Part I

Introduction

1 Basics of D2D communications

As one of the next-generation wireless communication systems, the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) is committed to providing technologies for high data rates and system capacity. Further, LTE-Advanced (LTE-A) was defined to support new components for LTE to meet higher communication demands [1]. In particular, the performance and quality of service (QoS) of local area services need to be improved significantly by reusing the spectrum resources. However, reuse of the unlicensed spectrum might not provide a stable controlled environment [2]. Therefore, the approach of exploiting the licensed spectrum for local area services has attracted much attention. In this chapter, we present the basic concepts of device-to-device (D2D) communications in the licensed spectrum bands. We first provide an overview of D2D communications underlaying the cellular network. We then discuss access methods, device synchronization, and discovery mechanisms. Next, mode selection, spectrum sharing, power control, and multiple-input–multiple-output (MIMO) techniques are briefly introduced. The concepts of D2D direct and D2D local area networks (LANs) are proposed, a simulation scenario for D2D direct is given as an example, and, finally, the issues and challenges in D2D communications are outlined.

1.1 Overview of D2D communications

The term D2D communications commonly refers to the techniques that enable devices to communicate directly without an infrastructure of access points or base stations. D2D communications amount to a technology component for LTE-A, where user equipments (UEs) transmit data signals to each other over a direct link/connection using the cellular resources instead of through the eNB (i.e., a base station). As an underlay to the cellular network, D2D communications allow one to increase the spectral efficiency [1, 3, 4, 5, 6, 7, 8, 9]. While D2D communications is considered as an add-on component in the 4G systems, it is expected to be a native feature supported by the next-generation (e.g., fifth-generation [5G]) cellular networks.

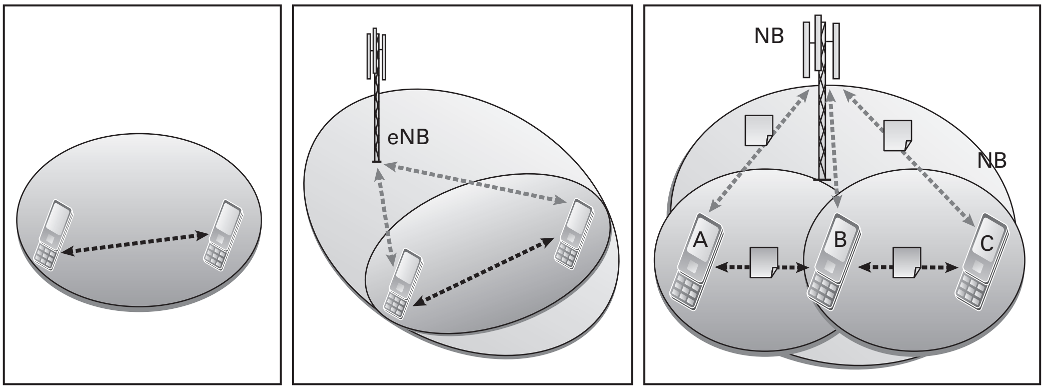

Figure 1.1. Device-to-device signal transmissions.

D2D communications may be of three types, as shown in Figure 1.1.

- Peer-to-peer communication: This is point-to-point communication, and most studies on D2D communication consider this type of transmission.
- Cooperative communication: This uses mobiles as relays to extend coverage, and exploits cooperative diversity through multiple collaborative mobiles to obtain space diversity.
- Multiple-hop (multihop) communication: This is similar to mobile ad-hoc network and mesh network, which may include complex data superposition, and data routing, e.g., wireless network coding.

Although the use of D2D communications brings an improvement in spectral efficiency and has large benefits in terms of system capacity, it also causes interference with the cellular network as a result of spectrum sharing. Thus, an efficient interference coordination must be formulated to guarantee a target performance level of the cellular communication. There exist several works about the use of D2D UEs for restricting co-channel interference [1, 3, 10, 11]. The authors in [12] utilize MIMO transmission schemes to avoid interference from the cellular downlink to D2D receivers sharing the same resources, with the aim of guaranteeing the required performance for the D2D communications. Interference management both from cellular to D2D communications and from D2D to cellular networks is considered in [13]. To further improve the gain from intra-cell spectrum reuse, properly pairing the cellular and D2D users for sharing the same resources has been studied [14, 15]. The authors in [15] propose an alternative greedy heuristic algorithm to lessen interference with the primary cellular networks using channel state information (CSI). The scheme is easy to operate yet cannot avoid signaling overhead. In [16], the resource-allocation scheme avoids the harmful interference by tracking the near–far interference, identifies the interfering cellular users, and ensures that the uplink (UL) frequency bands are efficiently used. Additionally, the goal is to prevent interference from cellular to D2D communication. In [17], the authors provide an analysis on optimal resource allocation and power control between the cellular and D2D connections that share the same resources for different resource-sharing modes, and evaluate the performance of the D2D underlay system both in a single-cell scenario and in the Manhattan grid environment. Then, the schemes are applied to further optimize the resource usage among users sharing the same resources.

