Chapter 15
Resource Allocation in D2D Communications

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Abstract The proliferation of mobile devices and data-hungry applications running on them leads to a massive growth of wireless data traffic. Supporting this ever-increasing data demands and communication rate requires reconsideration of the existing cellular network architecture. Device-to-device (D2D) communications, which allow two mobile devices in the proximity to communicate with each other, emerge as a potential solution to this challenge. It provides multifold gains in terms of transmission-rate gain, frequency-reuse gain, coverage-gain, and hop-gain. However, extensive deployment of D2D communications in the cellular networks poses several intrinsic challenges, such as severe interference to the primary cellular users, rapid battery depletion of D2D transmitters in relaying scenarios. Therefore, this chapter discusses various challenges in supporting D2D communications. It then surveys various existing resource allocation schemes to address these challenges. It also provides the achievable performance over different fading channels and computational complexity of the power allocation schemes.

Keywords 5G communication · D2D communication · LTE-A · Interference management · Resource allocation

15.1 Introduction

Owing to the unprecedented growth in the number of mobile users, the next generation of wireless networks, referred to as the fifth generation (5G), are envisaged to support enormous number of simultaneously connected users with access to numer-

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ous services and applications. The CISCO's latest visual network index (VNI) report forecasts that by 2021, the mobile users traffic will account for 71 % of the total IP traffic, and 82 % of it is video traffic (Index 2019). Media-rich applications such as 3D holography, high-definition video streaming, and cloud-based networking which require high data rate, and delay sensitive applications such as two-way gaming and tactile Internet (e.g., Google glass) (Fettweis 2014) which require a round-trip latency of about 1 ms cannot be supported by existing 4G networks. In summary, providing data at high rate and low latency to high number of users is a daunting challenge facing telecom researchers, service provider, and policymakers.

To cope up with these intense data demands of users, D2D communication, which allows proximate mobile users to communicate, has gained momentum as a prominent solution (Gamage and Shen 2018; Sobhi-Givi et al. 2018). However, despite having significant potential for providing higher throughput (Kai et al. 2019) and lower delay (Mi et al. 2015), implementing D2D communication poses several intrinsic challenges. For example, mutual interference among cellular users (CUs) and D2D users may deteriorate the performance of the network, and signaling overhead to set up D2D links. In order to address these issues, in this chapter, we study the resource allocation schemes where D2D users may share the cellular users channels.

Depending upon their frequency allocation, the operation of D2D communication can be divided into two parts: inband (Feng et al. 2013) and outband (Gui and Zhou 2018) D2D communication. In the inband communication, D2D users are allowed to share the channels allocated to the primary CU users with QoS control from the BS. While in outband communication, D2D users communicate on different frequency bands, such as ISM band, and may operate without any control of the BS. Specifically, inband D2D communication can be realized using two spectrum sharing techniques: underlay (Lee and Lee 2019; Zhang et al. 2018a) and overlay (Kazeminia et al. 2019). In underlay D2D communication, the D2D users are allowed to share the channels allocated to the CUs; however, the interference created to the CUs should be below certain thresholds. While in overlay communication, a dedicated part of the cellular radio resources is allocated to D2D communication, but the resource allocation is supposed to be done efficiently so that dedicated cellular resources are not underutilized (Zhao et al. 2017). The above-mentioned different ways of allocating the frequency channels to the D2D users are depicted in Fig. 15.1.

Recent surveys on D2D communication (Asadi et al. 2014; Mach et al. 2015) evaluate the state-of-the-art research activities and present various research challenges, such as spectrum management, links scheduling, interference handling, and resource allocation. Furthermore, many research works have been done to standardize the integration of D2D communication in LTE networks (Lien et al. 2016). In addition with academia, standardization efforts have been taken by many industries and standardization bodies, such as Qualcomm and 3GPP. The first architecture to implement D2D communication underlaying cellular networks is provided by Qualcomm's FlashLinQ (Wu et al. 2013). The 3GPP provides an analysis on the feasibility of proximity services (ProSe) and proposed the required architectural enhancement to accommodate the D2D use cases in LTE (Lin et al. 2014a). Furthermore, the 3GPP release-12 includes the ProSE as a public safety feature with specific focus on one

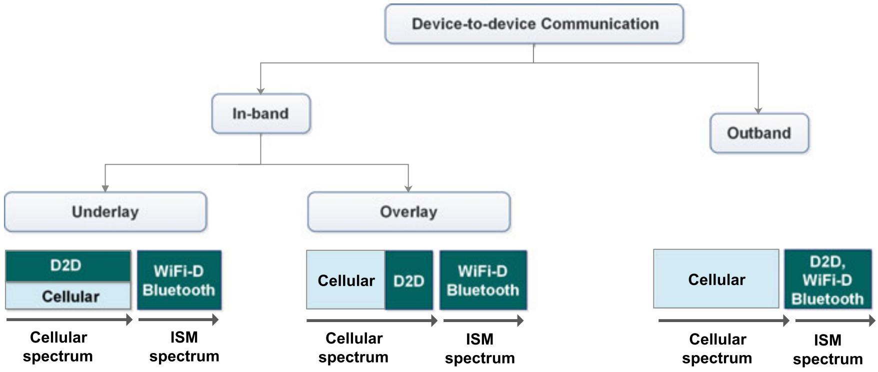

Fig. 15.1 Different ways to allocate frequency channels to D2D communication

to many communication scenarios (Lin et al. 2014a). In next section, we address the challenges in designing of optimal resource allocation schemes.

Chapter Outline: The remaining of this chapter is structured as follows:

- Section 15.2 provides a brief overview of the challenges in the designing of an optimal resource allocation schemes for D2D-enabled cellular networks.
- Section 15.3 provides the classification of the existing resource allocation schemes based on the challenge they are addressing.
- Section 15.4 provides an example of the resource allocation scheme with an objective of sum-throughput maximization.
- Finally, Section 15.5 provides concluding remarks along with some of the possible future works.

The acronyms used in this chapter are listed in Table 15.1.

15.2 Challenges in Resource Allocation for D2D Communication

The integration of D2D communication in current LTE network poses many challenges. In the following, we provide a brief overview of the main challenges in designing of the resource allocation schemes for D2D communication in cellular networks.

