Performance Evaluation of Next Generation Wireless Systems using Interference Alignment

A Thesis
Submitted in Partial Fulfillment of the Requirements for the Award of M.Sc. Degree in Electrical Engineering
Electronics and Communications
Port Said University

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2013
Abstract

Wireless communication systems are in continuous evolution as a result of the ever increasing demand for higher data rate services. Examples of next generation networks that will bring higher data rates and increase system capacity to end users and network operators are 3GPP Long Term Evolution–Advanced (LTE-A) and WiMAX 2. These systems are being developed under the scope of IMT-Advanced. Recently, direct device-to-device communication (D2D) as an underlay network to IMT-Advanced cellular networks [1] has been proposed which represents a promising technique that is expected to provide efficient utilization of the available wireless spectrum and is expected to provide access to the Internet and local services using licensed bands that can guarantee a planned environment.

Another research trend that has potential to boost the overall cellular spectral efficiency is Interference Alignment (IA) [2]. Simply put, IA allows signal vectors to be aligned in such a manner that they cast overlapping shadows at the receivers where they constitute interference while they continue to be distinct at the intended receivers [2].

In this thesis, we propose a framework for radio resource and Interference management in D2D underlay network via Clustering and Interference Alignment based on reusing radio resources over smaller distances. Results of our proposal demonstrate that resource reuse over the clusters offer overall rate increase proportional to the number of formed clusters. In addition, interference alignment offers up to 33% increase in the overall rates in the high transmission power regimes compared to the normal Point-to-Point (P2P) communication.

On another front, it is known that Channel state information (CSI) is crucial for achieving reliable communication with high data rates in MIMO systems through transmissions adaptation to current channel conditions. Usually, the
channel state information needs to be quantized before being fed back to the transmitter since they will be sent over a limited-rate feedback channel. In situations where the feedback is severely limited, a challenging issue is how to quantize the information needed at the transmitter and then how much improvement in the associated performance can be obtained as a function of the amount of feedback available.

Interference alignment schemes for the $K$-user interference channels (ICs) have been employed to realize the full multiplexing gain under the assumption that CSI is ideally known at each transmitter. However, the assumption of the perfect CSI is almost impossible to realize at the transmitters, especially for quantized feedback systems using feedback links with finite bandwidth.

In this thesis and for the special case of 3-user IC for both SISO and MIMO systems, we propose new strategies that aim at minimizing the quantization error through partial processing at receivers and reduction of the amount of feedback data to send to the transmitters. The proposed limited feedback strategies is shown to significantly reduce the processing complexity required for minimizing quantization errors at the receivers compared to the scheme proposed in [3] and interestingly improves spectral efficiency performance as well.
Attestation

I understand the nature of plagiarism, and I am aware of the University’s policy on this.

I certify that this dissertation reports original work by me during my University Master except for the following:

- The Interference Alignment (IA) overview in Chapter 2 was taken from [2], [4].
- The WINNER channel overview in Chapter 3 was taken from [5].
- The Device-to-Device communication review in Chapter 4 was largely taken from [6].

Signature

Date
Acknowledgements

Over the past two years I have received support and encouragement from a good number of individuals and I would like to express my gratitude to all those who gave me the possibility to complete the work in this thesis. I am highly indebted to Prof. Khaled El-Sayed and Dr. Mahmoud Hamed for their guidance and constant supervision. Their help, stimulating suggestions, knowledge, experience and encouragement helped me in all the times of study and research of this work. I am also grateful to Dr. Mohamed Farouq for his encouragement and support in completing this work.

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Moreover, I would like to express my gratitude towards my parents and fiancée for their kind cooperation as well as for giving me the support and encouragement I needed while working on this thesis.

“This work is part of the 4G++ project supported by the National Telecom Regulatory Authority of Egypt”
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<table>
<thead>
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<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
</tr>
<tr>
<td>BC</td>
<td>Broadcast Channel</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>CSI</td>
<td>Channel State Information</td>
</tr>
<tr>
<td>D2D</td>
<td>Device-to-Device (communication)</td>
</tr>
<tr>
<td>DoF</td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>IA</td>
<td>Interference Alignment</td>
</tr>
<tr>
<td>IC</td>
<td>Interference Channel</td>
</tr>
<tr>
<td>LFS</td>
<td>Limited Feedback Scheme</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution of 3GPP mobile system</td>
</tr>
<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
</tr>
<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>MSE</td>
<td>Mean Square Error</td>
</tr>
<tr>
<td>NC</td>
<td>Network Coding</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non Line of Sight</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>PF</td>
<td>Proportional Fairness</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference and Noise Ratio</td>
</tr>
<tr>
<td>SISO</td>
<td>Single Input Single Output</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
</tr>
<tr>
<td>ZF</td>
<td>Zero Forcing</td>
</tr>
</tbody>
</table>
List of Symbols

\( \bar{C}_i \) Zero Forcing equalizer for the \( i^{th} \) receiver.

\( D_n \) A \( N_u^{Cl} \times N_u^{Cl} \) matrix containing distances between D2D users within cluster \( n \).

\( f_c \) System frequency in \([GHz]\)

\( F_1 \) Jain’s fairness index.

\( g_{cd} \) Channel response of the interference link from the cellular connection to the D2D connection.

\( H_{jk} \) Channel coefficients between transmitter \( k \) and receiver \( j \).

\( H_{i,j}^{k,n,l} \) Channel between pair \( j \) transmitter in cluster \( l \) and pair \( i \) receiver in cluster \( n \).

\( N \) Number of channel extensions or number of antennas.

\( N_{Users}^{D2D} \) Number of D2D users in the cell.

\( N_{Pairs}^{D2D} \) Number of D2D pairs in the cell.

\( N_{RB}^{D2D} \) Number of RBs dedicated to D2D users.

\( N^{Cl} \) Number of Clusters.

\( N^{Cl}_u \) Number of D2D pairs per cluster.

\( N_G \) Number of IA groups.

\( P_c \) Power allocated to the cellular link.

\( P_d \) Power allocated to the D2D link.

\( P_i \) Available power at the \( i^{th} \) transmitter.

\( PL \) Distance dependent path loss.

\( P_{max} \) Maximum power that can be allocated to a user.

\( R_{NOS} \) Sum rate for Non-Orthogonal Sharing (NOS) of the resources.

\( U_i \) Interference suppression matrix for the \( i^{th} \) receiver.

\( V_i \) IA precoder designed by Douglas and Murat in [32] for user \( i \).

\( x_i \) Vector of transmitted symbols at the \( i^{th} \) transmitter.

\( \hat{x}_i \) Throughput for the \( i^{th} \) user.

\( Z_i \) Additive white Gaussian noise at the \( i^{th} \) receiver.

\( \alpha_{ik}^n \) Selection variable that indicates the allocation of RB \( k \) for pair \( i \) in cluster \( n \).

\( \gamma_h \) SINR needed for using the highest MCS.

\( \gamma_t \) Guaranteed SINR to prioritize the cellular connection.

\( \Gamma_i \) IA precoder designed by Cadambe and Jafar in [2] for user \( i \).

\( \xi_\sigma \) Zero-mean Gaussian distributed random variable with standard deviation \( \sigma \).

\( \lambda_i \) Degrees of freedom available for the pair \( i \).
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1 Introduction

Wireless communication systems are in continuous evolution as a result of the ever increasing demand for higher data rate services. Examples of next generation networks that will bring higher data rates and increase system capacity to end users and network operators are 3GPP Long Term Evolution – Advanced (LTE-A) and WiMAX 2. These systems are being developed under the scope of IMT-Advanced. Recently, direct device-to-device communication (D2D) as an underlay network to IMT-Advanced cellular networks has been proposed as a promising technique that is expected to provide efficient utilization of the available wireless spectrum. Moreover, Interference Alignment (IA) has shown the potential to boost the overall cellular spectral efficiency. In this thesis, we study the potential of deploying D2D communication as an underlay in cellular networks and the benefits of exploiting IA in this setup.

1.1 Wireless Standards Evolution

Mobile communications have grown very rapidly since its invention. The first generation (1G) system was designed only for voice communication using the analog circuit switched networks. The second generation (2G) system, which first introduced digital cellular technology, was established to provide voice communication as well as data communication but with very low data rates. However, the need for new data services derived operators to introduce the 2.5 G system to increase data rates first to 56 kbps, and then up to 114 kbps. Global System for Mobile Communications (GSM) Enhanced Data Rates for Global Evolution (EDGE) provided further enhancements to the data rates in the 2G systems of up to 236.8 kbps.
Wireless communications have evolved from the 2G systems through the deployment of third generation (3G) systems with their higher speed data networks to the much-anticipated fourth generation technology being developed today. Early 3G systems did not immediately meet the ITU 2 Mbps peak data rate targets in practical deployment although they did in theory. However, there have been improvements to the standards since then that have brought deployed systems closer to and now well beyond the original 3G targets. It is notable that fewer standards are being proposed for 4G than in previous generations, with only two 4G candidates being actively developed today: 3GPP LTE-Advanced and IEEE 802.16m, which is the evolution of the WiMAX standard known as Mobile WiMAX 2. The process for 4G started with 3GPP LTE and IEEE 802.16e being the two candidates introduced. Later, these two became known as 3.9G since they could not satisfy all the requirements for 4G systems.

Table 1.1 shows the evolution of 3GPP’s third generation Universal Mobile Telecommunication System (UMTS), the original wideband CDMA technology, starting from its initial release in 1999/2000. There have been a number of different releases of UMTS where the addition of High Speed Downlink Packet Access (HSDPA) and the subsequent addition of the High Speed Uplink Packet Access (HSUPA) announced the completion of the informal name 3.5G. The combination of HSDPA and HSUPA is referred to as High Speed Packet Access (HSPA). LTE arrived with the publication of the Release 8 specifications in 2008 and LTE-Advanced is introduced as part of Release 10.

The Long Term Evolution project was initiated in 2004. The motivation for LTE included the desire for a reduction in the cost per bit, the addition of lower cost services with better user experience, the flexible use of new and existing frequency bands, a simplified and lower cost network with open interfaces, and
a reduction in terminal complexity with an allowance for reasonable power consumption.

These high level goals led to further expectations for LTE, including reduced latency for packets, and spectral efficiency improvements above Release 6 high speed packet access (HSPA) of three to four times in the downlink and two to three times in the uplink. Flexible channel bandwidths—a key feature of LTE—are specified at 1.4, 3, 5, 10, 15, and 20 MHz in both the uplink and the downlink. This allows LTE to be flexibly deployed where other systems exist today, including narrowband systems such as GSM.