The existing works in the literature show that by proper resource management, D2D communications can effectively improve the system throughput with the interference between cellular networks and D2D transmissions being minimized. However, the problem of allocating cellular resources to D2D transmissions is not trivial. In the later parts of the book, we will discuss different resource-management methods for D2D communications.

1.2 Key technologies for D2D communications

1.2.1 Configuration of D2D communications

The D2D networks can be configured in the following three ways to allow or restrict their usage by certain users.

- Network-controlled D2D: In this scenario, the communication signaling setup and thereafter resource allocation for both cellular and D2D users are controlled by the base station (BS) and the core network. This centralized configuration benefits from efficient interference avoidance and resource management. However, when the number of D2D links becomes large, this scheme incurs a large amount of control signaling, which can increase the overhead and reduce the spectrum efficiency. Therefore, this fully network-controlled approach is particularly useful for scenarios with small numbers of D2D links.
- Self-organized D2D: In this scenario, D2D users themselves realize the communication in a self-organizing way by finding the empty spectrum hole. This configuration is similar to cognitive radio, which allows D2D users to sense a surrounding environment, thereby obtaining CSI, interference, and cellular system information. This distributed method can effectively avoid the controlling signaling overhead, and the time delay, but the self-organized nature of this method may cause communication chaos and instability due to lack of control by the operators in the licensed spectrum.
- Network-assisted D2D: The D2D users operate in a self-organized way, and, for resource management, exchange with the cellular system a limited amount of controlling information. The cellular network can use the status of D2D communications for better control purposes. This approach has the merits of the first two approaches.

1.2.2 Device synchronization and discovery

For D2D communications, synchronization between cellular networks and D2D users and among D2D users themselves will be necessary to minimize multiple-access interference and for proper handoff. The approaches in IEEE 802.11 or in LTE can be adopted to enable the synchronization among mobiles. Typically, device synchronization and discovery are realized in a joint way.

The fundamental problem of device discovery is that two devices have to meet in space, time, and frequency without any coordination. This can be made possible via some randomized procedure, and one of the peers assumes the responsibility of sending the beacon. For traditional peer discovery, both in the ad-hoc case and in the cellular case, the discovery is made possible by one party transmitting a known synchronization or reference signal sequence (the beacon). Depending on whether or not there are responses from the discovering UEs, the discovery approaches can be classified into two categories: beacon-based discovery and request-based discovery. According to whether there is network participation in the detection, the discovery procedure could be categorized into two types: network-assisted detection and non-network-assisted detection.

In the case of network-assisted D2D, the network can mediate in the discovery process by recognizing D2D candidates, coordinating the time and frequency allocations for sending/scanning for beacons, and thereby making the pairing process more energy efficient and less time consuming. A typical procedure is as follows.

- Use direct signal to discover a peer.
- Set the transmission power so that UEs within a certain distance can hear the broadcast.
- Whoever receives the broadcast confirms that with the eNB.

1.2.3 Mode selection

In a D2D underlay communications system, one of the most challenging problems is to decide whether communicating devices should use cellular or direct communication mode. In the D2D mode, data is directly transmitted to the receiver while the cellular communication mode requires the source device to transmit to the eNB and then the destination device receives from the eNB on downlink (DL). Here, three different mode selection criteria are considered.

(i) *Cellular:* All devices are in cellular mode.
(ii) *Force D2D:* D2D mode is always selected for all the communicating devices.
(iii) *Path-loss D2D:* D2D mode is selected if any of the path losses between a source device and its serving eNB, or a destination device and its serving eNB, is greater than the path loss in the direct link between the source node and the destination node.

1.2.4 Spectrum sharing and resource management

Spectrum-sharing methods for D2D communications can be categorized as follows.

- *Overlay D2D communications:* The D2D users occupy the vacant cellular spectrum for communication. This approach can completely eliminate cross-tier interference by dividing the licensed spectrum into two parts (i.e., orthogonal channel assignment). That is, one fraction of the subchannels will be used by the cellular users while another fraction would be used by the D2D networks. Although it is optimal from a cross-tier interference standpoint, this approach is inefficient in terms of spectrum reuse.

- *Underlay D2D communications:* In this spectrum-sharing scheme, multiple D2D users are allowed to work as an underlay with cellular users, and thus improve the spectrum efficiency. Co-channel assignment of the cellular and D2D users will be more efficient and profitable for operators, although this is far more intricate than the overlay scheme from the technical point of view.