Spectrum sharing and interference management: Due to limited spectrum available for the cellular communication, buying additional licensed band to enable D2D communication is not a feasible solution. Therefore, the allocation of spectrum should be done judiciously, and efficient interference avoidance mechanisms should be provided if the spectrum reuse factor is greater than one. Specifically for the scenarios where D2D users share the channels with cellular users (the underlay approach),

Table 15.1 List of acronyms

ASE	Area spectral efficiency
BS	Base station
CSI	Channel state information
CU	Cellular user
DL	Downlink
EE	Energy efficiency
eNB	Evolved node base station
HetNets	Heterogeneous networks
ISM band	The industrial, scientific, and medical band
LTE	Long-term evolution
MINLP	Mixed-integer nonlinear programming
PPP	Poisson point process
QoS	Quality of service
SE	Spectral efficiency
SINR	Signal-to-interference-plus-noise ratio
SIR	Signal-to-interference ratio
UL	Uplink
VNI	Visual network index

providing efficient interference management techniques is of utmost importance. Depending upon the sharing of uplink or downlink CU channels, D2D users create interference to the CUs, or the CUs create interference to the D2D receivers, respectively. This intra-cell interference created to and from the CUs degrades the system throughput. In fact, because of higher chance of presence of proximate D2D links to the CUs, it can severely decrease the performance of the cellular network. Therefore, to enable underlay D2D communication, the optimal resource allocation schemes in presence of interference are needed.

In order to avoid the mutual interference between the CUs and D2D users, overlay communication can be employed (Kazeminia et al. 2019); however, to avoid any wastage of licensed band, the resource allocation should be done efficiently. Besides, in outband D2D communications, the interference is completely eliminated, however, the mobile device should be multi-homed. Further, it decreases the network control over D2D communications, and consequently reliability of the links. In additions, D2D communications need to consider the interference and adapt accordingly to other technologies operating in the same unlicensed band.

Spectral and energy efficiency trade-off: Spectral efficiency (SE) which is defined as achievable sum throughout per unit of bandwidth is one of the most prominent parameter in designing of current cellular networks. In D2D integrated cellular networks, SE is majorly increased by supporting more number of D2D users on a single frequency channel. With proliferation of data-hungry applications running on the mobile devices, there is staggering increase in the power consumption of the wireless networks. Therefore, energy efficiency (EE) which measures how efficiently available transmission power is used for data communication is also becoming an important parameter in cellular network design. Ideally, the resource allocation schemes are needed to be designed in such a way that both the parameters are maximized simultaneously. However, often conflicting nature of these parameters hinders the maximization of both in a network. Therefore, it is imperative to provide resource allocation schemes which provide a good trade-off between spectral efficiency and energy efficiency.

Optimal performance, computational complexity, and signaling trade-off: For improving the performance of D2D-enabled cellular networks, resource allocation schemes need to solve the complex optimization problems that are non-convex and combinatorial in nature. In many cases, these optimization problems turn out to be NP-hard, which are intractable in nature, and have exponential time complexity. Thus, they are not manageable for large-scale networks. In addition, optimal solution often leverages the full channel state information (CSI) of all involved links, and in practical large cellular networks providing full CSI to all the users all the time is not a feasible solution. Therefore, the challenges in designing an optimal resource allocation scheme consist of finding a good trade-off between optimality and applicability, centralized versus distributed, and joint versus separate optimization solutions.

15.3 Classification of Existing Schemes for D2D Communication

In this section, we classify the existing resource allocation schemes based on the challenge or the objective of the formulated problem in D2D communication they are addressing.

15.3.1 Sum-Throughput Maximization

Most of the previous works on D2D communication formulate a joint channel and power allocation problem with an objective of sum-throughput maximization and ensure a certain level of QoS to the CUs and the D2D users by imposing a SINR threshold on both type of users.

The work of Ye et al. (2014) formulates a sum-throughput maximization problem for D2D-enabled cellular networks. The system model consists of a single BS, with the CUs and D2D users are distributed as a Poisson point process, and it allows multiple D2D pairs to share the channel with a CU. To solve the formulated problem efficiently, authors reformulate it into a Stackelberg game, and a low-complexity low-overhead distributed algorithm is proposed. Through numerical solutions, it is shown that the proposed scheme increases the system throughput and expeditiously manages the interference created by D2D users to CUs. However, the computational complexity of the proposed iterative algorithm increases exponentially with increase in number of D2D users.

The work of Yin et al. (2015) formulates a joint channel and power allocation problem with an objective of sum-throughput maximization of D2D users. Then, depending upon the availability of CSI at the BS, it provides centralized and distributed solutions for the resource allocation problem. For centralized solution, a successive convex approximation method is proposed, while for distributed solution the formulated problem is remodeled into a Stackelberg game where D2D pairs compete with each other in a noncooperative manner to maximize their individual data rate. The results obtained show that the average system throughput increases significantly with very less signaling overhead in distributed algorithm.

The work of Li et al. (2018) provides a framework to jointly improve the system fairness and throughput in a D2D-enabled underlay cellular network. An optimization problem is formulated to maximize the proportional fairness functions of all the users while considering the fairness and SINR requirement of the CUs and the D2D users. A two-stage joint power control and proportional scheduling algorithm is proposed, which optimally maximize the system throughput along with fairness. However, it only addresses the scenarios where a cellular channel is shared by only one D2D pair which is an underutilization of the spectrum.

The work of Lee and Lee (2019) proposes a joint channel and power allocation problem for maximizing the average achievable rate in a D2D-enabled underlay cellular network. The system model considers more number of D2D pairs than CUs. It derives the expression for outage probability for a CU, and putting it as a constraint, the optimal power allocation problem is solved. Through numerical simulations, it is shown that the provided framework significantly increases the achievable rate of admitted D2D users.

In Cai et al. (2015), authors formulate an overall system capacity maximization problem in a D2D-enabled cellular network. The system model allows multiple D2D pairs to share the single downlink channel. The formulated problem is MINLP, which is NP hard in nature. To solve the problem, authors utilize the graph-coloring approach, where D2D pairs are considered as vertices and the channels of cellular users are considered as a set of colors. The proposed heuristic scheme introduces two areas: interference limited area which identifies those D2D pairs that can transmit on the same channel, and signal-to-interference ratio limited area which identifies those D2D pairs that cannot share the same spectrum. The major limitation is sub-optimal solution at higher computational cost.

In Kai et al. (2019), an optimization problem is formulated with an objective of maximizing the sum-throughput of D2D users while maintaining the certain data rate thresholds to the CUs. The formulated problem turns out to be an instance of MINLP. To solve the formulated problem efficiently, it is decomposed into two sub-problems: sub-carrier assignment and power allocation. In sub-carrier assignment problem, it is assumed that the maximum transmit power of a user is divided equally among all the sub-carrier he is assigned. Then, by exploiting the successive convex approximation technique, the power allocation problem is remodeled into sequence of convex optimization problems. To solve it in an efficient manner, a low-complexity power allocation scheme is proposed. The numerical results show that there is significant gain in sum-rate, however not close to the sum-rate obtained using optimal (exhaustive) approach.