Table 1.1 Evolution of UMTS specifications [7]

<table>
<thead>
<tr>
<th>Release</th>
<th>Functional Freeze</th>
<th>Main Radio Features of the Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rel-99</td>
<td>March 2000</td>
<td>UMTS 3.84 Mcps (W-CDMA FDD &amp; TDD)</td>
</tr>
<tr>
<td>Rel-4</td>
<td>March 2001</td>
<td>1.28 Mcps TDD (aka TD-SCDMA)</td>
</tr>
<tr>
<td>Rel-5</td>
<td>June 2002</td>
<td>HSDPA</td>
</tr>
<tr>
<td>Rel-6</td>
<td>March 2005</td>
<td>HSUPA (E-DCH)</td>
</tr>
<tr>
<td>Rel-7</td>
<td>Dec 2007</td>
<td>HSPA+ (64QAM DL, MIMO, 16QAM UL), LTE &amp; SAE</td>
</tr>
<tr>
<td>Rel-8</td>
<td>Dec 2008</td>
<td>LTE work item – OFDMA air interface, SAE work item, new IP core network, 3G femtocells, dual carrier HSDPA</td>
</tr>
<tr>
<td>Rel-9</td>
<td>Dec 2009</td>
<td>Multi-standard radio (MSR), dual cell HSUPA LTE-Advanced feasibility study, SON, LTE femtocells</td>
</tr>
<tr>
<td>Rel-10</td>
<td>March 2011</td>
<td>LTE-Advanced (4G) work item, CoMP study, four carrier HSDPA</td>
</tr>
</tbody>
</table>

1.2 4G Requirements and Solution Proposals

The third generation of cellular radio technology was defined by the ITU-R through the International Mobile Telecommunications 2000 project (IMT-2000). The requirements for IMT-2000, defined in 1997, were expressed only in terms of peak user data rates:
• 2048 kbps for indoor office.
• 384 kbps for outdoor to indoor and pedestrian environments.
• 144 kbps for vehicular connections.
• 9.6 kbps for satellite connections.

Of significance is that there was no requirement defined for spectral efficiency in 3G. The situation is quite different for IMT-Advanced. The ITU’s high level requirements for IMT-Advanced include the following [7]:

• A high degree of common functionality worldwide while retaining the flexibility to support a wide range of local services and applications in a cost-efficient manner.
• Compatibility of services within IMT and with fixed networks.
• Capability for interworking with other radio systems.
• High quality mobile services.
• User equipment suitable for worldwide use.
• User-friendly applications, services, and equipment.
• Worldwide roaming capability.
• Enhanced peak data rates to support advanced mobile services and applications (in the downlink, 100 Mbps for high mobility and 1 Gbps for low mobility).

For the most part these are general purpose requirements that any good standard would attempt to achieve. The key requirement that sets 4G apart from previous standards is reflected in the last item, which gives the expectations for peak data rates that reach as high 1 Gbps for low mobility applications and 100 Mbps for high mobility. This is a huge increase from 3G, which specified a peak rate of 2 Mbps for indoor low mobility applications and 144 kbps vehicular. The peak rates targeted for 4G will have fundamental repercussions on system design.

In the feasibility study for LTE-Advanced, 3GPP determined that LTE-Advanced would meet the ITU-R requirements for 4G. Further, it was determined that 3GPP Release 8 LTE could meet most of the 4G requirements
apart from uplink spectral efficiency and the peak data rates. From a link performance perspective, LTE already achieves data rates very close to the Shannon limit, which means that the main effort must be made in the direction of improving the Signal-to-Interference-and-Noise Ratio (SINR) experienced by the users and hence provide data rates over a larger portion of the cell [8]. These higher requirements are addressed with the addition of the following LTE-Advanced features [7]:

- Wider bandwidths, enabled by carrier aggregation.
- Higher efficiency, enabled by enhanced uplink multiple access and enhanced multiple antenna transmission (advanced MIMO techniques).

Other performance enhancements are under consideration for Release 10 and beyond, even though they are not critical to meeting 4G requirements:

- Coordinated multipoint transmission and reception (CoMP).
- Relaying.
- Support for heterogeneous networks.
- LTE self-optimizing network (SON) enhancements.
- Home enhanced-node-B (HeNB) mobility enhancements.
- Fixed wireless customer premises equipment (CPE) RF requirements.

1.2.1 Carrier Aggregation

Achieving the 4G target downlink peak data rate of 1 Gbps will require wider channel bandwidths than are currently specified in LTE Release 8. At the moment, LTE supports channel bandwidths up to 20 MHz, and it is unlikely that spectral efficiency can be improved much beyond current LTE performance targets. Therefore the only way to achieve significantly higher data rates is to increase the channel bandwidth. IMT-Advanced sets the upper limit at 100 MHz, with 40 MHz the expectation for minimum performance. In order for LTE-Advanced to fully utilize the wider bandwidths of up to 100 MHz, while keeping backward compatibility with LTE, a carrier aggregation scheme has been proposed. Carrier aggregation consists of grouping several
LTE “component carriers” (CCs) (e.g. of up to 20 MHz), so that the LTE-Advanced devices are able to use a greater amount of bandwidth (e.g. up to 100 MHz), while at the same time allowing LTE devices to continue viewing the spectrum as separate component carriers. Additionally, in order to meet the requirements of IMT-Advanced as well as those of 3GPP operators, LTE-Advanced considers the use of bandwidths in the following spectrum bands (in addition to those already allocated for LTE) [8]:

- 450–470 MHz band (identified in WRC-07 to be used globally for IMT systems).
- 698–862 MHz band (identified in WRC-07 to be used in Region 22 and nine countries of Region 3).
- 790–862 MHz band (identified in WRC-07 to be used in Regions 1 and 3).
- 2.3–2.4 GHz band (identified in WRC-07 to be used globally for IMT systems).
- 3.4–4.2 GHz band (3.4–3.6 GHz identified in WRC-07 to be used in a large number of countries).
- 4.4–4.99 GHz band.

Because most spectrum is occupied and 100 MHz of contiguous spectrum is not available to most operators, the ITU has allowed the creation of wider bandwidths through the aggregation of contiguous and non-contiguous component carriers. Thus spectrum from one band can be added to spectrum from another band in a UE that supports multiple transceivers. Figure 1. 1 shows an example of contiguous aggregation in which two 20 MHz channels are located side by side. In this case the aggregated bandwidth covers the 40 MHz minimum requirement and could be supported with a single transceiver. However, if the channels in this example were non-contiguous—that is, not adjacent, or located in different frequency bands—then multiple transceivers in the UE would be required.
The term component carrier used in this context refers to any of the bandwidths defined in Release 8/9 LTE. To meet ITU 4G requirements, LTE-Advanced will support three component carrier aggregation scenarios: intra-band contiguous, intra-band non-contiguous, and inter-band non-contiguous aggregation. The spacing between center frequencies of contiguously aggregated component carriers will be a multiple of 300 kHz to be compatible with the 100 kHz frequency raster of Release 8/9 and at the same time preserve orthogonality of the subcarriers, which have 15 kHz spacing. Depending on the aggregation scenario, the n x 300 kHz spacing can be facilitated by inserting a low number of unused subcarriers between contiguous component carriers. In the case of contiguous aggregation, more use of the gap between component carriers could be made, but this would require defining new, slightly wider component carriers.

![Figure 1.1 Carrier aggregation in contiguous bandwidth (Intra-band, contiguous).](image)
Figure 1.2 Carrier aggregation in non-contiguous bandwidth, single band (Intra-band, non-contiguous).

Figure 1.3 Carrier aggregation in non-contiguous bandwidth, multiple bands (Inter-band, non-contiguous).

An LTE-Advanced UE with capabilities for receive and/or transmit carrier aggregation will be able to simultaneously receive and/or transmit on multiple component carriers. A Release 8 or 9 UE, however, can receive and transmit on a single component carrier only. Component carriers must be compatible with LTE Release 8 and 9.

In Release 10, the maximum size of a single component carrier is limited to 110 resource blocks, although for reasons of simplicity and backwards
compatibility it is unlikely that anything beyond the current 100 RB will be specified. Up to 5 component carriers may be aggregated. An LTE-Advanced UE cannot be configured with more uplink component carriers than downlink component carriers, and in typical TDD deployments the number of uplink and downlink component carriers, as well as the bandwidth of each, must be the same. More details about carrier aggregation are available in [7–9].

1.2.2 Coordinated multipoint transmission and reception (CoMP)

Cooperative Multipoint (CoMP) transmission and reception is a framework that refers to a system where several geographically distributed antenna nodes cooperate with the aim of improving the performance of the users served in the common cooperation area. Multiple eNBs may cooperate to determine the scheduling, transmission parameters, and transmit antenna weights for a particular UE. This cooperation will depend on a high-capacity backhaul link being available between eNBs. The objective of CoMP is to reduce interference for a UE set in the network that is close to multiple eNBs and therefore experiences an interference-limited environment. The interference to these UE sets may be reduced and can be predicted if there is some coordination between the interfering eNBs and the serving eNB.

CoMP techniques are being studied for both the downlink and the uplink transmission paths. In the downlink, two main CoMP transmission techniques are envisioned: cooperative scheduling/beamforming and joint processing. Their main difference lies in the fact that in the former scheme it is only one eNB that transmits data to the UE, although different eNBs may share control information. In the latter scheme, many eNBs transmit data simultaneously to the same UE. In the uplink, however, only a coordinated scheduling approach is envisioned. Coordinated multipoint will be studied further for 3GPP Release 11, [7–10].
1.2.3 Relays

LTE-Advanced is considering relaying for cost-effective throughput enhancement and coverage extension. The use of relays will allow the following improvements [8]:

- Coverage extension in rural areas.
- Temporary network deployment.
- Cell-edge throughput improvement.
- Urban or indoor throughput enhancement.

These improvements can be grouped as “coverage extension” and “throughput enhancement”. A relay node (RN) is connected wirelessly to the radio access network via a donor cell. In the proposals for Release 10, the RN will connect to the donor cell’s eNB (DeNB) in one of two ways [7]:

- In-band (in-channel), in which case the DeNB-to-RN link shares the same carrier frequency with RN-to-UE links.
- Out-band, in which case the DeNB-to-RN link does not operate in the same carrier frequency as RN-to-UE links.

Relays can be classified according to the layers in which their main functionality is performed as:

- A Layer 1 (L1) relay (Amplify and Forward) is also called a repeater. It takes the received signal, amplifies it and forwards it to the next hop.
- A Layer 2 (L2) relay (Decode and Forward) works up to the Medium Access Control (MAC) and Radio Link Control (RLC) layers, which enables the relay to decode transmissions before retransmitting them and thus minimize the interference created by Amplify and Forward relays.
- A Layer 3 (L3) or higher-layer relay can be thought of as a wireless eNB that uses a wireless link for backhaul instead of a wired and expensive link.

Effect of relaying on coverage and capacity has been discussed in [11–13]. The concept of dynamic relaying is proposed in [14]. More details about relaying can be found in [7], [8], [10], [15–17].
1.2.4 Heterogeneous Networks

In heterogeneous networks (HetNets) low-power nodes are distributed throughout macrocell networks. Low-power nodes can be micro eNBs, pico eNBs, home eNBs (HeNBs, for femtocells), relays, and distributed antenna systems (DASs). These types of cells operate in low-geometry environments and produce high interference conditions. Such deployments enable optimization of network performance at relatively low cost.

As the network becomes more complex, the subject of radio resource management is growing in importance. Work is ongoing to develop more advanced methods of radio resource management including new self-optimizing network (SON) features. Additionally, CoMP and intercell interference coordination (ICIC) techniques can play a critical role in obtaining good performance within heterogeneous deployments. Further information on heterogeneous and femtocell networks can be found in [7], [18–21].

1.2.5 Key Technologies for Rel-12 and Beyond

The biggest challenge facing mobile operators and their technology suppliers is in satisfying the exponential growth in data traffic. LTE networks are already providing headline speeds approaching 100 Mbps, but these are only possible under ideal conditions on lightly loaded networks and where user equipment is close to the base station radio antenna. Many technologies and features introduced in previous releases are being enhanced and supplemented with new additions in Releases 12 and 13. The following relevant candidate technologies has been identified [22]:

- Vertical and 3D beamforming.
- Relay Backhaul Enhancement.
- Enhanced MDT (Minimization of Drive Tests).
New licensed bands, including higher frequencies for hot-spot demand zones will be introduced. This will be used in combination with unlicensed spectrum, if suitable, while possibly exploiting cognitive radio techniques to access and manage the latter.

