Chapter two

Background

2.1 Introduction

With increasing demand of high data rate wireless access for multimedia services, the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) has been proposed to develop new technology components that can meet the requirements of IMT-Advanced systems. International Mobile Telecommunications-Advanced (IMT-Advanced) systems are mobile broadband communication systems which offer high bandwidths up to 100 MHz to support a wide range of services (e.g. multimedia services) [28].

One of the main issues in IMT-Advanced systems is how to improve the local area services and spectrum efficiency. Device-to-device (D2D) communications enable short-range ad-hoc networks underlaying the cellular networks by sharing the same radio resources.

Device-to-device (D2D) communication underlaid with cellular networks allows direct communication between mobile users. D2D is an attractive approach for dealing with local traffic in cellular networks. The initial motivation for incorporating D2D communication in cellular networks is to support proximity-based services, e.g. social networking applications or media sharing. Assuming there are proximate communication opportunities, D2D communication may also increase area spectral efficiency, improve cellular coverage, lower end-to-end latency, or reduce handset power consumption. In spite of these potential gains, the coexistence of D2D and cellular communication in the same spectrum is challenging due to the difficulty of interference management [29].

It also causes interference to the cellular network as a result of spectrum sharing. Thus, efficient interference coordination must be formulated to guarantee a target performance level of the cellular communication [30].

Although standalone D2D communications have been studied in literature for more than a decade, the concept of D2D communications in cellular networks is relatively new. Within past few years, both industry and academia have shown interest in this technology because the initial studies on D2D communications proposed significant performance gains. Moreover, recent studies confirm that the use of D2D communications in cellular networks is commercially justified because of the resulting spectrum and power efficiency gains over the conventional cellular networks [31].

2.2 Overview of interference management

A short overview of interference management in wireless communication systems is explained in this section. The purpose is to highlight the overall methods and future trends in how wireless systems deal with interference. The evolution from rigid and pre-planned interference management toward flexible, dynamic, and autonomous spectrum access is considered to be a key enabler in providing cost efficient and high data rate wireless access in the future. In this section an overview of interference management in wireless systems is given. One way to classify wireless systems is based on the primary channel access method that is, to contention based and scheduled access. An example of a contention based system is the 802.11 wireless local area network (WLAN)[32], whereas cellular systems, such as 3GPP LTE are mostly scheduled. The interference in wireless systems may be classified into self interference, multiple access interference, co- and adjacent channel interference, and coexistence interference. Each of these interference types and the corresponding main management techniques are briefly introduced in this section. The trends in interference management are also shortly discussed.

2.2.1 Cellular systems

The main service in 1st (e.g. Nordic Mobile Telephone, NMT) and 2nd generation (e.g. Global System for Mobile communications, GSM) cellular systems was voice for wide coverage. However, with the increase of wireless broadband internet connections and mobile internet services and usage, data is currently consuming the most of the capacity. In a circuit switched network, such as GSM, each connection (call) re-serves a dedicated channel for its exclusive use.

This suits voice transmission relatively well due to the static nature the connections and the delay requirements of the voice traffic. However, circuit switched networks are inefficient for data transmission since data traffic tends to be more bursty.

In a packet switched network the channels are shared among different connections. The data is grouped into packets, and the channel sharing is facilitated by statistical multiplexing, where base stations (BS) coordinate the transmissions such that the data packets do not collide with each other. An essential difference between circuit switched system and a packet switched system is the time scale of this coordination: in circuit switching it is done on the connection level whereas in packet switching it is done on the packet level. This enables much more spectrally efficient systems. While the 1st generation cellular networks were designed for voice and were exclusively circuit switched, the 2nd and, more prominently, 3rd generation systems (e.g. Universal Mobile Telecommunications System, UMTS) include a packet switched mode for data transmission, Furthermore, 4th generation cellular systems (e.g. Long Term Evolution, LTE, and LTE Advanced, LTE-A) are exclusively packet switched with both voice and data transmitted over the Internet Protocol (IP).