The work of Feng et al. (2013) addresses the problem of mutual interference minimization between CUs and D2D users. It formulates a sum-throughput maximization problem in a D2D-enabled underlay cellular networks where D2D users are sharing the uplink channels with uniformly distributed CUs. The objective of the optimization problem is to allocate the channels and powers to the CUs and the D2D users in order to maximize the sum-throughput of the system, as shown by the Eq. (15.1).

$$\max_{\rho, P_i^c, P_j^d} \left\{ \sum_{i \in C} \sum_{j \in D} [\log_2(1+\gamma_i^c) + \rho_{i,j} \log_2(1+\gamma_j^d)] \right\}, \tag{15.1}$$

where γ_i^c and γ_j^d denotes the SINR for the CUs and D2D users, respectively; $\rho_{i,j} \in \rho$ is a binary variable, and it indicates whether the channel of the ith CU is shared by the jth D2D user or not; variables C and D denote the number of the CUs and D2D users in the cell, respectively. This work also ensures the QoS of both type of users by maintaining SNR above certain thresholds. Since the above problem is again an instance of MINLP, which is hard to solve optimally, authors propose a three step solution: (1) QoS-aware admission control to decide whether a D2D pair is admissible or not, (2) power allocation to admissible D2D users, and (3) channel allocation to a D2D user by utilizing bipartite graph matching technique. Using numerical simulations, it is shown that the sum-throughput and number of D2D users admitted in a cell increases significantly. It compares their proposed scheme with other heuristic (Zulhasnine et al. 2010) and fixed margin scheme (Janis et al. 2009).

Figure 15.2 depicts that the sum-throughput decreases with increase in D2D geographical spread. The reason is as D2D receivers are far from their corresponding D2D transmitters, thus they have low SINR, and consequently lower contribution to the sum-throughput. It can also be observed that the gain in the sum-throughput increases if the channels are considered faded, and the resource allocation schemes are designed accordingly.

In addition to above-mentioned works, there exist many research works which solve the similar objective optimization problem with different approaches. Table 15.2 provides a brief summary of such works.

15.3.2 Spectral Efficiency Maximization

Some of the previous works address the problem of maximizing the spectral efficiency of the D2D-enabled cellular networks, as listed in Table 15.3. These works either tries to increase the number of users sharing the channels, or increase the data transmission rate per unit of bandwidth by adequately managing the interference.

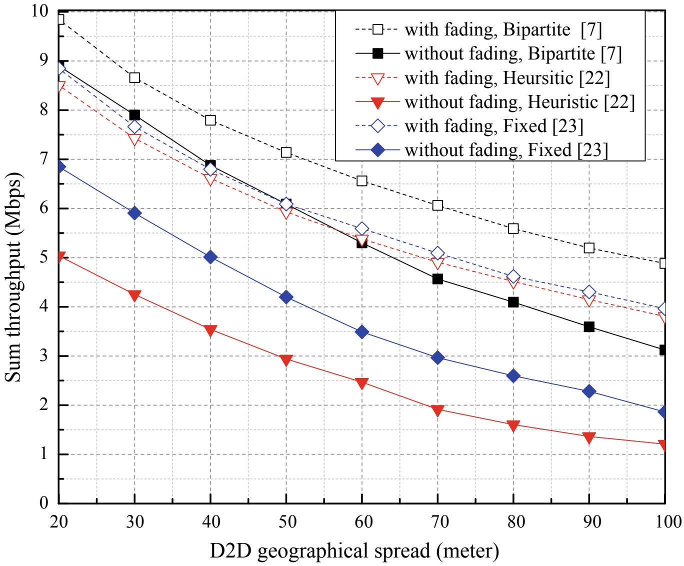

Fig. 15.2 Sum-throughput variation with D2D geographical spread for different power allocation schemes with impact of fading

Table 15.2 Resource allocation schemes for D2D communications that are addressing sum-throughput maximization, N_c is numbers of CUs, and N_D is number of D2D users

References	Spectrum share	Channel sharing direction	Complexity	Analytical tool
Ye et al. (2014)	Underlay	UL	$O(N_D \log_2(\mu_{\max}/\epsilon) + N_D^2 K)$, $K \in [4, 8]$, $\log_2(\mu_{\max}/\epsilon) \in [5, 10]$	Game theory
Yin et al. (2015)	Underlay	UL		Non-convex optimization and Game theory
Li et al. (2018)	Underlay	UL	$O(T * N_c^3)$, T is number of time slots	Graph theory (Hungarian algorithm)
Feng et al. (2013)	Underlay	UL	$O(N_c^3)$, $N_c = N_D$	Graph theory
Lee and Lee (2019)	Underlay	UL	non-trivial to determine	Exhaustive search, Heuristic scheme
Cai et al. (2015)	Underlay	DL	$O(2^{N_D} N_D)$,	Graph coloring theory
Kai et al. (2019)	Underlay	UL	$O((2N_D + N_c)K)$, K denote number of channels	Convex optimization

The work of Mustafa et al. (2014) proposes a three-tier network as a hierarchical heterogeneous networks (HetNet), where D2D communication is enabled as tier-3 network within macro-cell BS (tier-1) and small-cell BS (tier-2). This framework increases the spectral efficiency in terms of percentage of mobile users engage in D2D communication instead of tier-1 and tier-2. The numerical results show that there is significant increase in achievable capacity by hierarchical HetNet in comparison with traditional HetNet where D2D communication is not enabled. It also shows that spectral efficiency increases for D2D-enabled ultra dense networks. The major limitation of this work is the signaling overhead to set up D2D links in HetNets.

Authors in Kim et al. (2018) formulate a joint channel and power allocation problem with an objective of maximizing the spectral efficiency in a D2D-enabled underlay cellular networks. By exploiting the inner approximation method, a low-complexity iterative algorithm is proposed. Using numerical results, it is shown that with increase in transmit power of a D2D user, the average spectral efficiency increases upto a certain level, then it saturates. The limitation of this work is that it always assumes that a channel is shared by maximum one D2D pair, which is an inefficient utilization of spectrum (Table 15.3).

The work of Trigui and Affes (2018) provides an analytical framework to evaluate the CUs and D2D users SINR distributions in general fading scenario. It unifies various fading models by utilizing the H-transform theory. An average area spectral efficiency (ASE) maximization problem is formulated, and the expression for the access probability and the optimal transmit power which maximizes the ASE is derived. Numerical results show that the proposed opportunistic access scheme requires only statistical CSI instead of complete CSI for centralized solution, which leads to less delay in the network. It is also shown that the proposed framework handled all type of complex fading models, such as Weibull, shadowed $\kappa - \mu$.