Vertical and 3D beamforming techniques can mitigate inter-cell interference more effectively even without inter-eNB coordination. Moreover, massive antenna beamforming with arrays of as many as 64 antenna elements will enable additional frequency reuse within cell sectors. Beamforming can utilize the vertical domain by vertical sectorization, reaching capacity improvement over the traditional sectorization solution [23].

The MDT is expected to be enhanced so as to collect sufficient information for knowing e.g. following aspects to further reduce operators’ OPEX [22]:

- User perceived QoS at boundary of LTE and UMTS cell.
- Coverage problems caused by Closed Subscriber Group (CSG) cells.
- Altitude information when UE locates indoor.
- Inter Radio Access Technology (RAT) interference on the same frequency.

Moreover, Radio technologies and frequency bands focusing on LTE are expected to develop new solutions for public safety uses and proximity services (device-to-device, D2D) to overcome interoperability problems among different emergency service providers. Resilience to earthquake, tsunami and hurricane are increasingly important for public safety users. So, while D2D complies with LTE-based standardized technologies, it can still become pretty useful if the network has been wiped out in a natural disaster [24].

1.3 Thesis Background and Context

Recently, direct D2D communication as an underlay network to IMT-Advanced cellular networks [1] has been proposed. D2D represents a promising technique that is expected to provide efficient utilization of the
available wireless spectrum. Moreover, this technique has also been proposed as a new technology component for LTE-Advanced that is expected to provide access to the Internet and local services using licensed bands that can guarantee a planned environment. In comparison, unlicensed spectrum operation of Bluetooth and WLAN causes uncertainty as to whether the spectrum and services are truly available.

D2D current research areas include the study of D2D communication and cellular users interference, which are discussed in [1] and [25], where a power control optimization and coordination mechanism is used. The concept behind this coordination mechanism is to select one of four different resource allocation modes; downlink resource sharing, uplink resource sharing, separate resource sharing and conventional cellular system mode. Results in [1] show that by properly defining the maximum power on the D2D link, a good D2D link signal-to-interference-plus-noise ratio (SINR) is achieved while at the same time the impact on the cellular network is minor. Additionally, The results in [1] show that significant gains in the sum rate can be achieved by enabling D2D communications compared to the conventional cellular system. Necessary additions to an LTE-Advanced network to enable D2D session setup and management are proposed in [26]. In [27], a study of the potential D2D communication gains when used as an underlay to the downlink of a cellular network is presented where it is shown that multi-antenna receivers are required to achieve sufficient signal-to-interference-plus-noise ratios (SINRs) that allow D2D communication when D2D connections share the same cellular resources.

Another research trend that has potential to boost the overall cellular spectral efficiency is Interference Alignment (IA) [6]. Simply put, IA allows signal vectors to be aligned in such a manner that they cast overlapping shadows at the receivers where they constitute interference while they continue
to be distinct at the intended receivers [2]. Using IA, the interference channel is shown not to be essentially interference limited. IA offers the wireless interference channel with $K$ transmitter–receiver pairs the ability to simultaneously provide each user the opportunity to send at a data rate equal to half of his interference-free channel capacity to his desired receiver, even though the number of users $K$ can be arbitrarily large. Cadambe and Jafar (CJ) [2] have shown that the achievable degrees of freedom are bounded by the number of symbol extensions, and it is possible to achieve $K/2$ degrees of freedom per orthogonal time and frequency dimension as the number of channel extensions reaches infinity. This result allows the degrees of freedom to grow linearly with the number of users without cooperation in the form of message sharing thus allowing MIMO behavior. IA requires coding over multiple orthogonal frequency and time dimensions (symbol extensions of the channel) which eliminates the need for multiple antennas as in the MIMO situation.

On another front, it is known that Channel state information (CSI) is indispensable for achieving the full benefits of MIMO technology while lessening the complexity impact incurred through MIMO transmission and reception. The CSI makes it possible to adapt transmissions to current channel conditions, which is crucial for achieving reliable communication with high data rates in MIMO systems. CSI can be obtained via sending training symbols in the time domain or pilots in the frequency domain (if OFDM is used) that could be used to estimate the channel at the receiver side. The receiver then feeds back the channel estimates to the transmitter. Usually, the channel state information needs to be quantized since they will be sent to the transmitter over a limited-rate feedback channel. In situations where the feedback is severely limited, a challenging issue is how to quantize the information needed at the
transmitter and then how much improvement in the associated performance can be obtained as a function of the amount of feedback available.

There are two main approaches to implement channel state feedback: quantizing the channel or quantizing properties of the transmitted signal. It is apparent, however, that channel quantization offers an intuitively simple approach to closed-loop MIMO, but lacks the performance of more specialized feedback methods [29].

Interference alignment schemes for K-user interference channels have been employed to realize the full multiplexing gain under the assumption that CSI is ideally known at each transmitter. However, the assumption of the perfect CSI is almost impossible to realize at the transmitters, especially for quantized feedback systems using feedback links with finite bandwidth.

1.4 Thesis Overview and Organization

This thesis is organized as follows:

Chapter 1: In this chapter, we give an overview of the literature that represents the basis to the work in this thesis. We present a new promising technology component that has been proposed to IMT-Advanced cellular networks and is expected to provide efficient utilization of the available wireless spectrum which is called Device-to-Device Communication. Moreover, we talk about a new trend in wireless cellular networks that has changed the intuitive inferences first thought by earlier work on degree of freedom region characterization. Finally, we discuss the importance of channel state information in wireless networks and how this information can be obtained in both transmitters and receivers.

Chapter 2: In this chapter, we go through the main research results in the area of interference alignment where we introduce some of the different
approaches used to design the interference alignment schemes in: wireless X networks and the K-user interference channel. Then, we summarize some of the challenges faced when designing such schemes.

Chapter 3: In this chapter, we present the D2D system model. Then, we discuss some of the basic properties of wireless channels which are important for any channel model and we present the WINNER parameters of the B3 channel model used in our simulations in chapter 5. Finally, we give an overview of the WINNER channel model and how it can be used to set up a system level simulation model.

Chapter 4: This chapter gives an overview of the Device-to-Device communications technology. First, we discuss the advantages it can bring to the cellular networks. Then, we present some of the situations where it can be used and be of benefit. Finally, we present the work that addresses the interference issue with users deployed in normal cellular operation.

Chapter 5: In this chapter, we propose a framework for radio resource and Interference management in D2D underlay network via Clustering and Interference Alignment based on reusing radio resources over smaller distances. Specifically, we show that in a D2D environment, it is possible to achieve significant gains in attainable rates by constructing clusters of D2D pairs and reuse the available radio resources over the clusters. Additionally, within a cluster, it is possible to further enhance the spectral efficiency by constructing small-sized groups of D2D pairs over which IA is applied to offer additional degrees of freedom. Results in this chapter demonstrate that resource reuse over the clusters offer overall rate increase proportional to the number of formed clusters. In addition, interference alignment offers up to 33% increase in the overall rates in the high transmission power regimes compared to the normal Point-to-Point (P2P) communication.
Chapter 6: In this chapter and for the special case of 3-user IC for both SISO and MIMO systems, we propose new strategies that aim at minimizing the quantization error through partial processing at receivers and reduction of the amount of feedback data to send to the transmitters. The proposed limited feedback strategies is shown to significantly reduce the processing complexity required for minimizing quantization errors at the receivers compared to the scheme proposed in [1] and interestingly improves spectral efficiency performance as well.

Chapter 7: This chapter concludes the whole work and makes recommendations for promising areas of future research.
2 Interference Alignment Overview

2.1 Introduction

In the absence of precise capacity characterizations, researchers have pursued asymptotic and/or approximate capacity characterizations. Capacity characterizations have been found for centralized networks (Gaussian multiple access and broadcast networks with multiple antennas), but capacity characterizations for most distributed communication scenarios remain long standing open problems.

It can be argued that the most preliminary form of capacity characterization for a network is to characterize its degrees of freedom (DoF). The degrees of freedom represent the rate of growth of the network capacity with the log of the signal to noise ratio (SNR). In most cases, the spatial degrees of freedom turn out to be the number of non-interfering paths that can be created in a wireless network through signal processing at the transmitters and receivers. While time, frequency and space all offer degrees of freedom in the form of orthogonal dimensions over which communication can take place, spatial degrees of freedom are especially interesting in a distributed network.

Recent work on degrees of freedom characterization for interference networks led to the emergence of a new concept called interference alignment (IA), which has challenged the conventional throughput limits of both wired and wireless networks. This new concept has pointed out some of the earlier work incorrect inferences such as:

1. The number of degrees of freedom for a wireless network with perfect channel knowledge at all nodes is an integer.
2. The degrees of freedom of a wireless network with a finite number of nodes are not higher than the maximum number of co-located antennas at any node [2].
Interference alignment allows many interfering users to communicate simultaneously over a limited number of signalling dimensions (bandwidth) by confining the interference at each receiver into a space spanned by a small number of dimensions, while keeping the desired signals separable from interference. This enables the desired signals to be projected into the null space of the interference and thereby can be recovered free from interference. Interestingly, interference alignment does for wireless networks what MIMO technology has done for the point to point wireless channel. In both cases the capacity, originally limited to $\log(1 + SNR)$, is shown to be capable of linearly increasing with the number of antennas. While MIMO technology requires nodes equipped with multiple antennas, interference alignment works with the distributed antennas naturally available in a network across the interfering transmitters and receivers. For example, in the $K$-user wireless interference channel, interference alignment allows each user to simultaneously send at a data rate equal to half of his interference-free channel capacity to his desired receiver, even though the number of users $K$ can be arbitrarily large. Simply put, interference alignment suggests that interference channels are not fundamentally interference limited.

In this chapter, we will go through the main research results in the area of interference alignment. First, we will introduce some of the different approaches used to design an interference alignment scheme in: wireless $X$ networks and the $K$-user interference channel (IC). Then, we will summarize some of the challenges faced when designing such schemes.

### 2.2 Interference Alignment in Different Wireless Channels

#### 2.2.1 The Wireless $X$ Network

The $X$ network is a communication network, which consists of $M$ transmitters and $N$ receivers. There is a message to be sent from each
transmitter to each receiver, thus constituting $MN$ independent messages that need to be sent from all transmitters to all receivers. The Multiple access channel (MAC), the broadcast channel (BC), and the interference channel (IC) are all special cases of $X$ networks. Thus, any outer bound on the degrees of freedom region of an $X$ network is also an outer bound on the degrees of freedom of all its sub-networks. A general outer bound on the degrees of freedom region of an $M \times N$ wireless $X$ network when using interference alignment is derived in [4]. Three different scenarios are discussed in [4]; the case when all nodes are equipped with single antennas, the case where either $M = 2$ or $N = 2$, and a scrap on the case where all nodes are equipped with $A$ antennas. In all cases, channel coefficients are assumed to be time varying or frequency selective and drawn from a continuous distribution. A perfect interference alignment scheme is also constructed in this paper when the number of receivers $N = 2$ or the number of transmitters $M = 2$. This scheme achieves exactly the outer bound of degrees of freedom with a capacity characterization within $O(1)$, where the “$O$” notation is defined as follows:

$$f(x) = O(g(x)) \iff \lim_{x \to \infty} \frac{f(x)}{g(x)} = 0.$$  

Furthermore, other interference alignment schemes are designed in this paper to come close to the outer bound on degrees of freedom.

