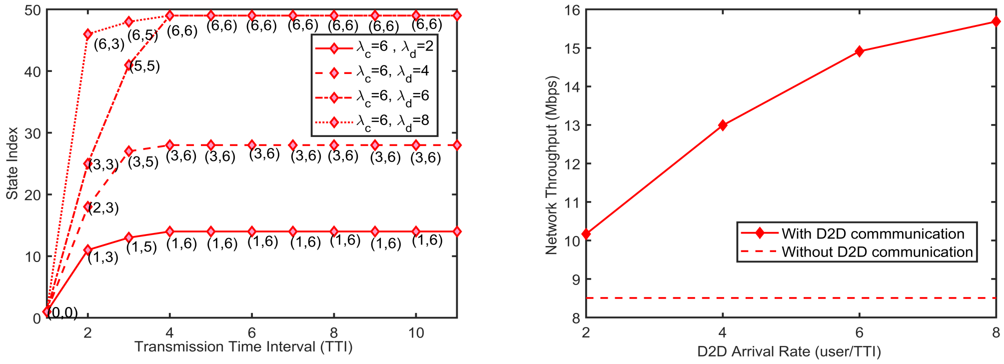
Figure 5.4b draws throughput based on predicted states (See Fig 5.4a) for $\lambda_c = 4$. An average number of cellular users in scheduler was equal to three users /TTI over time. The first two points in the throughput graph detail estimated throughput with a low D2D user arrival rate. Next states was estimated as blue states (DM mode). When D2D arrival rate increased, the scheduler transitioned from DM states (blue) to mixed states (yellow) with some D2D-allocated free RBs and others shared RBs. Given that the scheduler remained in mixed states most of the time, throughput improvement declined.



(a) (b)

Fig. 5.4: (a) Next state predication (b) Throughput/Frame ($\lambda_c = 4$)

Figure5.5a illustrates state predication when high cellular traffic $\lambda_c = 6$ users /TTI arrived. The scheduler remained in RS states (green) most of the time, wherein D2D users shared *RBs* with cellular users. Although the number of scheduled D2D increased with rising D2D arrival rate, the throughput achieved per link (cellular or D2D) decreased, primarily due to co-channel interference. Generally, throughput is saturated given user arrival rate is more than 6 users /TTI.



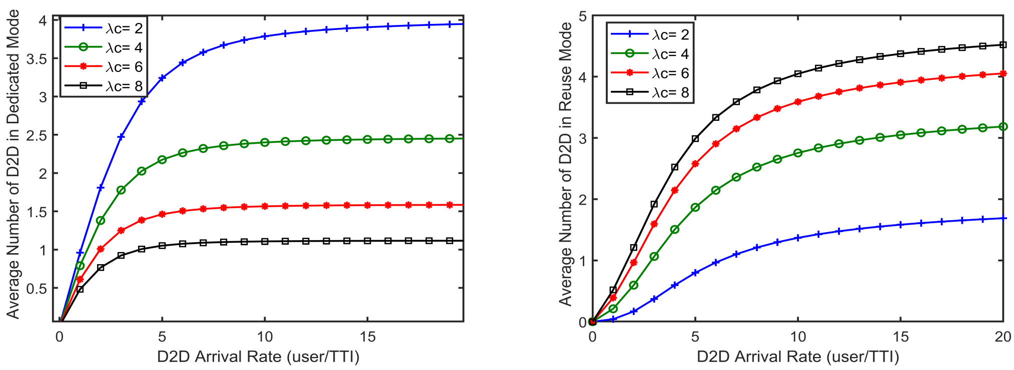
(a) (b)

Fig. 5.5: (a) Next state predication (b) Throughput/Frame ($\lambda_c = 6$)

5.6.2 Steady State Performance

1. **Expected number of D2D users in DM mode and RS mode**

   Based on steady-state distribution of the 2D-CTMC model, the expected number of D2D users in DM and RS modes were calculated (See Fig 5.6). Number of scheduled D2D users increased as D2D user arrival rate increased, albeit the change was limited by the number of RBs in the system. The blue line shows average number of D2D users when cellular arrival rate is $\lambda_c = 2$ users/TTI. Expected number of D2D users in DM mode was notably large when compared with D2D users in RS mode as a result of free RBs availability. As cellular user arrival rate increased and more cellular users were scheduled, average number of D2D users in DM mode declined. Also, average number of D2D users in RS mode increased.