Table 15.3 Resource allocation schemes for D2D communications that are addressing spectral efficiency maximization, N_c is numbers of CUs, and N_D is number of D2D users

References	Spectrum share	Channel sharing direction	Complexity	Analytical tool
Mustafa et al. (2014)	Overlay and outband	DL/UL	Non-trivial to determine	Heuristic schemes
Kim et al. (2018)	Underlay	UL	$2(N_c * N_D)$	Heuristic and inner approx.
Trigui and Affes (2018)	Underlay	UL	$\mathcal{O}(T * N_c^3)$, T is number of time slots	Hungarian algorithm

15.3.3 Energy Efficiency Maximization

Many research efforts have been put to address the problem of energy efficiency maximization both in cellular networks and D2D-enabled cellular networks. The optimization problem is formulated either to decrease the energy consumption of an individual transmitter or as whole of the system.

The work of Wu et al. (2015) formulates an optimization problem with an objective of maximizing the energy efficiency of D2D users with constraints on minimum data rate supported to each CU and D2D user. To make the system model more practical, it considers circuit power consumption alongside transmit power consumption. Depending upon the D2D users circuit power consumption, three different operative regions are identified, and corresponding power control mechanisms are provided. To make the system more computationally efficient, a distributed power control algorithm is proposed. The numerical results show that the energy efficiency increases significantly by controlling the transmit power of D2D users.

Authors in Della Penda et al. (2016) formulate an energy consumption problem in D2D-enabled cellular networks operating in dynamic time division duplex (TDD) mode. The formulated optimization framework jointly optimizes the mode selection, uplink/downlink transmission period, and transmission power to minimize the energy consumption. It is MINLP, therefore, heuristic schemes are proposed which provide the near-optimal solutions. The results obtained show that significant energy saving can be achieved by synergy of better channel gains of D2D links and the adaptive transmission time of dynamic TDD.

In Zhao et al. (2016), the authors formulate a mixed-integer optimization problem with an objective of minimizing the energy consumption in D2D underlay cellular networks. A more realistic scenario is considered where multiple D2D pairs are sharing the channel with cellular users, and they are moving within cells. By exploiting the dynamic graph modeling technique, theoretical lower bound on system energy consumption is derived, and it is revealed that adapting underlay D2D communication with proper transmission power control significantly decreases the energy consumption. Effect of various network parameters, such as flow delay, buffer size, and bandwidth is also shown.

In Khazali et al. (2018), the authors formulate an energy efficiency maximization problem for D2D users in a D2D-and-femtocell-enabled HetNets. They utilize the frequency fractional reuse structure to allocate the channels to the CUs and D2D users and show that it minimizes the interference among the simultaneously operating technologies. To solve the problem in an efficient manner, they remodeled the problem as a noncooperative game and proposed an iterative algorithm to allocate transmit powers to users. The results obtained show that by controlling the transmit power of CUs and D2D users, the energy consumption can be reduced significantly without much decrease in number of the CUs and the femtocell users. However, the complexity of the proposed algorithm increases exponentially with increase in number of CUs and D2D users.

The work of Jiang et al. (2015) formulates an energy efficiency maximization problem in a D2D-enabled cellular network, and it turns out to be an MINLP, which is NP hard and non-convex in nature. To find a tractable solution, it is then transformed into a fractional programming problem and an equivalent subtractive form. A two-layer iterative power and channel allocation scheme is proposed which converges fast to the optimal solution. The objective function of the energy efficiency maximization problems is expressed as follows:

$$\max_{\rho_{i,j}, P_{i,j}} U_{\mathrm{EE}} \tag{15.2}$$

$$U_{\mathrm{EE}} = \frac{\sum_{i=1}^{D} \sum_{j=1}^{C} \rho_{i,j} R(P_{i,j})}{\sum_{i=1}^{D} \sum_{j=1}^{C} \rho_{i,j} P_{i,j} + P_C}, \tag{15.3}$$

where $\rho_{i,j}$ is a binary variable, with value $\rho_{i,j} = 1$ denotes that the channel of the ith CU is shared with the jth D2D user, and $\rho_{i,j} = 0$ otherwise; $R(P_{i,j})$ denotes the sum-rate achieved with transmit power $P_{i,j}$; P_C and $P_{i,j}$ denote the maximum transmit power transmitted by the CU and the D2D user, respectively. Numerical results confirm that the proposed model significantly increases the EE even for larger number of D2D pairs in the cell. A list of such works is provided in Table Table 15.4.

Table 15.4 Resource allocation schemes for D2D communications that are addressing energy efficiency maximization, N_c is numbers of CUs, and N_D is number of D2D users

References	Spectrum share	Channel sharing direction	Complexity	Analytical tool
Wu et al. (2015)	Underlay	UL	$\log_2(\frac{\overline{M}-\underline{M}}{\epsilon_2}) \times 2K \left[\log_2(\frac{\overline{Q}-\underline{Q}}{\epsilon_1})\right]^2$, $\overline{M}-\underline{M}$, $\overline{Q}-\underline{Q}$ are feasible power region for CU and D2D user, ϵ_1 and ϵ_2 are error tolerance	Heuristic approach (Iterative algorithm)
Della Penda et al. (2016)	Underlay	UL/DL	Non-trivial to determine	Heuristic approach
Zhao et al. (2016)	Underlay	DL	$(O(B+R)N)$, B = no. of BS, R = no. of relays, N = no. of time slots	Graph theory
Khazali et al. (2018)	Overlay	UL	Iterative algorithm with $I_{\max}$ iterations	Game theory
Jiang et al. (2015)	Underlay	UL	$O(N_D N_C)$	Fractional programming

15.3.4 Energy Efficiency and Spectral Efficiency Trade-Off

In general, the performance of a communication system is measured by three performance parameters: energy efficiency (EE), spectral efficiency (SE), and QoS. Ideally, it is desired that all the parameters are maximized; however, in practical networks, these parameters are not independent to each other, sometimes improvement of one parameters may have negative impact on another one. Previously, many resource allocation schemes have been proposed which find a good trade-off between SE and EE in D2D-enabled cellular networks.