In Figure 2.1, an example of a $2 \times 2$ user $X$ network is shown where a $4/3$ degrees of freedom are shown to be achievable using interference alignment over 3 signaling dimensions, i.e., 3 antennas per user. In this example, both users are allowed to transmit two data where $x_{ij}$ represents the transmitted data stream from transmitter $j$ intended to receiver $i$, $V_{ij}$ represent the precoding vectors at transmitter $j$, and $H_{ij}$ represents the channel coefficients between transmitter $j$ and receiver $i$. 

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2.2.1.1 Wireless $X$ Network with Single-Antenna Nodes

An asymptotic interference alignment scheme is proposed in [4], where the total number of degrees of freedom achieved is shown to be close to $\frac{MN}{M+N-1}$ with a capacity characterization within $O(\log(SNR))$ for single-antenna nodes and using large channel extensions. Another useful result that is shown in this paper is that when the number of transmitters is much larger than the number of receivers or vice versa, the $M \times N \times X$ network achieves a number of degrees of freedoms that is close to that achieved by an $M \times N$ MIMO network. This is evident when $M \gg N$ or $N \gg M$, as $\frac{MN}{M+N-1}$ becomes very close to $\min(M, N)$.

2.2.1.2 Wireless $X$ Network with Multiple-Antenna Nodes

It is also shown in [4] that for an $M \times N \times X$ network where each node is equipped with $A$ antennas, the total number of degrees of freedom is outer bounded by $\frac{AMN}{M+N-1}$ per orthogonal time and frequency dimension. Moreover, a
lower bound of $\frac{AMN}{M+N-1/A}$ is shown to be achievable in [4]. This lower bound is close to the outer bound if either $M$ or $N$ is reasonably large.

In [30], a study on the case of the 2-user X network where each node is equipped with three antennas is conducted. Three different precoding schemes based on iterative random search approach are considered in this paper. The three schemes are designed based on zero-forcing (ZF), minimum mean square error (MMSE), and maximum signal-to-leakage ratio (SLR) criteria. The proposed schemes are designed to satisfy the interference alignment conditions and at the same time optimize system performance. Three optimization approaches are considered; for ZF criteria, the optimization objective is to maximize the minimum of SINRs for each data stream, for MMSE criteria, the optimization objective is to minimize the mean square error (MSE) of the detected data, and for SLR criteria, the precoding vectors are optimized based on maximization of SLR, and the receive steering vectors are optimized based on maximization of SINR. Simulation results show that the proposed schemes are very efficient and can provide good performance for the MIMO network.

2.2.2 The $K$-User Interference Channel

For a $K$-user IC, we have $K$ pairs of transmitters and receivers, where each receiver has a message from its intended transmitter and receives interference from the other $K$-1 transmitters. It is shown in [2] that, with perfect channel knowledge, the frequency-selective IC is not interference limited. In fact, after the first two users, additional users do not compete for degrees of freedom and each additional user is able to achieve 1/2 degree of freedom without hurting the previously existing users. What makes this result even more remarkable is that linear scaling of degrees of freedom with users is achieved without cooperation in the form of message sharing that may allow MIMO behaviour.
In Figure 2.2, an example of the 3-user IC is shown where interference alignment is applied. In this example, interference alignment is applied over 3 frequency dimensions and user 1 is allowed to transmit two data streams while users 2 and 3 are allowed to transmit one data stream where \( x_i \) represents the transmitted data stream at transmitter \( i \), \( V_i \) represents the precoding vector at transmitter \( i \), and \( H_{ij} \) represents the channel coefficients between transmitter \( j \) and receiver \( i \).

**Figure 2.2** An Example 3-user Interference Channel.
2.2.2.1 K-User Interference Channel with Single Antenna Nodes

Networks of single-antenna nodes with no cooperation between the transmitters or receivers could be considered uninteresting from the degrees of freedom perspective as intuition would suggest that these networks could only have one degree of freedom. However, it is shown in [2] that by using interference alignment, the total number of spatial degrees of freedom for the K-user IC is almost surely $K/2$ per orthogonal time and frequency dimension. Thus, only half the spatial degrees of freedom are lost due to distributed processing of transmitted and received signals on the interference channel.

In [2], Cadambe and Jafar (CJ) proposed an interference alignment scheme that is able to achieve a total of $K/2$ degrees of freedom as the number of channel extensions reaches infinity, for any arbitrarily chosen $K$. For the special case of 3-user interference channel, it is shown that the CJ scheme can offer a total of $\frac{3n+1}{2n+1}$ degrees of freedom, where $n$ is an integer that is related to the number of channel extensions $N$ by $N = 2n + 1, n \in \mathbb{N}$. It is also shown that the design of the precoding vector for the proposed interference alignment scheme becomes more complex as the number of users and channel extensions increase. Thus, we find that much of the following work on IA precoding design focuses on the case of 3-user IC and with limited channel extensions.

In [31], Shen, Host-Madsen, and Vidal (SHV) proposed an enhancement to the achievable rate in terms of high SNR offset and at the same time maintain the optimality of degrees of freedom achieved by the CJ scheme. Two new schemes have thus been proposed for the $K$-user IC with single antenna per node. While one of the schemes try to find better precoding subspaces than those obtained by the CJ scheme, the other one optimizes the precoding vectors within the subspaces obtained from this scheme. It is shown that by using the second scheme and by choosing ortho-normal precoding matrices at the transmitters, an increase in sum rate with probability one can be observed.
In [32], Douglas and Murat (DM) provided two new algorithms that optimize the precoding subspaces, which maximizes the data rate performance of the CJ scheme while maintaining the achievable degrees of freedom. One design is obtained as a global solution of a constrained convex (concave) optimization problem that maximizes the sum rate. The other design provides a low complexity closed-form solution to a constrained maximization problem with a suboptimal sum rate objective function. The proposed algorithms optimize the precoding subspaces obtained by CJ scheme to maximize the data rate performance of the scheme. It can also be combined with the ortho-normalization procedure proposed by SHV to achieve further gains in sum rate.

Both CJ and SHV schemes are designed to work with receivers employing ZF decoding. On the other hand, the proposed schemes by DM are mainly designed to work with receivers employing MMSE decoding.

2.2.2.2 The K-User Interference Channel with Multiple Antenna Nodes

It is shown in [2] that for the 3-user IC with \( M > 1 \) antennas at each node, one can achieve \( 3M/2 \) degrees of freedom with constant channel matrices, i.e., multiple frequency slots are not required. It is also shown that exactly \( 3M/2 \) degrees of freedom are achieved by zero forcing and interference alignment, which gives us a lower bound on sum capacity of \( 3M/2 \log(1 + \text{SNR}) + O(1) \). Since the outer bound on sum capacity is also \( 3M/2 \log(1 + \text{SNR}) + O(1) \) we have an \( O(1) \) approximation to the capacity of the 3-user MIMO IC with \( M > 1 \) antennas at all nodes.

Two precoding design schemes have been proposed in [2], one is for the case when \( M \) is even and the other is for the case when \( M \) is odd. Both schemes are shown to provide a total of \( 3M/2 \) degrees of freedom.
Thus, we can conclude that the 3-user interference network where all nodes are equipped with multiple antennas can achieve optimal degrees of freedom without the need for long channel extensions.

2.3 Summary

In this chapter we have provided a basic overview on interference alignment, gone through some of the different approaches used to design an interference alignment scheme in: wireless $X$ networks and the $K$-user interference channel (IC), and here we introduce some of the challenges faced when designing such schemes. Two main issues faced by interference alignment schemes are [33]:

1. *The number of alignment constraints* grows very rapidly as the number of interfering users is increased. For instance, in a $K$ user interference channel, each of the $K$ receivers needs an alignment of $K - 1$ interfering signal spaces, for a total of $O(K^2)$ signal space alignment constraints. Since there are only $K$ signal spaces (one at each transmitter) to be chosen in order to satisfy $O(K^2)$ signal space alignment constraints, the problem can quickly appear infeasible.

2. *The diversity of channels* which enables the relativity of alignment — which in turn is the enabling premise for interference alignment—is often a limiting factor, e.g., when each node has only one antenna and all channels are constant across time and frequency. Limited diversity imposes fundamental limitations on the extent to which interference can be aligned in a network.

Further issues to be dealt with by interference alignment schemes include the imperfect, noisy, localized and possibly delayed nature of channel knowledge feedback to the transmitters where such knowledge is crucial to achieve interference alignment. The corresponding solutions to such issues are discussed in [33].
3 Background on System and Channel Models

3.1 Introduction

General Packet Radio Service (GPRS) system is the first standardized cellular system that enabled the transmission of packets with a limited data rate of only $56 - 114$ kbit/second. Since then, the momentum has led us to cellular systems with significant improvement in data transmission capability. The commitment to higher data system throughput has been guaranteed for next generation cellular systems by IMT-Advanced systems. With the introduction of the MIMO technique and iterative codes such as Turbo codes and Low-Density Parity Check (LDPC) codes, the link-level performance has been pushed very close to the Shannon limit. These technological components are merged to standardized 3G cellular systems and beyond, for example, Wideband Code Division Multiple Access (WCDMA) and 3GPP Long Term Evolution (LTE) systems. As further improvement on link-level performance is limited, the research energy is tilting towards system-level perspectives.

3G and beyond cellular systems have a frequency reuse factor of 1 to improve the spatial spectral efficiency. With a smaller frequency reuse distance, the problem of inter-cell interference becomes an issue. Users located around the cell border are more vulnerable to the co-channel interference from the neighboring cells. As users in the cell center usually experience a more satisfactory SINR, research activities have been put in improving the throughput of cell edge users. In LTE-Advanced systems, proposals such as the deployment of relays and Coordinated Multi-Point (CoMP) transmission [16], [17], [9] are discussed. In this work, we consider the improvement enabled by inter-user communication. The considered scenario is illustrated in Figure 3.1 where inter-user communication between users is assumed. As illustrated
in Figure 3.1, the capability of inter-user communication enables the possibility of D2D and relaying communication, in addition to the normal cellular operation.

![Diagram](image)

**Figure 3.1** A cellular network with D2D and Relaying Concept

### 3.2 Basic Properties of Wireless Channels

In communication networks, the underlying physical propagation channel places a fundamental limit, described by the Shannon’s law, on performance. The propagation channel characteristics are dependent on the environments. While the propagation channel is stationary and more predictable for a wired channel, a wireless channel can be extremely random. A wireless channel can
vary from a simple Line-of-Sight (LOS) scenario to a sophisticated one that is highly affected by obstacles and the movement of terminal devices. As a generic analysis of wireless channels is not easy, modeling of the wireless channels is typically done in a statistical fashion. To capture the possibilities and restrictions that a propagation channel imposes on a wireless system, a wireless channel model should be able to reflect the essential properties of the environment honestly. Many wireless channel models have been developed for different applications.

The ultimate task for a channel model is to output estimates of the experienced path loss of a signal during its radio propagation, so that the statistics of the estimated path loss can simulate the real situation.