(a) (b)

Fig. 5.6: Expected number of D2D users (a) DM Mode (b) RS Mode

2. **Long Term Network Throughput**

   Network throughput was evaluated using analytical and simulation models. Two scheduling algorithms (e.g., Round Robin [RR]and Maximum

Throughput[Max-T]) were used for cellular and D2D users. Separation distances between D2D transmitter and its receiver simulated 50m and 100m, respectively.

- RR scheduling: users were assigned sequentially without taking channel conditions into consideration.
- Max-T scheduling: users were assigned according to highest SINR.

Figure (5.7) presents results of RR and Max-T algorithms at separation distances 50m and 100m at $\lambda_c = 2$. Results were matched when D2D user arrival rate was less than three users/TTI, as all active users were scheduled in both algorithms. When λ_d exceeded 4 users/TTI, Max-T throughput outperformed RR algorithm, primarily because users with the highest SINR were scheduled by Max-T and RR did not consider SINR. On average, the Max-T algorithm surpassed the RR algorithm by nearly 800 kbps and 300 kbps for separation distances of 50m and 100m, respectively. Network throughput with D2D communication was improved by a factor ranging from 1.5 to 4 when separation distance was 50m. When separation distance increased to 100m, gain factor was improved 0.8 to 3.8 times as a result of changing λ_d = 1:10 users/TTI.

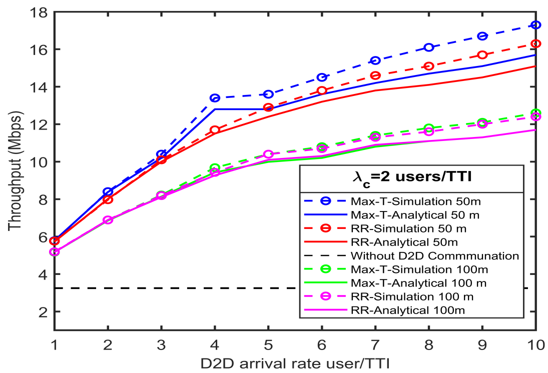


Fig. 5.7: Network throughput $\lambda_c = 2$ user/TTI

Figure 5.8 shows network throughput for $\lambda_c = 4$. Increasing the number of cellular users caused more D2D users to operate in RS mode. Overall throughput decreased by nearly 2 Mbps, as one can see when comparing results with Figure 5.7. Max-T outperformed RR results in both 50m and 100m separation distances. Figure 5.9 details achieved gain when arrival rate was 6 users/TTI. All RBs assigned to cellular and incoming D2D user operated in RS. Network throughput gain was very small compared to the gain when cellular arrival was 2 and 4 users/TTI. Network throughput increased by nearly 4.256 Mbps and 2.36 Mbps for D2D separation distance of 50m and 100m, respectively.

Overall, both scheduling algorithm and D2D user mode impacted network throughput. When most of D2D users scheduled on free RBs, RR algorithm results were very close to Max-T result, since all users have similar average SINR. However, when cellular user arrival increased, D2D users in RS mode experienced low SINR. As such, the Max-T algorithm outperformed RR. Max-T chose users with the highest SINR from among active users, while RR assigned RBs without considering SINR.