Authors in Zhou et al. (2014) formulate an energy efficiency maximization problem with constraint on the SE requirement and maximum transmission power in a D2D-enabled underlay cellular networks. To closely relate to the practical networks, the circuit power consumption is also considered. The objective and constraints of the formulated general EE-SE trade-off problem are as follows:

$$\max U^d_{i,\mathrm{EE}}, = \max \left(\frac{\sum_{k=1}^{K} \log_2 \left(1 + \frac{p_i^k g_i^k}{p_c^k g_{c,i}^k + \sum_{j=1, j=i}^{N} p_j^k g_{j,i}^k + N_0} \right)}{\sum_{k=1}^{K} \frac{1}{\eta} p_i^k + 2p_{cir}} \right) \tag{15.4}$$

$$C_1 : U^d_{i,\mathrm{SE}} \geq R^d_{i,\min}, \tag{15.5}$$

$$C_2 : 0 \leq \sum_{k=1}^{K} p_i^k \leq p^d_{i,\max}, \tag{15.6}$$

where $U^d_{i,\mathrm{SE}}$ is the SE (bits/s/Hz) of ith D2D user; $g^k_{c,i}$ is the interference channel gain between the kth CU to the ith D2D receiver; η denotes the efficiency of power amplifier; $g^k_{j,i}$ denotes the interference link from the jth D2D pair transmitter to the ith D2D pair receivers; K denotes the total number of channels. To solve the problem efficiently, a resource allocation scheme based on the noncooperative game is proposed, where each user behaves in a greedy manner and tries to maximize the individual EE. By using numerical simulations, it is shown that for high values of transmission power, there is little gain in SE, while significant loss in EE. The limitation of this work is that the computational complexity to find trade-off increases significantly with increase in number of D2D users and CUs. Through numerical simulations, it is shown that for increasing value of SE, EE has typical bell-shaped characteristic, an initial increase in EE, then rapid decrease. Indeed this trend is expected for EE, because to fulfill high requirement of SE, more power is allocated to D2D transmitters, thus high power consumption, and more interference to CUs. Thus, less increase in sum-throughput, and more increase in power consumption, so overall decrease in EE.

The work of Hao et al. (2018) formulates a multi-objective optimization problem to investigate the trade-off between EE and SE in a D2D-enabled underlay cellular networks. It addresses two scenarios: first, channel state information (CSI) is available at the BS, second, CSI is not available. By exploiting the ϵ-constraint and strict robustness, the formulated problem is transformed into a deterministic single-objective optimization problem. However, finding an optimal solution requires exponential computational power. To decrease it, a two-stage iterative algorithm is proposed which solves the channel and power allocation problem separately. Numerical results demonstrate that there exist an intrinsic relationship between EE-SE performance of CUs and the minimum rate requirement of D2D pairs. A major limitation of these approaches is that they are iterative in nature; therefore, convergence of the proposed algorithm is not guaranteed. It highly depends upon the number of D2D pairs per channel.

The work of Zhang et al. (2018b) investigates the EE-SE trade-off for dynamic D2D communications in underlay cellular networks. The mobile device is assumed to be moving, and to capture the dynamic channel characteristics vehicle-to-vehicle channel model is utilized. Depending upon the vehicular traffic density (VTD), whether high or low, it formulates two optimization problems. Using numerical simulations, it is shown that, for high VTD, a small decrease in EE around its peak value leads to significant gain in SE, while in low VTD scenarios, a slight decrease in SE results in higher gain of EE. Moreover, to improve the practicability of the proposed solution, a more general performance metric "economic efficiency" is employed, which measures profitability in terms of monetary unit per second. The limitation of this work is that it only considers that a CU channel is shared by only one D2D pair, which is underutilization of spectrum.

In Wei et al. (2015), authors analyze the EE-SE trade-off for the multihop D2D communications in the cellular networks. They specifically addressed the scenario where a D2D user may help other two D2D users to exchange information. The proposed work compares the EE and SE performance of the possible three communication modes: (1) when there is direct D2D communication between the transmitting and receiving node, (2) multihop D2D communication through another user, and (3) conventional communication through centralized BS. The presented work also finds the optimal transmit power of D2D users that maximize the EE of each mode. By using numerical simulations, it is shown that for larger transmission distance, the EE of multihop D2D communication is better, while for smaller transmission distance, the SE of multihop is better in comparison with direct and conventional communications. However, orthogonal channel allocation is assumed for D2D communications which may lead to an inefficient utilization of available spectrum. Table 15.5 provides a brief summary of such works.

15.3.5 Delay Minimization

To support the real-time applications, many research efforts have been done to exploit D2D communications for relay communications. Researchers try to formulate optimization problems with objective of minimizing the delay or number of hops in relay communications, while ensuring a certain level of QoS to CUs and D2D users.

Table 15.5 Resource allocation schemes for D2D communications that are addressing energy-spectral efficiency trade-off, N_c is numbers of CUs, and N_D is number of D2D users

References	Spectrum share	Channel sharing direction	Complexity	Analytical tool
Zhou et al. (2014)	Underlay	UL	$O(I^d_{i,\text{dual}} I^d_{i,\text{loop}} K)$, $I^d_{i,\text{dual}}$ and $I^d_{i,\text{loop}}$ are the required number of iterations required for convergence, and for solving dual problem, K is number of CUs	Game theory
Hao et al. (2018)	Underlay	UL	$O(K Q (N_D - 1) (N_C + K)^{\mu} (N_C N_D + K)^{\nu})$	Heuristic (Pareto optimality)
Zhang et al. (2018b)	Underlay	UL	Predefined $I_{\max}$ number of iterations for convergence	Heuristic approach
Wei et al. (2015)	Overlay	UL	Non-trivial to determine	Network coding and heuristic approach

The recent work by Huang et al. (2019) formulates a joint channel and power allocation problem for delay-aware D2D communication. The system model consists of D2D users sharing uplink channels with CUs, with a CU channel is allowed to share by maximum one D2D pair. By utilizing Lyapunov optimization framework, an optimal delay-aware traffic admission, mode selection and resource allocation (DTMR) scheme is proposed. The results obtained show that the proposed scheme reduces the queue length of every user, and increases average per-user data rate.

Mi et al. (2015), formulate an optimization problem with an objective of minimizing the average delay and average drop rate in a D2D-enabled underlay cellular network. The formulated problem is remodeled into an infinite horizon average cost Markov decision process (MDP). To solve the problem efficiently, a two-stage channel and power allocation scheme is proposed. In the first stage, a heuristic approach is proposed which considers the imbalance of queue lengths, and in the second stage, the transition probabilities in the system states are derived. To allocate the optimal power to D2D transmitters, the *Bellmen equation* is solved. By using numerical simulations, it is shown that the proposed scheme decreases the average packet delay and average drop rate in comparison with baseline models, such as fixed power and round robin. It is further extended in Lei et al. (2015) where authors consider dynamic data arrival, and reformulate the resource allocation problem into an infinite horizon average reward constrained MDP. It is shown that the delay can be minimized either by a deterministic policy or a simple mixed policy which randomize between two deterministic policy.