2.2.2 Wireless local area networks

Wireless local area networks (WLAN) provide high speed data connections mainly over smaller areas such as office buildings, public spaces, and at home. The IEEE 802.11 standards define variety technologies for WLAN, Regarding interference management, the main difference between 802.11 and cellular systems are in the channel access method.

In 802.11, each node accesses the spectrum in a distributed manner by first sensing if the channel is idle, and transmitting only when it is idle. In order to prevent multiple nodes from starting a transmission simultaneously, and consequently interfering with each other, the duration of the sensing phase of an idle channel is randomized. Thus interference is avoided provided that the nodes can sense the busy channels with sufficient reliability. This contention based channel access called carrier sense multiple access (CSMA) is efficient and has low latency when the number of contending transmitters is sufficiently low. Therefore it is suitable for local area

communication where there are only a few users under the coverage area of an access point. On the other hand, the cellular systems with scheduled access can handle better a large amount of users per base station, and are more suitable for providing continuous coverage.

2.2.3 MIMO OFDM

The physical layer in many current wireless systems is based on multicarrier modulation, in particular, orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA). For instance, 3GPP LTE utilizes OFDMA and 802.11n OFDM. It is also likely a key technology in the forthcoming wireless systems due to its inherent benefits. A single carrier receiver has to cope with inter-symbol interference in a frequency selective (i.e. time dispersive) channel using e.g. multiple tap equalizers. Multicarrier modulation converts the wideband channel to a set of parallel narrowband channels (subcarriers) experiencing flat fading. Hence, a single-tap equalizer is sufficient per subcarrier, which simplifies the receiver design. In OFDM the frequency band is divided to a large number of subcarriers which are ideally orthogonal such that there is no inter-carrier interference. Hence, each subcarrier may be modulated independently which facilitates achieving rates closer to the frequency selective channel capacity. The conversion between the parallel subcarriers and the serial time-domain samples is done via the fast Fourier transform (FFT), which is a computationally efficient algorithm for performing the discrete Fourier transform (DFT). Furthermore, inter-symbol interference is eliminated by adding a cyclic prefix to each OFDM symbol. Multicarrier systems are also suitable for multi antenna transceiver techniques (multiple input multiple output, MIMO) since a flat fading channel enables straightforward implementation of MIMO schemes. The spatial degrees of freedom in a MIMO system may be used for improving the capacity and/or link reliability through a trade-off among spatial multiplexing, beamforming, and diversity techniques. Despite the several benefits, OFDM has also drawbacks – it requires accurate frequency synchronization, is sensitive to Doppler spread, and has high peak to average power ratio (PAPR).