The term path loss indicates the reduction in power density of the signal in its propagation. Path loss is the result of many effects, such as distance-dependent loss, reflection, diffraction, and scattering, and is very environment-specific. The same transmission distance between a transmitter and a receiver at two different locations does not indicate the same path loss, as the surrounding environmental clusters are typically very different. A precise channel model capable of predicting the path loss between two positions requires careful consideration of all kinds of effects encountered during the radio propagation. These kinds of precise channel models are not plausible for applications in wide area communication due to their complexity. Typically, path loss is considered to consist of several parts that take into account different effects during radio propagation. They are distance-dependent path loss, shadow fading, and multipath fading.

3.2.1 Distance-Dependent Path Loss

The mechanism of electromagnetic wave propagation reveals that, in free space, the strength of a transmitted signal decays with a rate that is inversely
proportional to the square of the travel distance. The simplest explanation is to consider an omni-directional antenna. The emitted power transmits towards all directions. The perceived power density in a unit area is then inversely proportional to the square of the travel distance. In a realistic environment, the transmitted signal encounters obstructions so that it is not attenuated in exactly the same way as in free space. However, the fundamental physical rules teach us that the signal strength is still decaying with increasing travel distance in a certain manner.

### 3.2.2 Shadow Fading

The shadow fading term considers the environmental clusters where the transmitter and the receiver reside, respectively. The shadowing term simulates various effects that are introduced due to the obstructions encountered in the radio propagation, such as reflection, diffraction, etc. Inherently, shadow fading is a random loss around the average loss specified by the distance-dependent loss. Measurements have shown that a log-normal distribution describes the effect of shadow fading well. Thus, the path loss can be expressed by

\[
L(d) = L(d_0) + 10n \log \frac{d}{d_0} + \xi \sigma, \tag{3.1}
\]

where \( n \) is the path loss exponent indicating the rate at which the path loss increases with distance, \( \xi \sigma \) is a zero-mean Gaussian distributed random variable (in dB) with standard deviation \( \sigma \), and \( L(d_0) \) is the loss measured from a reference distance \( d_0 \).

### 3.2.3 Multipath Fading

Multipath fading is used to describe the rapid fluctuations of the received signal strength over a short movement. This is induced by the fact that the received signal is the sum of interfering signals arriving at different times. The
difference in the arrival time of the interfering signals is because they arrive at the receiver via different transmission paths. In systems with carrier frequency in the order of Giga Hz, a movement of the receiver in the order of one meter is more than enough to bring the channel from a constructive interference to a destructive interference situation.

3.3 Channel Model

A comprehensive evaluation of communication systems requires channel models that allow realistic modelling of the propagation conditions in different environments. For this, channel modelling for different environments has been one of the earliest research fields in wireless communications. On the other hand, leaving the capability of capturing the propagational insights aside, we do need reference models based on which different techniques are able to be compared. A number of reference channel models have been developed for this purpose. Examples include COST [34], WINNER [5], and ITU [35]. A comparison between COST 273 and WINNER is available in [36]. In this work, we consider a WINNER B3 – Indoor hotspot scenario.

The WINNER B3 channel model represents the propagation conditions pertinent to operation in a typical indoor hotspot, with wide, but non-ubiquitous coverage and low mobility (0-5 km/h). Traffic of high density would be expected in such scenarios, as for example, in conference halls, factories, train stations and airports, where the indoor environment is characterised by larger open spaces, where ranges between a BS and a MS or between two MS can be significant. Typical dimensions of such areas could range from 20 m × 20 m up to more than 100m in length and width and up to 20 m in height. Both LOS and NLOS propagation conditions could exist.

Distance-dependent path loss is calculated from the parameters A, B, C as
where \( d \) is the distance between the transmitter and the receiver in \([m]\), \( f_c \) is the system frequency in \([GHz]\), the fitting parameter \( A \) includes the path-loss exponent, parameter \( B \) is the intercept, parameter \( C \) describes the path loss frequency dependence, and \( X \) is an optional, environment-specific term (e.g., wall attenuation in the A1 NLOS scenario). The most important characteristics of the path loss model are given in Table 3.1.

### Table 3.1 Parameters of the WINNER II B3 Path Loss Model

<table>
<thead>
<tr>
<th>BS height ((h_{BS}))</th>
<th>6 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS height ((h_{MS}))</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Distance ( d ) ([m])</td>
<td>5 m &lt; ( d ) &lt; 100 m</td>
</tr>
<tr>
<td>LOS path loss</td>
<td>( A = 13.9, B = 64.4, C = 20 )</td>
</tr>
<tr>
<td>NLOS path loss</td>
<td>( A = 37.8, B = 36.5, C = 23 )</td>
</tr>
<tr>
<td>LOS shadow fading std. ([dB])</td>
<td>3 dB</td>
</tr>
<tr>
<td>NLOS shadow fading std. ([dB])</td>
<td>4 dB</td>
</tr>
</tbody>
</table>

### 3.4 WINNER Channel Model Overview

The European WINNER (wireless world initiative new radio) project began in 2004 with the aim to develop a new radio concept for beyond third generation (B3G) wireless systems. Work Package 5 (WP5) of the WINNER projects focused on multi-dimensional channel modelling for carrier frequencies between 2 and 6 GHz and bandwidths up to 100 MHz. In total six organisations were formally involved in WP5 (Elektrobit, Helsinki University of Technology, Nokia, Royal Institute of Technology (KTH), the Swiss Federal Institute of Technology (ETH) and the Technical University of Ilmenau).

In September 2007, the WINNER channel model - Phase II (WIM2) was described. This model is evolved from WIM1 and the WINNER II interim channel models. The WINNER channel model – Phase 1 (WIM1) was described at the end of 2005. WIM1 has a unified structure for indoor and
outdoor environments and is based on double-directional measurement campaigns carried out in the 5 GHz ISM2 band with bandwidths of up to 120 MHz. It covers six different propagation scenarios, i.e. (i) indoor small office, (ii) indoor hall, (iii) urban microcell, (iv) urban macrocell, (v) suburban macrocell, and (vi) rural. Both line-of-sight (LOS) and non-line-of-sight (NLOS) propagation conditions are catered for. The WIM2 extended the propagation scenarios to: (i) indoor office, (ii) large indoor hall, (iii) indoor-to-outdoor, (iv) urban microcell, (v) bad urban microcell, (vi) outdoor-to-indoor, (vii) stationary feeder, (viii) suburban macrocell, (ix) urban macrocell, (x) rural macrocell, and (xi) rural moving networks. In the course of the WINNER project channel models were implemented in MATLAB and made available through the official web site.

The WIM2 channel model is defined for both link-level and system-level simulations. WINNER MIMO radio channel model enables system level simulations and testing. This means that multiple links are to be simulated simultaneously. System level simulation may include multiple base stations, multiple relay stations, and multiple mobile terminals. The channel model takes the user defined parameters, the MIMO radio link parameters and antenna parameters as an input. Channel matrices can be generated for multiple BS-MS links with one function call. The output is a multi-dimensional array which contains the channel impulse responses for the given radio links. In addition, the randomly drawn channel parameters for each link will be given as an output.
3.4.1 Coordinate Systems in WIM2

The WIM2 Channel Model uses two main coordinate systems in order to fully describe positions and directivity of antenna elements in 3D space, the 2 coordinate systems used are:

a) **GCS – Global Coordinate System:**
   used to define radio-network system layout, and as a reference system for polarization).

b) **ACS – Array Coordinate System:**
   describes array geometry and rotated radiation patterns of antenna elements.

Furthermore, the channel model uses a third **Element-Coordinate-System (ECS)** to represent radiation pattern of each antenna element which is not suitable since it increases simulation complexity. Therefore, it is concluded that the most suitable representation for element field patterns is **Effective-Aperture-Density-Functions (EADF)** (See [37] for details) defined for all elements in the array in respect to common ACS.
3.4.2 Antenna Arrays Definition and Construction

A certain type of antenna array requires only single construction, which is performed independently from WIM simulations - in a pre-processing phase. It is not a good strategy to construct arrays each time when WIM is used, instead defined antenna arrays are stored and retrieved when needed [5].

In order to define an antenna array it is necessary to define its geometry (positions and rotation of elements), and to provide the element field patterns.

Following are some examples of the supported options for Array Structures, where in Example1, the antenna array position and rotation of each array element are defined with respect to the ACS and field pattern samples are defined in the ECS. On the other hand, Example2 and Example3 define array elements positions and rotations according to the common array types ‘UCA’
and ‘ULA’, respectively, defined in the next section. Moreover, field patterns are defined in the ECS and ACS, respectively.

```
Example1=AntennaArray('Pos',Position,'Rot',Rotation, 'FP-ECS', FieldPattern);
Example2=AntennaArray('UCA',N,r, 'FP-ECS', FieldPattern);
Example3=AntennaArray('ULA',N,d, 'FP-ACS', FieldPattern);
```

3.4.2.1 Antenna Arrays Definition – Array Geometry (AG)

We notice that Geometry is defined using ‘Pos’ and ‘Rot’ arguments followed by $ELNUMx3$ matrix, where $ELNUM$ is the number of elements. We also notice that Array Geometry can be defined using common array types Uniform-Circular-Array ‘UCA’ and Uniform-Linear-Array ‘ULA’ with few parameters only.

For UCA, elements are placed starting from x-axis (phi=0) every $\Delta\phi = \frac{2\pi}{N}$, $\Delta\phi = \frac{2\pi}{N}$, and $n^{th}$ element is rotated for $(n-1)\Delta\phi$ $(n-1)\Delta\phi$ in counter-clockwise direction. On the other hand, ULA elements are placed along x-axis in such a way that the center of the array is at $[0; 0; 0]$. In ULA, when $N$ is even, there is no antenna element at $[0; 0; 0]$, where $N$ represent the number of Antenna Elements.

As default geometry, if there are no parameters defining geometry, single antenna positioned at centre of ACS, without rotation is considered. Table 3. 2, explains the parameters of Array Geometry.
Table 3.2 Array Geometry Parameters [5]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group</th>
<th>Definition</th>
<th>Default value</th>
<th>Unit</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>AG</td>
<td>ELNUMx3 matrix, where n-th row contains ( [x, y, z] ) position of n-th antenna element in ACS.</td>
<td>-</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Rotation</td>
<td>AG</td>
<td>ELNUMx3 matrix, where n-th row contains ( [\text{Rot}_x; \text{Rot}_y; \text{Rot}_z] ) rotation of n-th antenna element around axes of ACS.</td>
<td>( 0_{\text{rad}} )</td>
<td>rad</td>
<td></td>
</tr>
<tr>
<td>ELNUM</td>
<td>AG</td>
<td>Number of physical antenna elements in array. Used as 1st argument for 'UCA' and 'ULA' options. Implicitly defines the first dimension of Position, Rotation and FieldPattern.</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>AG</td>
<td>Radius of UCA.</td>
<td>1</td>
<td>m</td>
<td>Optional</td>
</tr>
<tr>
<td>d</td>
<td>AG</td>
<td>Distance between antenna elements in ULA.</td>
<td>( 1/\text{ELNUM} )</td>
<td>m</td>
<td>Optional</td>
</tr>
</tbody>
</table>

3.4.2.2 Antenna Arrays Definition – Field Pattern (FP)

The field patterns of individual array elements are described using the EADF defined in ACS. This was done because EADF has proven to be superior in terms of memory requirements and interpolation errors. The two different argument types, ‘FP-ACS’ and ‘FP-ECS’, are used to distinguish between FPs that are expressed in ECS and ACS.