Kazeminia et al. (2019) formulate a dynamic spectrum sharing and power control problem in a D2D-enabled overlay cellular networks. To ensure the average queue length should be below certain threshold, a constraint on maximum delay is considered. Again by utilizing Lyapunov optimization technique, the formulated problem is transformed into a maximum weighted sum-rate problem with the average power consumption as a penalty term. To solve the optimization problem efficiently and priorly to the next scheduling frame, a low-complexity heuristic scheme is proposed. By using numerical simulations, it is shown that the dynamic spectrum sharing approach significantly reduces the queuing delay with the same power consumption of the static approach. However, overlay communication is assumed, which may lead to an underutilization of available spectrum. A list of previous works addressing delay minimization is provided in Table 15.6.

15.4 Resource Allocation for Sum-Throughput Maximization

In this section, we formulate a sum-throughput maximization problem in a D2D-enabled underlay cellular networks and proposed a channel and power allocation problem to efficiently solve the problem.

15.4.1 System Model

We envisioned a D2D-enabled underlay cellular network of cell radius R, as depicted in Fig. 15.3, in which the locations of the CUs are assumed to be uniformly distributed. The D2D users are assumed to follow the Poisson point process (PPP) Π_d, and the node density is λ_d. The CUs and D2D users are assumed to share the same uplink channels. The total number of uplink channels are denoted as $\mathcal{K} = \{1, 2, \ldots, N_c\}$. To generalize, we use the common index for CU and orthogonal channels as $1, 2, \ldots, N_c$. To characterize the channel between the ith transmitter and the jth receiver, i.e., h_{ij}, Nakagami fading model is assumed. In uplink channel sharing mode, let kth channel is used by the kth CU and $\mathcal{D}_k \subseteq \mathcal{D}$ D2D transmitters. It is assumed that all the CUs transmit at orthogonal channels, and this helps in avoiding severe co-channel interference among CUs.

15.4.2 Problem Formulation

The achievable rate of the kth CU sharing channel with other D2D pairs which are transmitting on the kth channel is expressed as follows:

Table 15.6 Resource allocation schemes for D2D communications that are addressing delay minimization, N_c is numbers of CUs, and N_D is number of D2D users

References	Spectrum share	Channel sharing direction	Complexity	Analytical tool
Huang et al. (2019)	Overlay	UL	$\mathcal{O}((N_c + 3N_D)K)$, K denotes number of resource blocks	Lyapunov optimization
Mi et al. (2015)	Underlay	UL	$\mathcal{O}(N_c^2(N_c + p))$, p denotes number of possible control inputs	Heuristic scheme
Kazeminia et al. (2019)	Overlay	UL	$\mathcal{O}(N_{\mathrm{RB}}^2 L_D^6 L \log N_{\mathrm{RB}})$, N_{RB} is number of RBs; L_C and L_D denote the number of CU links and D2D links, respectively; $L = L_C + L_D$ and $L \log N_{RB}$ is a function of rate of increase of iteration	Heuristic approach
Lei et al. (2015)	Underlay	UL/DL	$\mathcal{O}(\lvert\mathcal{S}\rvert^2 \lvert\mathcal{A}_x\rvert)$, $\mathcal{S}$ and $\mathcal{A}_x$ denote state space and auction space, respectively	Dynamic optimization

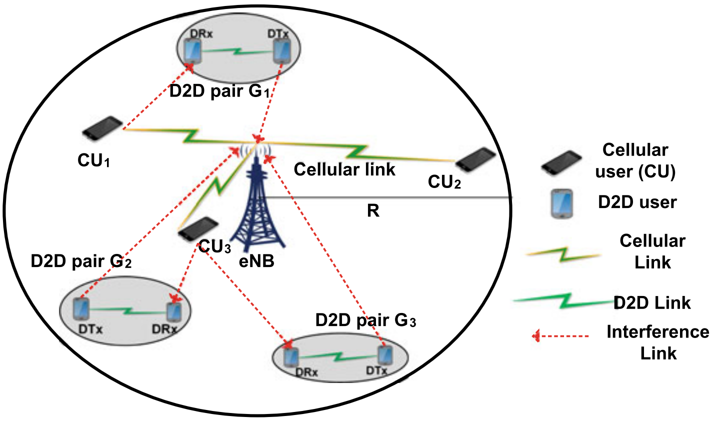

Fig. 15.3 Depiction of a D2D-enabled underlay cellular networks, where D2D pair G_1 reuses channel with CU_1, and D2D pair G_2 and D2D pair G_3 reuse uplink channel with CU_3

$$R^{c}_{k,g} = B_k \log_2 \left(1 + \frac{p_{c,k} h^{k}_{c,b} d^{-\alpha}_{cb}}{\sum_{g=1}^{|\mathcal{D}_k|} p_{g,k} h^{k}_{g,b} d^{-\alpha}_{gb} + N_0} \right), \tag{15.7}$$

where $h^{k}_{c,b}$ and $h^{k}_{g,b}$ represent the channel gain from the kth CU and gth D2D transmitter to the BS, respectively; $p_{c,k}$ and $p_{g,k}$ denote the transmit power of the kth CU and the gth D2D pair transmitter; $d_{c,b}$ and $d_{g,b}$ represent the distance between the CU and the D2D transmitter to the base station, respectively; α is path-loss exponent; N_0 denotes the variance of additive white Gaussian noise (AWGN) noise. Similarly, the achievable SINR of the gth D2D pair sharing channel with other D2D pairs and the CU which are transmitting on the kth channel is as follows:

$$\Gamma^{k}_{r,g} = \frac{p_{d,k} h^{k}_{g,r} d^{-\alpha}_{gr}}{\sum_{j=1, j \neq g}^{|\mathcal{D}_k|} p_{j,k} h^{k}_{j,r} d^{-\alpha}_{jr} + p_{c,k} h^{k}_{c,r} d^{-\alpha}_{cr} + N_0}. \tag{15.8}$$

In (15.8), $h^{k}_{j,r}$ is channel gain from the co-channel D2D transmitter to the receiver of other co-channel D2D pairs. The achievable rate of the gth D2D pair is

$$R^{D}_{k,g} = B_k \log_2 \left(1 + \Gamma^{k}_{r,g} \right). \tag{15.9}$$

To determine the sum-throughput gain achieved by sharing the channels, we need to find the sum-throughput when channels are not shared. Therefore, the achievable data rate of the kth CU in absence of interference created by D2D links is determined as:

$$\widehat{R^{c}_{k}} = B_k \log_2 \left(1 + \frac{p_{c,k} h^{k}_{c,b} d^{-\alpha}_{cb}}{N_0} \right). \tag{15.10}$$

From (15.7) and (15.10), it can be deduced that the data rate of the kth CU decreases, and the reason for this decrement is interference created by the co-channel $|\mathcal{D}_k|$ D2D transmitters. The value of decrement is calculated by (15.11).

$$\Delta R^{c}_{k,g} = \widehat{R^{c}_{k}} - R^{c}_{k,g}. \tag{15.11}$$

Similarly, the gain in achievable rate after channel sharing can be determined as follows:

$$\Delta R_{k,g} = \sum_{g \in \mathcal{D}_k} R^{D}_{k,g} + R^{c}_{k,g} - \widehat{R^{c}_{k}} = \sum_{g \in \mathcal{D}_k} R^{D}_{k,g} - \Delta R^{c}_{k,g} \tag{15.12}$$

The lowest bound on the achievable throughput gain can be calculated by assuming all the D2D transmitters transmit at maximum power, because this created maximum co-channel interference.