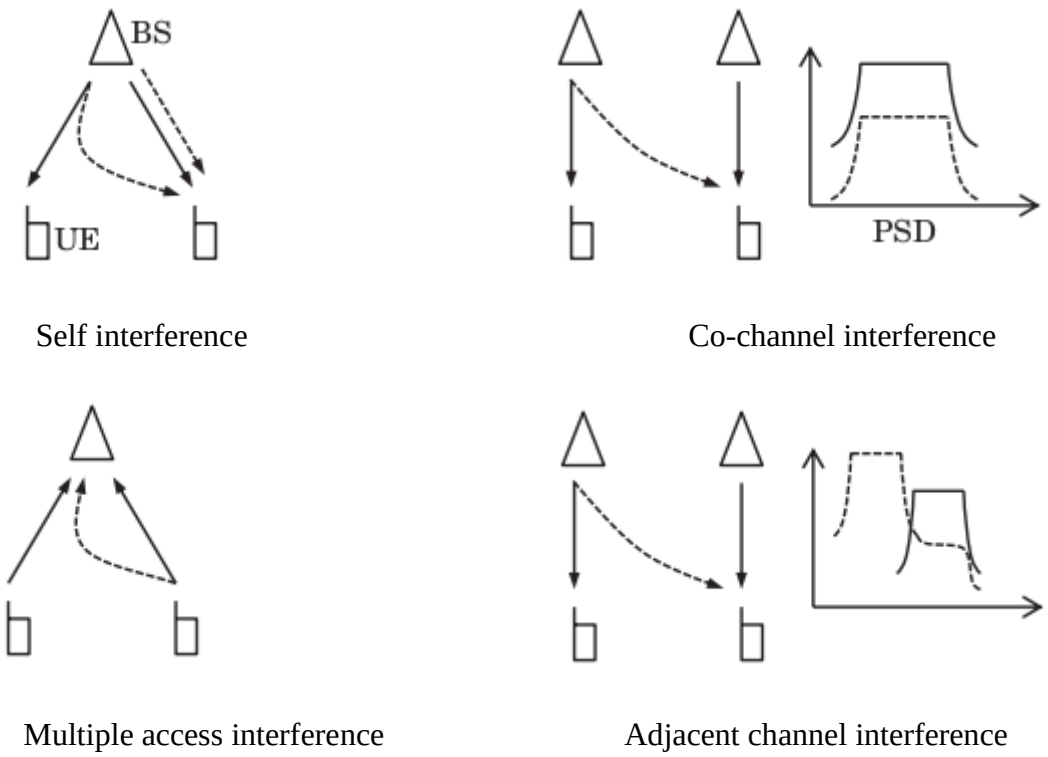


Figure 2.1: An illustration of different interference types occurring in wireless systems.

2.2.4 Interference in wireless systems

The following interference types may be identified within and among different wireless systems

• Self interference, e.g. intersymbol interference (ISI)

• Multiple Access Interference (MAI)

• Co-channel Interference (CCI)

• Adjacent Channel Interference (ACI)

• Coexistence Interference (CEI)

Figure 2.1 illustrates the interference types. In this section, each of these types is briefly presented. Dashed lines represent interference.

2.2.4.1 Self interference

Self interference includes interference that occurs among signals that are transmitted from a single transmitter. The specific mechanism and amount of self interference depends on the modulation type. For instance, in OFDM there may be ICI among the subcarriers due to carrier frequency offsets caused by oscillator mismatches, and the Doppler Effect and fast fading caused by motion of the transceivers. Another source of self interference is transceiver non idealities, such as amplifier non-linearity and IQ imbalance. ISI occurs in OFDM when the delay spread of the channel exceeds the length of the cyclic prefix or guard interval, and also when the receiver is not accurately enough time-synchronized to the transmission. Interference between the UL and DL transmissions in an FDD system may be also classified as self interference, as it occurs among signals send on the same two-way connection. This interference is mitigated by employing duplex filters. The interstream interference in a multistream MIMO transmission may be also considered as a form of self interference. In the simplest case of multistream transmission a separate codeword is transmitted from each of the transmit antennas. The code words then interfere with each other at the receiver, but the interference may be mitigated through multi-antenna receiver processing. The strength of the interstream interference depends on the rank and eigen value spread of the MIMO channel. In principle, it is required that there is a sufficient number of independent channels (significant singular values) for spatial multiplexing. The impact of self interference is minimized by selecting the physical layer numerology such that the operating conditions and implementation technology are taken into account. These are also in part factors that are device manufacturer dependent. Self interference mitigation involves trading off between the cost and battery/power consumption of equipment, bandwidth efficiency, and robustness to extreme operating conditions. For example, short-range local area networks with limited mobility and wide area networks supporting vehicular mobility pose different demands on this respect.

2.2.4.2 Multiple access interference

Multiple access interference (MAI) is interference among the transmissions from multiple radios utilizing the same frequency resources to a single receiver. When multiple transmissions in