As default field pattern, if neither ‘FP-ACS’ nor ‘FP-ECS’ are defined, isotropic, vertically polarized antenna with XPD=\( \infty \) is used. Table 3.3, explains the parameters of Field Pattern.
Table 3.3 Array Geometry Parameters [5]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group</th>
<th>Definition</th>
<th>Default value</th>
<th>Unit</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>FieldPattern</td>
<td>FP</td>
<td>4D array containing field patterns of antenna elements. The dimensions of FieldPattern are [ELNUM Pol EL AZ] = SIZE(FieldPattern)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POL</td>
<td>FP</td>
<td>Number of polarizations used to characterize FieldPattern. The first dimension in FieldPattern is used to store vertical polarization, the second for horizontal. Missing polarization dimensions of FieldPattern are substituted with zeros.</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EL</td>
<td>FP</td>
<td>Number of equidistant FieldPattern samples taken over elevation angle.</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ</td>
<td>FP</td>
<td>Number of equidistant FieldPattern samples taken over azimuth angle.</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevation</td>
<td>FP</td>
<td>Vector of elevation angles corresponding to 3rd dimension of FieldPattern.</td>
<td>-</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td>Azimuth</td>
<td>FP</td>
<td>Vector of azimuth angles corresponding to 4th dimension of FieldPattern.</td>
<td>-</td>
<td>deg</td>
<td></td>
</tr>
</tbody>
</table>

3.4.2.3 Arrays Construction Examples

The function `arrayparset` is used to generate six different array structures. The function `dipole(Az, Slant)` is used to generate the field pattern samples at different azimuth values defined by Az for a dipole antenna slanted by the value Slant. For example, `Arrays(1)` represent a ULA array with two antenna elements spaced 1 cm from each other.

```matlab
function Arrays=arrayparset
NAz=120; %3 degree sampling interval
Az=linspace(-180,180-1/NAz,NAz);
pattern=zeros(1,2,1,length(Az)); %[NumElem Pols(2) NumEle NumAz]
pattern(1,:,1,:)=dipole(Az,12); % slanted by 12 degree
Arrays(1)=AntennaArray('ULA',1,0.01,'FP-ECS',pattern,'Azimuth',Az); %ULA-1 1cm spacing
Arrays(2)=AntennaArray('ULA',4,0.01,'FP-ECS',pattern,'Azimuth',Az); %ULA-4 1cm spacing
Arrays(3)=AntennaArray('ULA',8,0.01,'FP-ECS',pattern,'Azimuth',Az); %ULA-8 1cm spacing
Arrays(4)=AntennaArray('UCA',4,0.01,'FP-ECS',pattern,'Azimuth',Az); %UCA-4 1cm radius
Arrays(5)=AntennaArray('UCA',8,0.01,'FP-ECS',pattern,'Azimuth',Az); %UCA-8 1cm radius

NAz=360; %1 degree sampling interval
Az=linspace(-180,180-1/NAz,NAz);
pattern=ones(2,2,1,NAz);
dist = 3e8/5.25e9*0.5;
Arrays(6)=AntennaArray('ULA',2,dist,'FP-ECS',pattern); % isotropic antenna
```
3.4.3 System Level Layout Design

3.4.3.1 Construction of Semi-Random Layout

The function `layoutparset.m` is used to generate random positions for all stations, and assigns random scenario and propagation conditions to all links. MSs and BSs locations are randomly generated within e.g. the 500x500m$^2$ cell area where a default height of 32 m is used for BSs and 1.5 m for MSs. The following command is used to call the function `layoutparset.m`.

```
layoutpar=layoutparset(MsAAIdx, BsAAIdxCell, K, Arrays)
```

where;

- **Arrays**: Vector of *Antenna Array* definitions, as can be generated by the methods described in the previous section.
- **MsAAIdx**: Vector of UE’s/MS’s *Antenna Arrays* indices.
- **BsAAIdxCell**: Vector of Cell/BS *Antenna Arrays* indices.
- **K**: Number of links which are formed by random BS-MS pairing.

There are some assumptions that are made by the WIM2 channel model for the multi-sector base station, these assumptions are:

- Different sectors of multi-sector-BS are closely located and therefore links between a MS and different sectors in the same BS exhibit high correlation.
- Links from a MS to different sectors are still not identical due to the specific array orientation, and directional filtering, and because they use different low-level parameters.
- Sectors of the other BSs are assumed to be located “very far away”, so that there is no considerable correlation between links from a specific MS toward sectors belonging to different BSs.
3.4.3.1.1 Example Layout Parameters

```
>> MsAAIdx = [1 1 2 3];
>> BsAAIdxCell = {{[1 3]; [2]; [1 1 2]}};
```

In this scenario 4 MS are considered where the first two will use array type defined in \textit{Arrays(1)} the third MS will use \textit{Arrays(2)} and the fourth \textit{Arrays(3)}. Moreover, three multi-sector-BSs are present in the scenario where:

- The first has two sectors, that are using \textit{Arrays(1)} and \textit{Arrays(3)}.
- The second is one-sector-BS with \textit{Arrays(2)}.
- The third has three sectors: two of them are using \textit{Arrays(1)} and one is using \textit{Arrays(2)}.

3.4.3.2 Layout Manual Editing

To edit the scenario layout manually, we start from the previous semi-random layout and then:

- (BS, MS) pairs could be defined by modifying 	exttt{layoutpar.Pairing}.
- Position and orientation of each station could be manually adjusted using 	exttt{layoutpar.Station.Pos/Rot} parameters.
- Change of per-link scenario and propagation conditions can be modified through 
  	exttt{layoutpar.ScenarioVector/PropagConditionVector}

These parameters are given in more detail in Table 3.4 and Table 3.5.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group</th>
<th>Definition</th>
<th>Default value</th>
<th>Unit</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stations</td>
<td>POS + ANT</td>
<td>Parameters of the stations being included into system simulations.</td>
<td>see Table 5.5</td>
<td>-</td>
<td>MATLAB structure</td>
</tr>
<tr>
<td>Pairing</td>
<td>-</td>
<td>A 2xK matrix whose k-th column contains indices of Stations constituting k-th link.</td>
<td>see layoutparse t.m</td>
<td>-</td>
<td>To define pairing Stations are ordered: first all BS Sectors, than MS (1 AA is assumed per MS)</td>
</tr>
<tr>
<td>NofSect</td>
<td>-</td>
<td>A parameter defining the number of sectors in each of the BSs.</td>
<td></td>
<td>-</td>
<td>see layoutset.m</td>
</tr>
<tr>
<td>ScenarioVector</td>
<td>ENV</td>
<td>A 1xK vector mapping scenarios to links. Scenarios are [1=A1, 2=A2, 3=B1, 4=B2, 5=B3, 6=B4, 7=B5a, 8=B5c, 9=B5f, 10=C1, 11=C2, 12=C3, 13=C4, 14=D1, 15=D2a].</td>
<td>ones(1,K)</td>
<td>{1,2,...,15}</td>
<td></td>
</tr>
<tr>
<td>PropagConditionVector</td>
<td>ENV</td>
<td>A 1xK vector mapping propagation condition (NLOS/LOS) to links. If WIMPAR UseManualPropCondition = 'yes', link propagation conditions (NLOS=0/LOS=1) are defined by this vector.</td>
<td>zeros(1,K)</td>
<td>{0,1}</td>
<td>Possible values 0=NLOS and 1=LOS.</td>
</tr>
<tr>
<td>StreetWidth</td>
<td>ENV</td>
<td>A parameter for B1 and B2 path loss model. Average width of the streets, same for all users.</td>
<td>20</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>NumFloors</td>
<td>ENV</td>
<td>A parameter for A2/B4 path loss model. NumFloor is the floor number in which the indoor MS/BS is located. E.g. in A2 scenario NumFloors is 5 if BS is located on the 5th floor. On ground floor (=street level) NumFloor = 0.</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>NumPenetratedFloors</td>
<td>ENV</td>
<td>A parameter for A1 NLOS path loss model [1], table 4-4. Number of penetrated floors between BS and MS.</td>
<td>0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Dist1</td>
<td>POS</td>
<td>Distance definition for B1 and B2 path loss model. Dist1 is a distance from BS to the &quot;last line-of-sight point&quot;, typically street crossing, see [1], fig 4-3. Default value is NaN, which denotes random distance determination in PATHLOSS function.</td>
<td>NaN</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
### Table 3.5 Stations (Array) Parameters [5]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group</th>
<th>Definition</th>
<th>Default value</th>
<th>Unit</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos</td>
<td>POS</td>
<td>( [x, y, z] ) position in GCS</td>
<td></td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Rot</td>
<td>POS</td>
<td>( [\text{Rot}_x, \text{Rot}_y, \text{Rot}_z] ) rotation of array by respective axes of GCS</td>
<td></td>
<td>rad</td>
<td></td>
</tr>
<tr>
<td>Element</td>
<td>ANT</td>
<td>vector of array elements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CommonAperture</td>
<td>ANT</td>
<td>EADF common to all elements (if empty each element has to provide its own pattern). This parameter is used only during Array construction when provided field patterns are defined in ECS. In this case rotation of ECS 3D field patterns is performed to calculate their EADF representation in ACS.</td>
<td></td>
<td></td>
<td>Temporary parameter used only in preprocessing phase</td>
</tr>
<tr>
<td>Aperture</td>
<td>ANT</td>
<td>if preprocessing is used, this field contains EADF for the whole array</td>
<td></td>
<td></td>
<td>structure</td>
</tr>
<tr>
<td>Velocity</td>
<td>POS</td>
<td>( [v_x, v_y, v_z] ) velocity of this station</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 3.4.3.2.1 Manual Edited Example

In this example, we present a single three sector base station along with two mobile stations.

```matlab
>> MsAAIdx = [1 1];
>> BsAAIdxCell = {[1 1 2]};
>> layoutpar=layoutparset(MsAAIdx, BsAAIdxCell, NumOfLinks, Arrays);
>> layoutpar.ScenarioVector=10*ones(1, NumOfLinks); % C1 scenario
% first we define the position and rotation of the three sector base station.
% defining sector #1 parameters
>> layoutpar.Stations(1,1).Pos=[20; 30; 30];
>> layoutpar.Stations(1,1).Rot=[0; 0; 0];
>> layoutpar.Stations(1,1).Velocity=[0; 0; 0];
% defining sector #2 parameters
>> layoutpar.Stations(1,2).Pos=[20; 30; 30];
>> layoutpar.Stations(1,2).Rot=[0; 0; 2*pi/3]; % 120 degree rotation in z-direction
>> layoutpar.Stations(1,2).Velocity=[0; 0; 0];
% defining sector #3 parameters
>> layoutpar.Stations(1,3).Pos=[20; 30; 30];
>> layoutpar.Stations(1,3).Rot=[0; 0; 4*pi/3]; % 240 degree rotation in z-direction
>> layoutpar.Stations(1,3).Velocity=[0; 0; 0];
% defining MS#1 parameters
>> layoutpar.Stations(1,4).Pos=[60; 90; 1.5];
>> layoutpar.Stations(1,4).Rot=[0; 0; 0];
```
3.4.4 WIM2 Model Input and Output Parameters

The Matlab command that is used to call the WIM2 channel model is:

```
[H, [DELAYS], [FULL_OUTPUT]] = WIM (WIMPAR, LAYOUTPAR, [INITVALUES])
```

Where the global simulation parameters are defined in the input parameter WIMPAR, such as:

- CenterFrequency [Hz]
- NumTimeSamples
- SampleDensity
- DelaySamplingInterval [sec]
- PathLossModelUsed
- ShadowingModelUsed