The overlay approach is easy to realize, but might not be spectrally efficient. While the underlay method incurs a relatively greater signaling overhead, it can achieve a better overall system performance. To optimize the system performance over spectrum sharing of both D2D and cellular modes, radio resource management is important. Radio resource management can be performed in either a noncooperative or a cooperative manner. In a noncooperative solution, each D2D user can manage its spectrum so as to maximize the throughput and quality of service (QoS). By contrast, in a cooperative approach, the D2D users can gather partial information about spectrum usage and perform spectrum allocation taking into account the effect that it would have on its co-channel neighbors. In this way, the average cellular and D2D users' throughput and QoS, as well as their performances, can be locally optimized.

1.2.5 Power control

Power control is an important and effective way to coordinate the co-channel interference. Power control can be performed by two methods.

- Self-organized power control: The D2D users make power changes in a self-organized way according to a predefined signal-to-interference-plus-noise ratio (SINR) threshold in order to meet the QoS without affecting the cellular users.
- Network-managed power control: Both cellular and D2D users adaptively adjust their transmit power according to the SINR report. Typically, the D2D users can control the transmit power first, and then the cellular users make changes afterward. This iterative process terminates when all the users have satisfied their SINR requirements.

Obviously, the first method is not going to change the behaviors of cellular users since the D2D users are treated invisibly. This method is simple, but less efficient than the second method, which allows all of the users to adjust their transmit powers. However, the network-controlled approach requires some information exchange among cellular users, D2D users, and the eNB.

1.2.6 Uplink and downlink transmission with MIMO

The use of multiple-input and multiple-output (MIMO) antennas can improve system capacity by multiplexing signals in the spatial domain and increase robustness by exploiting space diversity. Specifically, by performing transmit or receive beamforming, the use of multiple antennas at the eNB and the UE can reduce the co-channel interference to other users and thus improve spectrum efficiency.

The different MIMO-based methods are as follows.

- *eNB beamforming:* This type of multi-user MIMO-like approach can be performed at the cellular downlink to reduce interference to the D2D users so that D2D communications can be allowed.
- *D2D beamforming:* This avoids any harmful interference being caused by the D2D transmissions to the cellular and other D2D users.
- *Virtual D2D beamforming:* This borrows the ideas of cooperation among mobile nodes such that multiple D2D users collaboratively form the beamforming matrices to improve the system performance.

1.3 Device-to-device local area networks

D2D communications can be classified into two main categories: *D2D direct* and *D2D local area networks* (D2D LANs). Specifically, D2D direct simply refers to conventional one-hop communication [1]. In multihop D2D LAN, the network-controlled smart devices can realize cluster-wise communications in an ad-hoc manner, and meanwhile work in the license band to achieve maximal flexibility and performance. Figure 1.2 shows a typical single-cell scenario with multiple users consisting of conventional

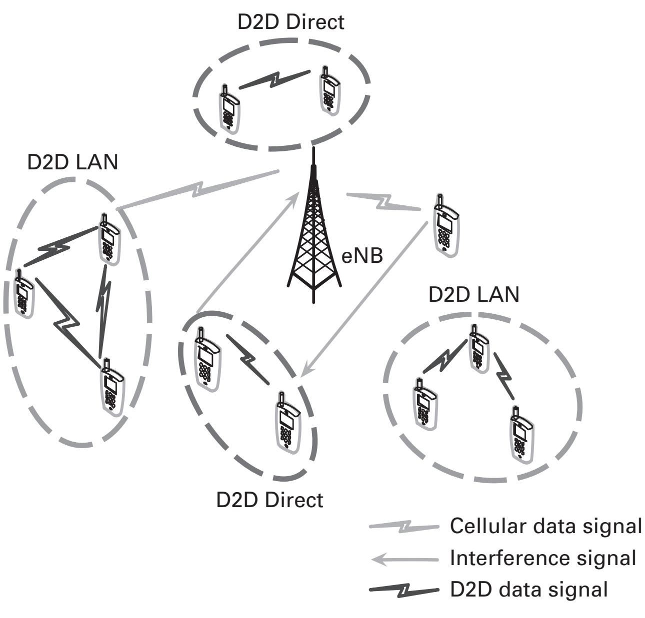

Figure 1.2. D2D communications underlaying cellular networks, including cellular communication, D2D direct, and D2D LAN.

cellular communications, one-hop D2D direct transmission, and D2D LAN for group communication.

With regard to D2D LAN, the network-controlled mobiles can form group communications, and thus provide various functionalities for specific application purposes. Similarly to D2D direct, these mobiles in the LAN can also work as an underlay to cellular networks for spectrum reuse, which makes the resource-allocation problems even more challenging. The representative scenarios for D2D LANs are as follows.