cellular uplink take place simultaneously, they are interfering with each other. Even though the physical layer would allow orthogonal (in the time, frequency, code, or spatial domain) multiple access in theory, orthogonality may not be maintained in practice due to synchronization errors, RF circuitry non-idealities, and the effects of wireless propagation channel. Cellular systems employ several mechanisms in order to maintain sufficient orthogonality in multiple access scenarios. Firstly, power control is essential. Since the terminals transmitting to the BS are distributed over the cell area, there is a large variation in the path loss between the BS and the terminals. If all terminals would transmit with the same power the difference of the received powers can be high enough for the stronger signals to mask the weaker signals due to the limited dynamic range of the receiver. A well-known example is the UL power controls in Code Division Multiple Access (CDMA) systems, which is essential to make the CDMA uplink feasible. Furthermore, various transmitter non-idealties cause that perfect orthogonality cannot be maintained even if the receiver would be ideal. In case of Frequency Division Multiple Access (FDMA) and OFDMA, the power on the used sub-bands or sub-carriers leaks also on the neighboring sub-bands. The ratio of the power transmitted on the desired sub-band to the power transmitted on the adjacent sub-band is called the adjacent channel power ratio (ACPR, usually given in dB). The ACPR may easily be smaller than the range of the observed uplink path loss values (in dB) from the terminals to the BS. This means that a FDMA UL needs to be power controlled. In CDMA systems the need for uplink power control is even more critical due to non-orthogonality of the spreading codes. For combating MAI in CDMA uplink, Multiuser Detection (MUD) has been studied extensively in the past, se. The uplink multiple access may have also a time domain multiple access (TDMA) component whereby there may also be MAI in between consecutive transmissions. The difference in the terminal to BS distances implies that the propagation delay of the transmissions is different among the terminals. This is compensated for by a so-called timing advance, where the propagation delay is compensated by tuning the transmission timing accordingly. The larger the cell radius is, the more timing advance is needed, while in wireless local area networks (WLAN) this effect may be largely neglected. The remaining time dispersion of the transmissions is then handled by using a guard interval between the consequtive TDMA time slots.

A more recent addition in wireless systems is Spatial Domain Multiple Access (SDMA). In SDMA uplink, several users transmit on the same time-frequency resources to the base station (or to multiple base stations, as is the case in uplink coordinated multipoint transmission, UL CoMP). When the base station is equipped with a sufficient number of antennas the signals may be separated at the BS in spatial domain. The requirement is that the uplink channels for each simultaneously transmitted symbol are linearly independent. This technique is also called multiuser MIMO (MU-MIMO) or virtual MIMO. Depending on e.g. the accuracy of channel estimates, there will be MAI among the MU-MIMO transmissions. MU-MIMO may also be used in downlink, when the BS sends data to several users on the same time-frequency resources. When the channel state is known at the transmitter, the transmission may be precoded such that interference is minimized. The downlink transmission occurs through a broadcast channel, and therefore this interference may be categorized as self interference.

2.2.4.3 Co-channel interference

Co-Channel Interference (CCI) is interference between links that reuse the same frequency band (channel). In cellular systems this is also known as intercell interference. In earlier cellular systems, up to 2nd generation GSM, the impact of CCI is minimized by employing fixed frequency reuse patterns. The cellular frequency reuse may be considered as the seminal invention of the cellular wireless communication technology, which dates back to 1945 and to United States Federal Communications Commission (FCC). In a cellular network employing frequency reuse the band is divided to a set of orthogonal channels. The number of orthogonal channels is called the reuse factor of the system. Each cell is assigned a single channel such that the distance between neighboring cells using the same channel is maximized. Figure 2.2 illustrates cellular frequency reuse with reuse factor equal to 7. High reuse factor leads to low CCI on the expense of reduced bandwidth per BS. In order to enable higher peak data rates and mean spectral efficiency, there has been a shift to a reuse factor equal to 1 (that is, no fixed frequency reuse pattern) as a part of the development of 3rd and 4th generation networks. Such network is called a reuse-one network, and in it all cells may utilize the full system bandwidth and the system becomes interference limited in terms of its capacity.

Even though reuse-one networks provide higher average spectral efficiency and maximize the peak spectral efficiency, they have also drawbacks. The cell-edge users will experience very low SINR levels due to the high amount of CCI. For example, LTE systems display a heavy tailed SINR distribution, where the 15 percent of measured SINR values in a deployed LTE system in

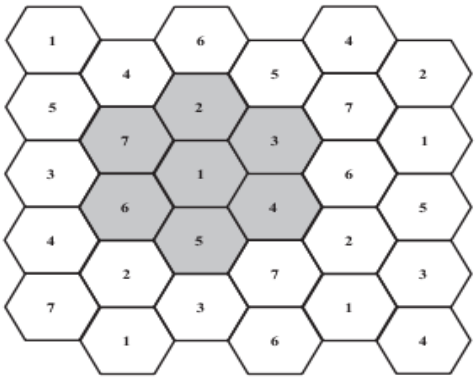


Figure 2.2: cellular frequency reuse on a hexagonal grid of cells with reuse factor equal to 7