The SampleDensity should be set as follows

\[
\text{wimpar.SampleDensity} = \frac{\text{speed_of_light}}{2 \times \text{CarrierFreq} \times \text{Channel_Sampling_Time} \times \text{newMsVelocity}}
\]

This is to have a time sample interval as follows

\[
\text{The time sample interval} = \frac{\text{wavelength}}{(\text{MsVelocity} \times \text{SampleDensity})}
\]

We notice that for block fading, \( \text{channel\_sampling\_Time} \) should be equal to 1 TTI (one sub-frame). On the other hand, for fast fading, \( \text{channel\_sampling\_time} \) should be equal to \( T_s \), where

\[
T_s = \frac{1}{F_s}
\]  

(3.3)

3.4.4.1 Initialization of the Structural Model Parameters

This option is provided to enable consecutive calls of \text{wim.m} functions, without (default) random initialization of structural parameters. This means that structural parameters obtained after one simulation run could be used to initialize new run, preserving in that way previous channel conditions – what somehow means continuation of the previous simulation run. This enables performing seamless channel simulation in several simulation runs.

\[
\text{[INITVALUES]} \text{new\_run} = [\text{FULL\_OUTPUT}] \text{old\_run}
\]  

(3.4)

3.4.4.2 WIM2 Model Output

The cell array \( H \) of size \( K \), number of links, is a multi-dimensional array which contains the channel impulse responses for the given radio links. Each element of this cell array contains a \( U \times S \times N \times T \) matrix, where

- \( U \) number of receiver elements
- \( S \) number of transmitter elements
- \( N \) number of paths/clusters/taps
- \( T \) number of time samples
In addition, the randomly drawn channel parameters for each link will be given as an output, FULL_OUTPUT, which is a Matlab structure with the elements given in Table 3. 6.

### Table 3. 6 FULL_OUTPUT Elements [5]

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Definition</th>
<th>Unit</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>delays</td>
<td>A K x N matrix of path delays. This is identical to the second output argument.</td>
<td>sec</td>
<td></td>
</tr>
<tr>
<td>path_powers</td>
<td>A K x N array of path powers.</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>aoas</td>
<td>A K x N x M array of subpath angles of departure</td>
<td>degrees</td>
<td></td>
</tr>
<tr>
<td>aoas</td>
<td>A K x N x M array of subpath angles of arrival</td>
<td>degrees</td>
<td></td>
</tr>
<tr>
<td>path_losses</td>
<td>A K x 1 vector</td>
<td>linear scale</td>
<td></td>
</tr>
<tr>
<td>MsBSDistance</td>
<td>1 x K vector of MS-BS distances</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>shadow_fading</td>
<td>A K x 1 vector</td>
<td>linear scale</td>
<td></td>
</tr>
<tr>
<td>signas</td>
<td>A K x 4 vector of per link large scale parameters (ASD ASA DS SF)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>propag_condition</td>
<td>A K x 1 vector indicating LOS / NLOS condition (0=LOS, 1=NLOS)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Keluster</td>
<td>A K x 1 vector defining narrowband K-factors of links.</td>
<td>linear scale</td>
<td>Only with LOS</td>
</tr>
<tr>
<td>Phi_LOS</td>
<td>Final phases for LOS path, K x 1 array.</td>
<td>deg</td>
<td>Only with LOS</td>
</tr>
<tr>
<td>scatterer_freq</td>
<td>A K x N x M array of subpath Doppler frequencies</td>
<td>Hz</td>
<td>Only with B5 CDL</td>
</tr>
<tr>
<td>subpath_phases</td>
<td>A K x N x M array giving the final phases of all subpaths when polarization option is used, A K x P x N x M array, where P=4. In this case the second dimension includes the phases for [VV VH HV HV] polarized components.</td>
<td>degrees</td>
<td></td>
</tr>
<tr>
<td>delta_t</td>
<td>A K x 1 vector defining time sampling interval for all links.</td>
<td>sec</td>
<td></td>
</tr>
<tr>
<td>IndexOfDividedClust</td>
<td>A K x 2 matrix. Index to two strongest clusters. These clusters are spread to three delay positions if parameter IntraClusterDfUsed = 'yes'.</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>xpr</td>
<td>A K x N x M array of cross-polarization coupling power ratios.</td>
<td>linear scale</td>
<td>Only with PolarisedArrays case.</td>
</tr>
</tbody>
</table>

3.4.4.3 OFDM Channel Outputs

In this section we will describe the steps used to convert the obtained channel impulse responses for the given radio links into the frequency domain. In this section we will only consider the case where each node is equipped with one element antennas. Thus, the dimensions of the K elements of the Winner channel model cell array output H is confined to a 1 x 1 x N x T matrix, simply referred to, from now on, as an N x T matrix. The WIM2 model provides the output matrix DELAYS of size K x N which represents the time delay for each of the K links for N paths.
First, we round the values of DELAYS to be represented as integers of the sampling time $T_S$.

\[
\text{Delays\_rounded} = \text{round}(\text{DELAYS}\times F_s);
\]

The number of taps corresponding to the system sampling time is then calculated as

\[
\text{Tap\_Number} = \max(\text{Delays\_rounded})+1;
\]

For each tap, we find all the paths that have time delay that is close or equal to the tap time delay and then add their corresponding gain and phase shift response

\[
\text{Tap\_positions} = \text{find}(\text{Delays\_rounded}(K,:) == \tau-1);
\]

\[
h(\tau, t) = \sum(h(K)(\text{Tap\_positions}, t));
\]

where $\tau$ represents the tap time delay index and $t$ represents the time sample. The matrix $h(\tau, t)$ is then converted to the frequency domain using the Fast Fourier Transform (FFT) with a size suitable for the system sampling frequency.

### 3.4.4.4 Sample Output

In this section we provide an example output for the mean gain per resource block (RB) for the two links provided in the earlier example in section 3.4.3.2.1. Table 3. 7 summarizes the parameters used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency (GHz)</td>
<td>2</td>
</tr>
<tr>
<td>Sampling Frequency (MHz)</td>
<td>30.72</td>
</tr>
<tr>
<td>FFT Size</td>
<td>2048</td>
</tr>
<tr>
<td>Number of RBs</td>
<td>100</td>
</tr>
</tbody>
</table>

In Figure 3. 5, average channel gain per RB is shown for the first link for 100 RBs. The average channel gain for the second link is shown in Figure 3. 6.
Figure 3. 5  Average Channel Gain per RB for Link #1.

Figure 3. 6  Average Channel Gain per RB for Link #2.
4 Device-to-Device Communication underlay in Cellular Networks

The demand on enhanced data transmission for diverse mobile multimedia rich services has been addressed in next generation communication systems under, for example, the scope of IMT-Advanced systems. One aspect that deserves more attention in considering IMT-Advanced systems is the emerging needs for high data rate local services. In [26], [27], a proposal has been made to handle local P2P traffic by enabling direct D2D communication as an underlay to the IMT-Advanced cellular systems. The introduction of D2D communication achieves higher spectral efficiency as D2D connections reuse the same resources as the underlying cellular network. The mutual interference between D2D and normal cellular connections can be coordinated since users engaged in D2D communication are still under the control of their serving BSs (e.g., eNodeBs in LTE-Advanced systems). D2D communication is a promising technology component which allows a tight integration into an LTE-Advanced network [27].

4.1 Introduction

D2D communication as an underlay to a cellular network is illustrated in Figure 4.1. Direct communication between UE_1 and UE_2 via D2D radio is controlled by the eNodeB. The cellular services are provided to other UE as usual with the D2D operation transparent to them. In principle, D2D communication is different from cooperative relaying in that the D2D connections are to handle possibly bidirectional local P2P traffic in a more spectrally efficient manner than it would be when using the BSs as relay i.e., normal cellular operation.
D2D communication can operate in different modes for resource sharing both in cellular DL/UL transmission. The cellular network can assign dedicated resources to the D2D links so that the mutual interference between the two types of systems is negligible. Alternatively, the D2D connections can reuse the same resources used by the cellular links nonorthogonally. Similar to the principles of cognitive radio systems, it is crucial that D2D communication does not generate harmful interference to the primary system (i.e., normally operating cellular system). This is easier with D2D communication as it is controlled in cooperation with the cellular network. D2D communication enables cellular operators to offer cost-efficient access to the licensed spectrum [26] as those promised by Wireless Local Area Networks (WLAN). WLANs have become increasingly popular in recent years as they provide economic and convenient access to the Internet and local services in the license exempt bands. Similar services enabled by D2D communication exhibit additional advantage of providing a planned environment for more reliable transmissions.

Different standards addressing the needs for D2D operation in the same bands as infrastructure-based operation can be found, such as Wi-Fi\(^1\). For Wi-Fi technology that is based on IEEE 802.11 standards, UE can sense and access the radio medium only if the channel is free. Accordingly the access points do not have full control over the resources used by the ad hoc D2D links. Wi-Fi technology supports a Wi-Fi direct mode that allows direct D2D connection between peers. However, Wi-Fi direct mode requires users to manually pair the peers, as is the case for Bluetooth technology. In the D2D underlay communication, the pairing can be handled by BSs and thus provides new use cases and better user experiences [26].

\(^1\) see http://www.wi-fi.org/
4.2 Coexistence of Cellular and Ad Hoc Networks

The embedded ad hoc network introduced in earlier work is for relaying purpose. In principle, ad hoc networks can be embedded for handling local P2P traffic in cellular networks since this is how the ad hoc networks were designed for in the very beginning. Nevertheless, some problems remain for applying the ad hoc networks in a two-tier network. Firstly, the spectral utilization of the
licensed bands is not improved since two different frequency bands are assumed for two different air interfaces. In addition, the ad hoc D2D connection supported by WLAN protocols may be inefficient as interference coordination is usually not possible. Although opportunistic use of ad hoc D2D connections by WLANs provides performance improvement, WLANs cannot be counted on as reliable means for this purpose [26].

The D2D operation discussed in [26] and [25] assumes that the cellular and D2D connections are under the control of cellular networks. The traffic originated from users can be either provided through the cellular or the D2D connections. Thus, D2D and cellular traffic can be treated as coming from the same pool. The interference situation can be planned for effective interference management. In addition, the possibility of selecting different resource sharing schemes in [25] facilitates more efficient spectral usage. This allows not only better spectral utilization of licensed bands, but also provides the possibility of more effective protection of the cellular network.

4.3 New Local Services with D2D Communication

D2D communication is envisioned in [38] as an enabler of new types of local services such as the case where a media server is installed at a rock concert tour from which visitors can download promotional material using the D2D radio. The organizers of the rock concert simply put up the media server which registers to the cellular network and it is immediately operational. Alternatively, the cellular network could handle the traffic from the media server. However, this would cause a heavy load to the cellular network. When using the D2D radio, the cellular network can handle phone calls and internet data traffic without the additional load from the promotional material. Moreover it can control the interference from the D2D communication to the cellular network to limit its impact to the cellular communication.
As a second alternative, WLAN or Bluetooth could be used. However, since they operate in the license exempt band, the organizers cannot be sure if the media server will work at every place they visit. There is always the possibility of the presence of interfering communication systems or other sources of interference.

The D2D operation itself can be transparent to the user. Once the user enters a URL, the network detects traffic to the media server and hands it over to a D2D connection. Since both D2D devices have already a secure connection to the cellular network, it is easy to setup a secure D2D connection. Thus, compared to WLAN or Bluetooth no manual pairing or access point definition is required.