- *Group communications:* When large numbers of similar requests are received by the eNB, the LAN can be used to efficiently offload data. For example, in stadium or concert networks, when many mobiles ask for the content, some "*seed*" UEs can be first selected to obtain the complete information from the eNB, and then these seeds can share data with the remaining mobiles to reduce the eNB's effort.
- *Multihop relay communications:* When some smart devices are out of the coverage of the eNB, the mobiles in the D2D LAN can serve as relays for completing the file delivery among mobiles. This is particularly useful for disaster situations as well as suburb areas.
- *Collaborative smartphone sensing:* Since smartphones have the capability of environment sensing, which is similar to wireless sensor networks, the data can be collaboratively aggregated to some "sink" UEs and then transmitted to the eNB.

One representative example of an application of D2D LAN is mobile social networks, where social interests play a major role in enhancing the smartphone transmission in D2D LAN, and a contract game can be used to model utilities of the social-related individuals.

1.4 D2D direct: a simulation scenario

A single-cell scenario is considered as illustrated in Figure 1.3. For simplicity, just one cellular user (UE1) and one D2D pair (UE2 and UE3), which is in D2D mode, are located in the cell. Three users share the same radio resources at the same time. As a result, co-channel interference should be considered. The position of UE2 is fixed as long as the distance from BS to it is D. The position of the other D2D user UE3 is uniformly distributed inside a region of radius L from UE2. As in a traditional cellular system, UE1 is free to be anywhere inside the cell, following a uniform distribution. In the simulation, the locations of three users are updated in each iteration.

According to Figure 1.3, three communicating users are in the system. UE2 and UE3 are in D2D mode, and UE1 is a cellular user. We set the maximum distance between UE2 and UE3 to be 25 meters. Actually, as much as 100 meters distance between them can be effective. The results presented here give only a representative scenario. Table 1.1 shows the main simulation parameters.

The wireless propagation is modeled according to WINNER II channel models, and the D2D channel is based on an office/indoor scenario while the cellular channel is based

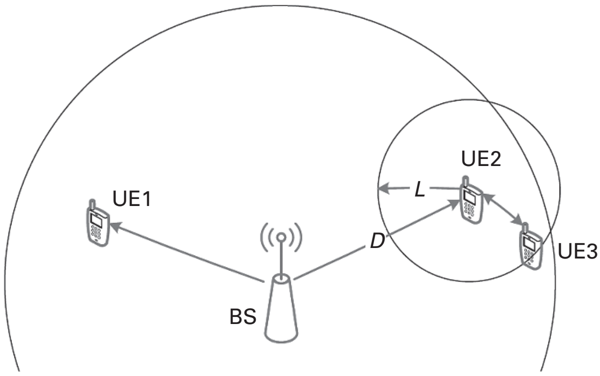

Figure 1.3. The scenario of underlay D2D communications.

Table 1.1. Main simulation parameters

Parameter	Value
Cellular	Isolated cell, one-sector
System area	User devices are distributed within a range of 500 m from the BS
Noise spectral density	−174 dBm/Hz
System bandwidth	5 MHz
Noise figure	5dB at BS/9 dB at device
Antenna gains and patterns	BS: 14 dBi; device: omnidirectional 0 dBi
Cluster radius	5 m, 10 m, 15 m, 20 m, 25 m
Transmit power	BS: 46 dBm; device: 24 dBm (without power control)

on an urban macrocell scenario. Table 1.2 gives path-loss models. d is the link distance in meters, and n_{walls} is the number of walls penetrated in the link. $d'_{\text{BP}} = 4h'_{\text{BS}}h'_{\text{MS}}f_{\text{c}}/c$, where f_{c} is the center frequency in Hz, $c = 3.0 \times 10^8$ m/s is the propagation velocity in free space, and h'_{BS} and h'_{MS} are the effective antenna heights at the BS and the MS, respectively. The effective antenna heights h'_{BS} and h'_{MS} are computed as follows: $h'_{\text{BS}} = h_{\text{BS}} - 1.0\,m$, and $h'_{\text{MS}} = h_{\text{MS}} - 1.0$ m, where h_{BS} and h_{MS} are the actual antenna heights, and the effective environment height in urban environments is assumed to be 1.0 m. The LOS probability is given in Table 1.3.

Next, D2D and cellular SINR distribution with power control are investigated. The LTE uplink open-loop-fraction power-control scheme (OFPC) is given as [19]

$$P = \min\left\{P_{\max}, P_0 + 10 \cdot \log_{10} M + \alpha \cdot L\right\}. \tag{1.1}$$

The parameters for the power-control scheme are given in Table 1.4.

In this scenario, the interference between D2D and cellular users due to UL resource sharing has been taken into account. When the distance between D2D and co-channel cellular users is not larger than the maximum distance of D2D communications, the interference channel can be based on an indoor/office scenario. However, when co-channel interference comes from a more distant location, the D2D channel