Urban environment fell below 0 dB (i.e., the received interference plus noise power exceeds the received signal power). Depending on the scheduling principle, the variance of the SINR distribution translates to either lower average spectrum efficiency (e.g. round robin scheduling) or reduced fairness (e.g. max C/I scheduling). It is evident that CCI is the dominant factor limiting the performance of reuse-one wireless data networks.

2.2.4.4 Adjacent channel interference

Adjacent channel interference (ACI) is interference between links that communicate geographically close to each other using neighboring frequency bands. For instance, several network operators may deploy their own networks in the same area and operate on frequency bands that are close to each other. Hence, ACI needs to be taken into account in the system specifications so that it will not hamper the system performance. In practice, the minimum coupling loss between a transmitter and a receiver on adjacent bands may be estimated and the transceivers may be designed such that ACI remains at a tolerable level. In order to do so the

transceivers must utilize adequate filtering on stop-bands. The needed quality of the filters may be controlled by reserving a guard band between the bands.

A related interference type to ACI is coexistence interference (CEI) which occurs among heterogeneous radio access technologies. CEI may arise on the same frequency band or between adjacent frequency bands. As an example, the higher frequency digital TV bands are not used because of GSM induced interference. Other examples include interference between 2nd generation and 3rd generation networks and interference between different systems operating on the unlicensed bands. A straightforward way of dealing with CEI is to take it into account in spectrum use regulations, network planning, and filtering in devices. However, in many cases these approaches lead to inefficient spectrum use, more costly devices, and/or higher operator expenditures. Flexible spectrum use and cognitive radio technology provide an alternative approach. An example is wireless data networks utilizing the unused television bands (TV white spaces). In that case the CEI may be minimized by channel allocation based on the geo location of the devices and database access to spectrum occupancy information, or periodic sensing of the spectrum. Authorized Shared Access (ASA) is an example of such access, where the spectrum use is licensed but dynamically controlled through an ASA database/server. Thorough understanding of propagation environment is important and also the possibility of asynchronity needs to be taken into account in preventing CEI.

2.3 Evolution of interference management

Due to the nature of wireless propagation there is always interference among links that operate on the same spectrum in the same geographical area. Therefore, every wireless system has to employ on interference management in order to provide efficient and reliable communication, guarantee fairness among the users, attain a good coverage, and reach a high system capacity. As the use of wireless systems is rapidly increasing it is not sufficient to just increase point to point link capacity through wider bandwidths and physical layer technologies such as MIMO. It is also necessary to increase the base station density and, on the other hand, decrease the capital and operational expenditures of the system.

These two goals are conflicting as increasing the base station density is very expensive. Therefore, cutting the operator costs is possible only through relying less on high performance RF, tedious network planning, and expensive infrastructure and core network. This means that more autonomous and distributed interference management and network functionalities are needed.

An important trend in interference management has been that the related functionalities in the network are handled closer to the transceivers themselves. The vast amount of research on wireless systems has produced numerous techniques that increase the system performance. The implementation of more and more intricate transmission and reception schemes has become possible as the processing power available at the devices has increased. The development has been also fueled by the advances in the understanding and modeling of the propagation environment. The benefits of the development come from the increased areal spectral efficiency as shorter and shorter spacing between the various communication links can be accommodated. The spacing may be reduced in different domains and considering different degrees of freedom, i.e. in time, frequency, location, and spatial domain. In the time domain this relates to, for example, the evolution from circuit switched networks to packet switched networks and trunking in general. In the frequency domain a notable advance has been the development of multicarrier systems. In location domain the transition to smaller cellular reuse factors has become possible, all the way to reuse-one networks. Spatial domain improvements are due to multi antenna techniques, which enable sharing the frequency resources even within a cell by exploiting spatial diversity and signal separation in the spatial domain. Code-domain may be mentioned here as well, since spread spectrum systems allow multiplexing several UEs transmissions on the same frequency band through CDMA.