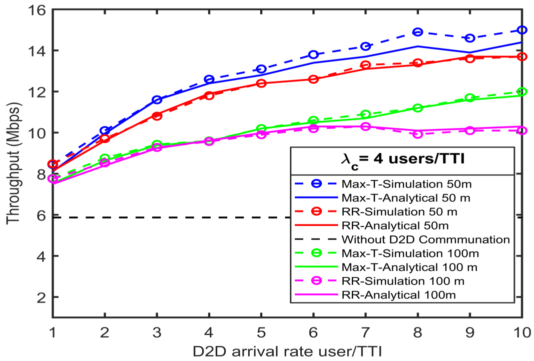


Fig. 5.8: Network throughput $\lambda_c = 4$ user/TTI

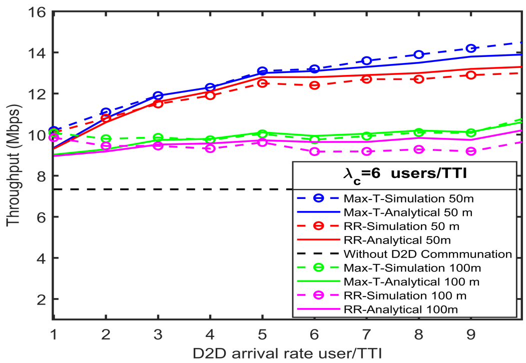


Fig. 5.9: Network throughput $\lambda_c = 6$ user/TTI

5.7 Conclusion

An analytical model based on 2D-CTMC for LTE scheduler with D2D communication was proposed in this work, and a closed form solution of the steady state probabilities were found. Overall network throughput was computed for various scheduling algorithms, and network performance differed accordingly. Although simulation and analytical results were comparable, the analytical model proved accurate and more time efficient. This model can be used to estimate cellular network throughput with D2D communication as well as number of D2D users in each mode. The proposed LTE scheduler model can serve as a building block for analyzing and designing an LTE system with D2D communication. Moreover, It can be used to select an appropriate scheduling algorithm based on cellular traffic and D2D user modes.

CHAPTER 6

Conclusions and Future work

6.1 Conclusions

The integration of D2D communication under HeNets is a promising solution for supporting the increasing demands of subscribers traffic and for enhancing the performance of the next generation cellular network. Allowing direct communication between proximal users improves performance metrics, such as end-to-end latency, energy consumption, and spectral efficiency.

This dissertation addresses some of D2D communication challenges introduced into a cellular network. The main contributions of this work are discoveries about mode selection, resources, and power allocation. Efficient D2D resource allocation resulted in a significant gain in HetNets throughput without degrading cellular connection performance. Furthermore, a comprehensive framework for energy-efficient D2D communication was established, the optimization problem is NP-hard and extremely difficult to solve. To remedy this, an instantaneous network load was utilized to simplify the optimization problem, and different optimization approaches were applied. An optimal solution with low computational complexity was achieved in low load networks, revealing that the proposed solution complexity increased as an increasing number of D2D users operated in reuse mode. An analytical model for LTE scheduler with D2D communication was also developed in this work. Steady state probabilities for scheduler were derived, and average numbers of D2D users in dedicated and reuse modes were calculated. Furthermore, the accuracy of our the analytical model was validated by simulation results.

6.2 Future Work

Possible extensions of the work presented in this dissertation propose interesting research. For example, investigations in Chapters 3 and 4 considered a single-cell scenario, neglecting the impact of interference from neighboring cells. It would be worthwhile to investigate multiple cell scenarios, as well. Furthermore, the contribution of this work was based on DL reuse. One logical extension would be investigating the performance of the proposed solutions in UL reuse. Also, this dissertation neglected the effect of fast fading on channel models, even though such information can be obtained given different channel models. Finally, regarding a dynamic mode selection scheme such as the one described in Chapter 4, it would be interesting to consider additional features (e.g., user locations, mobility). Finally, machine learning is a powerful tool in solving 5G network problems. It will be interesting to apply machine learning for D2D communication under HetNets. For example, clustering algorithms can be applied for user association of HetNets with D2D communication, and reinforcement learning can be used when channel state information is unknown for mode selection and resources allocation.

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