Let R_c and R_d denote the achievable sum-throughput of all the CUs and D2D pairs, respectively, and can be derived using following expressions:

$$R_c = \sum_{k=1}^{K} R_{k,g}^{c} \tag{15.13}$$

$$R_d = \sum_{k=1}^{K} a_{g,k} R_{k,g}^{D}, \tag{15.14}$$

where $a_{g,k}$ denotes the binary variable which determines whether a channel is shared or not. $a_{g,k} = 1$ denotes that the kth is shared, otherwise not. In order to increase the sum-throughput which is summation of the achievable rate of CUs and D2D users, our objective is to maximize the sum-throughput of all users while maintaining SNR's above thresholds. Thus, the optimization problem can be defined as

$$\begin{aligned} \mathbf{P}_1 : \max_{p_{d,k}, p_{c,k}, a_{g,k}} & \left(R_c + R_g\right) \\ \text{subject to} \quad & C_1 : 0 \le p_{c,k} \le P_c^{\max} \quad \forall c \in \mathcal{C} \\ & C_2 : 0 \le p_{d,k} \le P_d^{\max} \quad \forall k \in \mathcal{K}, g \in \mathcal{D}_k \\ & C_3 : \Gamma_c^k \ge \gamma_{k,\text{th}} \\ & C_4 : \Gamma_{r,g}^k \ge \gamma_{g,\text{th}} \\ & C_5 : a_{g,k} \in \{0, 1\}, g \in \mathcal{D}, k \in \mathcal{C}. \end{aligned} \tag{15.15}$$

Constraint C_1 denotes the maximum power that can be allowed to a CU; constraint C_2 indicates the maximum power that can be allowed to a D2D transmitter. Constraints C_3 and C_4 determine the minimum SINR level should be maintained above certain threshold, and constraint C_5 denotes the binary channel indication variable. By seeing the structure of the formulated problem, it is deduced that it is an MINLP, and solving an MINLP problem is computationally hard; therefore, we provide a heuristic approach which solves the problem $\mathbf{P}_1$ in polynomial time.

15.4.3 Outage Probability Analysis

This subsection derives the closed-foam expressions for the outage probability (OPs) experienced at a typical receiver of a D2D pair. Outage occurs when the SINR at the receiver is less than a decoding threshold Lin et al. (2014b). Here, we consider a D2D pair is under outage when the SINR at its receiver falls below the decoding threshold. As per our system model, the SINR at the rth receiver of a D2D pair on the kth channel is given in (15.8). For initial outage calculation, we utilize the full channel inversion for uplink communication ElSawy et al. (2014); therefore, the transmit power by D2D-Tx and CU is $\rho_d d_{g,r}^{\alpha}$ and $\rho_{bs} d_{cb}^{\alpha}$, respectively, where ρ_d and ρ_{bs} denote the receiver sensitivity of D2D receiver and BS, respectively. We focus on spectrum sharing which means the hybrid network is interference limited and the impact of thermal noise (N_0) can be neglected. Hence, SIR is assumed in place of

SINR, and (15.8) is simplified to

$$\mathrm{SIR}_k^r = \frac{h_{g,r}^k \rho_d}{I_k^r}, \tag{15.16}$$

where I_k^r $(I_k^r = \sum_{j=1, j\neq g}^{|\mathcal{D}_k|} p_{j,k} h_{j,r}^k d_{jr}^{-\alpha} + p_{c,k} h_{c,r}^k d_{cr}^{-\alpha})$ denotes the total interference at the rth D2D receiver on the kth channel. The probability that SIR of a typical D2D receiver is less than a threshold γ_{th}, i.e, outage probability can be expressed as follows:

$$P(\mathrm{SIR}_k^r < \gamma_{\mathrm{th}}) = E_{I_k^r, h_{g,r}^k}\left\{P\left(\frac{h_{g,r}^k \rho_d}{I_k^r}\right) < \gamma_{\mathrm{th}}\right\}, \tag{15.17}$$

where $E_{I_k^r, h_{g,r}^k}\{.\}$ stands for the expectation with respect to I_k^r and $h_{g,r}^k$. By following the power gain-based reference link and assuming the reference link suffering from Nakagami fading model with shape parameter m as in Guo et al. (2014, 2016), (15.17) can be written as:

$$P_{\mathrm{out}}^k(\gamma_{th}) = 1 - \sum_{l=0}^{m-1} \frac{-s^l}{l!} \frac{\mathrm{d}^l}{\mathrm{d}s^l} \mathbb{M}_{I_k^r(s)}|_{s=m\frac{\gamma_{th}}{\rho_d}}, \tag{15.18}$$

where $\mathbb{M}_{I_k^r(s)} = E_{I_k^r}\left[\exp\left(-sI_k^j\right)\right]$ is the moment generating function (MGF) of I_k^r. An advantage of considering Nakagami-m model is that it covers all the fading models; therefore, the expression for OP in Rayleigh fading can also be derived (by placing $m = 1$). Next, we find the MGF of interference created at the rth receiver.

We condition on the rth D2D-Rx which is located at a distance d from the base station. The isotropic network region and PPPs rotation-invariant property says that OP derived at the rth receiver is the same for those receivers which are at the same distance d from the base station. Therefore, according to Silvnyak's theorem, Daley and Vere-Jones (2007), the MGF of the I_k^r can be derived as follows:

$$\begin{aligned}
\mathbb{M}_{I_k^r}(s,d) &= E_{I_c^r}\{\exp\left(-sI_c^r\right)\} \\
&\quad \times E_{g_k\in G_k\ g}\left\{\exp\left(-s\sum_{G_k\ g} I_k^r(r)\right)\right\} \\
&= \mathbb{M}_{I_c}^r(s,d)\, E_{G_k}\left\{\exp\left(-s\sum_{g_k\in G_k} I_k^r(r)\right)\right\} \\
&= \mathbb{M}_{I_c}^r(s,d)\exp\left(\lambda_d|\mathcal{A}|\left(\mathbb{M}_{I^r}(s,d)-1\right)\right),
\end{aligned} \tag{15.19}$$

where $\mathbb{M}_{I^r}(s, d)$ denotes the MGF of interference from other D2D pairs which communicate using the kth channel. $\mathbb{M}_{I_c^r}(s, d)$ denotes MGF of interference created from shared CU.