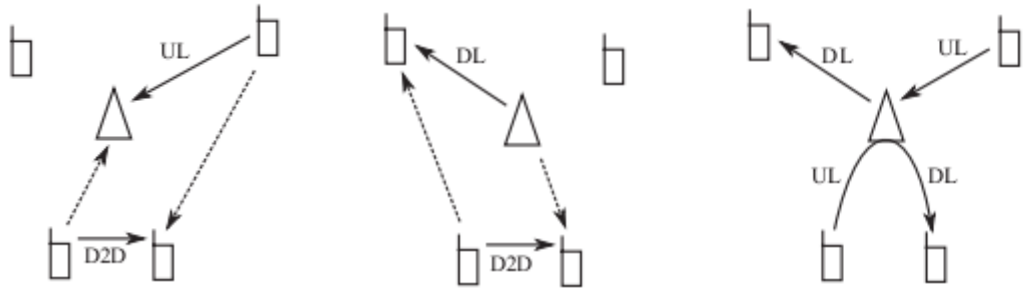
In the past, interference management has been carried out off-line. It has required tedious network planning effort and has been centralized by its nature. This approach has the benefits of being a robust and reliable approach. On the other hand, it is inflexible, time-consuming, costly, and inefficient in spectrum usage. In the future interference management becomes more and more dynamic, autonomous, and decentralized.

Opportunistic spectrum access enables higher and higher system spectral efficiency. The spectrum use may be organized and negotiated among the devices themselves. The goal is that future wireless systems would achieve high capacity, and at the same time, the deployment, operation, and maintenance of the networks would become cheaper, simpler, and autonomous.

2.4 Interference management for the D2D underlay

D2D transmissions cause severe interference if they are allowed in the proximity of cellular mode devices (either mobile terminals or base stations) and on the same time-frequency resources. Unless this interference is carefully managed it will result in unacceptable degradation both in cellular and D2D link qualities. The interference between the D2D and cellular links is illustrated in Figure 2.3. When the D2D link is active on a radio resource that is in use by a cellular UL transmission, interference is induced from the UL transmitting UE to the D2D receiving UE.

Interference is also induced from the D2D transmitting UE to the cellular BS. Similarly, when the D2D transmission shares radio resources with the cellular DL transmission, interference is induced from the cellular BS to the D2D receiving UE. Also, interference is induced from the D2D transmitting UE to the DL receiving UE. In both cases the BS may allocate orthogonal resources to the D2D and UL transmissions so that interference does not occur. This is straight forward, if the cellular UL or DL band is not fully utilized.



(a) D2D sharing UL resources (b) D2D sharing DL resources (c) Virtual D2D connection

Figure 2.3: resources sharing between cellular and D2D links (a), (b), (c)

Several methods for managing the interference between the cellular and D2D devices have been proposed. These can be categorized to methods that involve interference aware admission control, resource sharing mode selection, power control, scheduling, and spatial (MIMO) processing. In the following each of these areas is discussed.

2.4.1Admission control and mode selection

A straight forward way of managing the interference is to admit D2D communication only on a limited set of resources when the traffic load on the cellular links is low. When the cellular load is high, no resources are allocated to D2D communication. Such kind of conservative policy requires little signaling overhead and guarantees that the performance of the cellular connections is not compromised. On the other hand, higher system capacity is not achieved since local traffic may need to be transmitted using BS relaying when the network load is higher. This is the case if there is no other radio access technology available for the D2D traffic.

In a more general sense, the RRM (Radio Resource Management) functionality at the BS needs to choose a proper mode for the D2D transmission. The available options are relaying through the BS, D2D link on dedicated resources, or D2D link on shared resources together with a cellular UL or DL transmission.