15.4.4 Channel Allocation Algorithm

Based on the expression of OPs, the BS may easily make a decision whether two D2D pairs are allowed to share resource with a CU or not. If they are allowed to share resources with a CU, we may have more options for selecting a CU such as:

Objective 1: Choose that CU that minimizes the outage probability of a particular D2D pair, either G_1 or G_2.

$$i^* = \underset{i \in C}{\operatorname{argmin}}\, P_{\text{out}}^{G_1}, \text{ or } i^* = \arg\min_{i \in C} P_{\text{out}}^{G_2} \tag{15.20}$$

Objective 2: Choose that CU_i that minimizes the maximum of OPs of two D2D pairs.

$$i^* = \underset{i \in C}{\operatorname{argmin}} \max\left(P_{\text{out}}^{G_1}, P_{\text{out}}^{G_2}\right) \tag{15.21}$$

Objective 3: Choose that CU that minimizes the sum of OP of two D2D pairs.

$$i^* = \underset{i \in C}{\operatorname{argmin}} \left(P_{\text{out}}^{G_1} + P_{\text{out}}^{G_2}\right) \tag{15.22}$$

Depending on the requirement of service on each D2D pair, the base station would use the optimal objective for selecting the CU. For example, if D2D pair 1 needs higher QoS than D2D pair 2, the base station opts for Objective 1 to guarantee performance for D2D pair 1. Objective 2 tries to minimize the maximum of outage probabilities of the two D2D pairs, thus tries to maintain the SINR of both pairs above some threshold value. Objective 3 tries to minimize the sum of outage probabilities of both D2D pairs.

15.4.5 Power Allocation

After the channel allocation step, the binary variable $a_{g,k}$ vanishes. Therefore, we need to only allocate the transit power to the D2D transmitters such that they maximizes the sum-throughput. For this step, we utilized "Generalized Distributed Constrained Power Control Algorithm (GDCPC) (Im et al. 2008)." The algorithm fulfills the SIR requirement of every D2D user while limiting the interference to other receiving nodes upto a tolerable level. The algorithm ensures the interference constraint and concomitantly QoS constraint by distributing the total interference to CU into

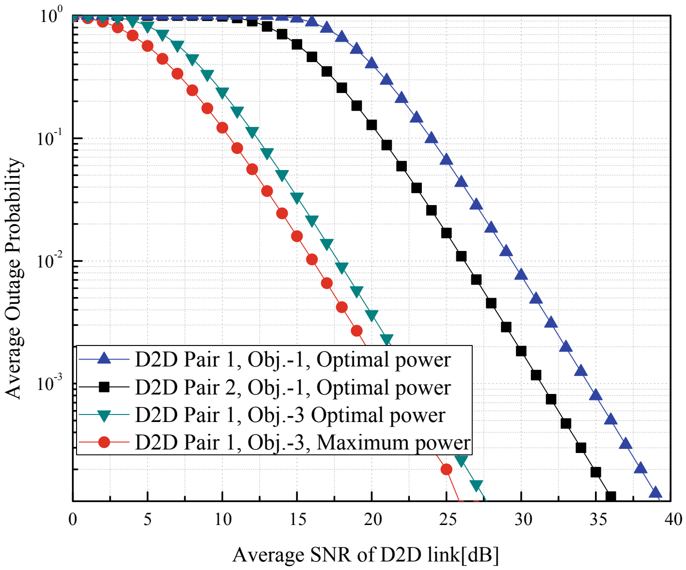

Fig. 15.4 Outage probability variation with average SNR of the D2D multicast group, CU = 5, $M = 10$

the individual constraint of D2D transmitter, and it can be written as

$$h_{g,b}^{k} p_{g,k} \leq \frac{I_{th}^{k}}{G_k} \quad \forall g \in G_k \tag{15.23}$$

By rearranging (15.23), we derive the upper bound on the maximum power of a D2D transmitter.

$$p_{g,k} = \frac{I_{th}^{k}}{h_{g,b}^{k} G_k} \tag{15.24}$$

It may be noted that to calculate the $p_{g,k}$, we need to know the other co-channel D2D pair, and it can be obtained from the channel allocation step. Also, this may be obtained from the beacon signals that are transmitted by the BS. Therefore, maximum transmission power of a D2D transmitter is derived as

$$p_{g,k}^{\max} = \min\{P_{g,D}^{\max}, \frac{I_{\text{th}}}{h_{g,b}^{k} G_k}\} \tag{15.25}$$

where $P_{g,D}^{\max}$ is the maximum transmission power that a mobile device may radiate, that is 30 dBm.

15.4.5.1 Effect of SNR on the Outage Probabilities of D2D Pairs

Figure 15.4 depicts the outage probability variation with average SNR of D2D links. It is assumed that a cellular channel is shared by maximum of two D2D links. Two observations can be drawn from this figure. First, for objective 1 where the CU for resource sharing is chosen such that it minimizes the OP of D2D pair 1 instead of D2D pair 2, with optimal power allocation, the gap between their respective achievable SNR is nearly 2.5 dB. Second observation is impact of power allocation on OPs. When selection criteria is objective 3, the gap between their achievable SNR with the proposed and maximum power allocation is nearly 3 dB. This shows the efficacy of proposed algorithm in decreasing the outage probability of D2D pairs.

15.5 Conclusion and Future Works

This chapter begins by a brief introduction to the potential usage and different modes of operation of D2D communication in next generation of wireless networks. Then, to seamlessly integrate the D2D communication in cellular networks, it presents the challenges in designing the optimal resource allocation schemes. Next, it provides the classification of the existing resource allocation schemes based on the challenges they are addressing. Then, a sum-throughput maximization problem is formulated, and to solve that a heuristic scheme is proposed. The results obtained with presented resource allocation schemes show the potential of D2D communication to provide higher data rate, lower end-to-end latency, and improved spectral and energy efficiencies. These results may further lead to integration of this technology in the next generation of wireless networks by helping with the design and analysis of relevant D2D resource allocation schemes. Further, most of the existing schemes deal with the sum-throughput maximization; however, an interesting extension would be to provide resource allocation scheme considering various utility maximization problem for D2D-enabled cellular networks. Also, the insights so obtained with centralized resource allocation schemes will be useful for designing fast and more pragmatic distributed resource allocation schemes for D2D-enabled cellular networks.

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