The optimal mode for D2D communication is strongly dependent on the node locations and D2D link distance; On the other hand, past results indicate that a simple mode selection scheme is sufficient if the D2D link distance is short. Specifically, when the D2D link distance is in the order of one hundredth of a cell radius, it suffices to simply categorically enforce D2D mode transmission for the D2D links. Otherwise, interference awareness in mode selection is crucial. The propagation environment and the relative locations of the cellular and D2D devices affect the SINR distributions. In some cases it is more favorable to employ UL sharing while other cases favor DL sharing. This indicates that there is potential for performance gains from interference awareness in selecting between DL and UL sharing. Several studies show that interference aware mode selection is able to provide reliable D2D and cellular link quality while maintaining a large proportion of direct D2D transmissions and thus large system capacity.

2.4.2 Power control

Another simple interference management principle is to allow only very low power D2D transmissions. This limits the range of the D2D links but guarantees that the interference toward cellular links will remain at a tolerable level. The advantage of this approach is that it requires minimal signaling. The low power D2D transmission mode could be naturally implemented using wide-band transmission, e.g. through spread spectrum modulation. The BS may, for instance, merely periodically broadcast the current allowed D2D power level, and let the D2D communication take place in an ad-hoc manner. However, interference aware power control is needed in case longer D2D transmission range is to be supported. Also neighboring cell terminals are impacted by the interference so that inter-BS coordination would be needed. Furthermore, the signaling requirements also increase. This is because the power control scheme needs to take into account also the different received signal power at each DL receiver. Therefore, accurate interference aware power control for D2D transmissions sharing cellular DL radio resources becomes complicated. The situation is different when D2D transmissions share cellular UL resources. In this case, the interference is experienced at the BS no matter which cellular terminal is scheduled for UL transmission. Hence, power control is easier to arrange. Also, the received signal power at the BS has much narrower dynamic range when UL power control is employed for the cellular transmissions.

2.4.3 Multiuser scheduling

A more elaborate way of managing the interference between D2D and cellular links is to let the BS manage the radio resource usage by scheduling decisions such that the impact of interference is minimized. The extent to which such schemes may be applied depends on the nature of the channel state information (CSI) available at the BS. The CSI may be collected through explicit channel sounding and measurements. Alternatively the link qualities could be monitored under varying scheduling decisions thereby implicitly learning the interference conditions. Also channel reciprocity may be exploited. In any case, interference aware RRM is more readily feasible in local area scenarios with only a few users per cell. In such a scenario the dimensionality of the problem is manageable and excessive signaling may be avoided. In addition, it has been shown

that information on large scale propagation conditions including path loss and shadowing may be sufficient for achieving most of the gains.

The implementation becomes more feasible by ignoring fast fading and frequency selectivity since there is significantly less large scale channel data. On the other hand, in local area scenarios low mobility and short delay spread are typically assumed, which reduces the CSI overhead. If accurate channel state information is available, the frequency selectivity of the channels may be considered as frequency diversity, which actually improves the system capacity. A more straightforward interference management scheme is to allocate dedicated time-slots for D2D communication. The BS may then act as a support node to the D2D links by managing the radio resource use of the D2D links.

2.4.4 Spatial domain techniques

When the BSs and terminals are equipped with multi antenna transceivers, part of the interference may be mitigated in the spatial domain. Such operation has been proposed for interference mitigation for cognitive radios, where a secondary communication system employs null steering toward primary system transceivers. The spatial domain interference suppression is possible both at the receiver and at the transmitter.

Interference may be also avoided at the transmitter by interference aware MIMO precoding. If accurate interference channel state information is available at the transmitter, beamforming algorithms may be employed to steer a null toward the interfered receiver and also maximize the gain toward the intended receiver. Accurate estimates of the channel matrices toward the D2D receiver and the intended DL receiver are needed for such schemes. This can be facilitated through accurate receiver feedback.

The selection of a cellular UE and a D2D pair that are sharing the same sub band was done randomly in the evaluations. In case there are multiple DL receivers and D2D pairs in the cell it is possible to use channel state information in the selection of the DL receivers and D2D pairs. This is because choosing a precoder that transmits to the null space of the D2D receiver does not in general match fully with the signal space of the DL receiver. However, the pairing of a D2D

receiver and a DL receiver may be done such that the null space of the D2D receiver and the signal space of the DL receiver are more separated to begin with. This would enhance the gains as the null steering would then imply fewer penalties to the DL transmission.