The D2D communication also allows sharing of for example photos or videos taken by a mobile device between users. The videos can be shared without pairing Bluetooth devices or setting up an ad-hoc connection. Again the cellular network will hide the complexity of setting up the D2D connection from the user.

### 4.4 Cooperative Transmission Through Network Coding

The D2D communication between terminals is an enabler of cooperative transmission and relay-based communications through network coding which is studied in [27]. A novel network protocol applied to uplink cellular traffic protocol with an efficient decoding approach at the receiver is proposed. Network Coding is currently emerging in multi-hop multi-user wireless networks. Comparing to traditional routing techniques, network coding allows information processing in the intermediate nodes. Performance gains in energy-efficiency, fairness, robustness, or coverage are obtained. It is shown in [38] that carefully designed non-binary network codes can substantially decrease
outage probability/frame error rate (FER), for multiple-user cooperative communications. Moreover, a study of user grouping is conducted to determine which set of users shall be selected and grouped to perform the network coding operation as it was obvious that random selection will not yield the optimal capacity of the system.

4.4.1 Network Coding

Figure 4.2 illustrates the usage of network codes on top of the channel codes. The relaying and local messages are encoded by network codes in the relay node. The network coding scheme is fixed in each relay node (deterministic codes). The network codes are designed such that any two successfully received blocks out of four transmission blocks can rebuild two source message blocks.

In the first time slot, the two source nodes use proper channel coding to transmit their own messages $I_1$ and $I_2$ respectively (in e.g., different frequency-orthogonal channels). In the second time slot, if both relay nodes successfully decode the channel codes, the transmitted messages for UE$_1$ and UE$_2$ are encoded using network coding as $I_1 + I_2$ and $I_1 + 2I_2$, respectively. Here “+” operation is in, finite field or Galois field, GF(4). Then, the resulting blocks are channel encoded and transmitted. If a relay node cannot decode correctly, it instead repeats its own message using the same channel code. Upon receiving repeated codewords, the BS performs MRC (maximum ratio combination) of these codewords and decodes.

The receiver can rebuild the source blocks $I_1$ and $I_2$ upon receiving any two of the four transmitted blocks and a network error event occurs only when three or more blocks cannot be decoded correctly from channels. Thus, a higher diversity gain is achieved and better performance is expected.
4.4.2 User Grouping

A random selection of users groups will not yield the optimal system capacity. More specifically, if we choose to pair users randomly then we could end up pairing users with non-complementary channel conditions to the base station, and consequently losing the advantage provided by network coding. The proposed network coding scheme allows only one of the network coded pair to increase its SINR through the relay connection whereas the other user has to be decoded through its direct connection's SINR. Therefore, if both of the grouped users have a bad channel towards the base station, one of them will be decoded with a low SINR. Similarly, if both users have a good channel towards the base station, the capacity would decrease as compared to a direct transmission due to the time division among the users and the base station.
Consequently, grouping users with complementary characteristics is essential in order to ensure a good performance of the network coding scheme. More details about user grouping can be found in [38].

4.5 Interference Coordination in a D2D Enabled Cellular Network

Proposals for D2D communication underlaying cellular networks that share the radio resources non-orthogonally can be found in [25], [26], [39], [40], [41]. A single air interface for D2D and cellular operation is assumed. Furthermore, in these proposals, D2D users are under the control of the cellular network to facilitate the coordination of mutual interference. Tight cooperation of D2D and cellular operation is envisioned, depending on the extent of local awareness of the BSs to the interference situation between cellular and D2D users sharing the same resources.

The four different possibilities considered on how to share the available resources are:

- **DL resource sharing:** D2D communication happens in DL resources so that all the DL resources of the cellular user are interfered.
- **UL resource sharing:** Similar to DL resource sharing, D2D communication happens in UL resources, and all the UL resources of the cellular user are interfered.
- **Separate resource sharing:** The D2D communication takes half of the available resources from the cellular user, either from DL or UL resource. There is no interference between cellular and D2D communication.
- **Cellular mode sharing:** The D2D users communicate with each other through the BS that acts like a relay node. They take half of the available resources either from the DL or the UL resources of the cellular user.
Noting that this mode is conceptually the same as a traditional cellular system.

To incorporate D2D operation into a cellular network without harmful impact on cellular operation, resources of cellular UL phases provide features that admit less overload than cellular DL phases. Figure 4. 3 demonstrates the direct and interfering links in both UL and DL phases. In the cellular UL phases, the transmit power of cellular users is power-controlled to maintain a target, for example, received SNR at the BSs. The impact of D2D transmitters on the BS can thus be learnt without any extra mechanism compared to state-of-the-art cellular architectures. In principle, no such power control scheme is assumed in the cellular DL phases. Assuming the awareness of the SINR target and the power control results i.e., the maximum allowed transmit power, at D2D users, D2D transmitters can decide the D2D transmit power to emit a tolerable interference to cellular UL transmissions.

The performance of D2D connections can be improved with slightly more D2D-oriented considerations. For D2D operation in the cellular DL phases, conservative D2D transmit power can be planned to limit the degradation of cellular DL users. However, this results in limited space for D2D operation in the cellular DL resources. For enhancement, an interference-avoiding MIMO scheme is proposed in [39]. As the interference to the D2D receivers is generated by the BSs in the cellular DL phases, it is possible to mitigate the interference by precoded DL transmission if the BSs are equipped with multiple antennas. By knowing the interference channel between a BS and a D2D receiver, the BS can align its transmission to the null space of the interference channel. Furthermore, the BS is still free to apply any MIMO transmission scheme for its DL transmission on the projected subspace. The results show significant SINR gain for D2D operating in cellular DL phases in the cost of minor cellular SINR degradation.
4.5.1 D2D Communication with Full CSI

With full CSI, the resource sharing between the cellular and D2D connections can be optimized [1], [25]. Considering a case where one cellular user (UE$_i$) and two D2D users (UE$_2$ and UE$_3$) share the radio resources, as illustrated in Figure 4.4, where $g_i$ is the channel response between the BS and UE$_i$ and $g_{ij}$ is the channel response between UE$_i$ and UE$_j$. The sum rate for sharing the resources non-orthogonally (Non-Orthogonal Sharing, NOS) can be found by summing up rates from the cellular link and the D2D link

$$R_{NOS}(P_c, P_d) = \log_2 \left( 1 + \Gamma_c(P_c, P_d) \right) + \log_2 \left( 1 + \Gamma_d(P_c, P_d) \right), \quad (4.1)$$

Where

$$\Gamma_c(P_c, P_d) = \frac{g_{1c}P_c}{g_{dc}P_d + I_c} \quad \text{and} \quad \Gamma_d(P_c, P_d) = \frac{g_{2d}P_d}{g_{cd}P_c + I_d}.$$

We have denoted by $g_{cd}$ the channel response of the interference link from the cellular connection to the D2D connection, and vice versa for $g_{dc}$. We used $I_c$ and $I_d$ to indicate the interference-plus-noise power at the receiver of the cellular link and the D2D link, respectively.

With a greedy sum rate maximization strategy, the optimal power allocation of (5.1) is a feasible solution of the optimization problem

$$\left( P_c^*, P_d^* \right) = \arg \max_{(P_c, P_d) \in \Omega_1} R_{NOS}(P_c, P_d), \quad (4.2)$$

$$\Omega_1 = \{ P_c, P_d \mid 0 \leq P_c, P_d \leq P_{\text{max}} \},$$

where $\Omega_1$ defines the feasible set of $(P_c, P_d)$. It is shown that the optimal power allocation to (4.2) is searched over the following 3 possible sets $\Delta \Omega_1 = \{ (P_c, P_d) : (0, P_{\text{max}}), (P_{\text{max}}, 0), (P_{\text{max}}, P_{\text{max}}) \}$ [42].
To prioritize the cellular connection, we can set a SINR constraint to lower-bounded $\Gamma_c$. In practice, the higher transmission rate is also constrained by the limited amount of modulation and coding scheme (MCS). Hence, one can impose an upper limit on the SINR. The sum rate optimization subject to the mentioned constraints is

$$ (P^*_c, P^*_d) = \arg \max_{(P_c, P_d) \in \Omega_2} R_{NOS}(P_c, P_d), $$

$$ \Omega_2 = \{P_c, P_d | 0 \leq P_c, P_d \leq P_{\text{MAX}}, \gamma_I \leq \Gamma_c(P_c, P_d) \leq \gamma_h, \Gamma_d(P_c, P_d) \leq \gamma_h \}, $$

(4.3)

where $\Omega_2$ defines the feasible set of $(P_c, P_d)$, $\gamma_h$ is the SINR needed for using the highest MCS, and $\gamma_I$ is the guaranteed SINR to prioritize the cellular connection.

In [25] and [1], the optimization is also performed for both transmit power and radio resources for an orthogonal resource sharing mode. The optimization of a reference mode where the BS is used as a relay for D2D operation (conceptually the same as traditional cellular connection) is addressed. As shown in [25] and [1], non-orthogonal resource sharing between D2D and cellular communication does not always yield better performance than orthogonal resource sharing where dedicated resources are assigned separately for both types of communication. Therefore, it is sensible to admit mode selection on resource sharing between D2D and cellular communication for better spectrum utilization, in a single cell scenario as illustrated in Figure 4.4, if the BS is empowered for coordination.

The optimization of resource sharing between paired connections does not impede the application of inter-cell interference control mechanisms for efficiently managing inter-cell interference based on the power control or resource scheduling. In fact, the resource sharing schemes in [1], [25] which aim at improving intra-cell spatial reuse of spectrum enabled by D2D underlay
communication shall work on top of the inter-cell interference control schemes from the perspective of overall system performance. The proposed mechanism in [26] for integrating D2D functionality in LTE-Advanced systems indicates that proper coordination from BSs, including mode selection, is feasible.

Figure 4.3 Illustration of direct and interfering links in a D2D enabled cellular network.
4.5.2 D2D Communication with Limited CSI

With practical considerations, the CSI between a transmission pair is acquired at the receiver by the insertion of training symbols at the transmitter. In time-varying channels, reliable CSI requires frequent enough insertion of training symbols. In addition, for Frequency Division Duplex (FDD) systems where the channel reciprocity property does not exist, the acquisition of DL CSI at the BSs requires users to feed the measurement of channel responses back. The feedback rate required for achieving reliable CSI at BSs depends on the channel fading rate, which is related to user mobility. In principle, reliable CSI at BSs is not problematic in state-of-the-art cellular systems such as 3GPP LTE [43]. However, for interference coordination in D2D underlay systems, additional loads on users for inter-user channel measurement are required. Tracing instantaneous CSI on inter-user links may indicate a high feedback rate.
(dependent on user mobility) which may not be favored for practical implementation. To reduce the amount of such channel reports, it is likely that users only report an average version of CSI. As instantaneous interference coordination such as the analysis in [25] requires reliable CSI, using only average CSI usually indicates performance degradation.

One interesting aspect of the D2D underlay system would be the achieved performance with very limited CSI for coordination. In [44], a single cell scenario with one cellular user and one D2D pair is studied, assuming only channel statistics on all the related links for coordination. The cellular user (UE₁) is assumed to reside in the cell area with uniform probability. One of the D2D users (UE₂) is assumed to stay at a fixed distance $D$ from the BS, and the other D2D user (UE₃) is assumed to reside at most $L$ distance from UE₂ with uniform probability, as illustrated in Figure 4. 5. The upper limit on the D2D transmission range can be justified by the fact that D2D communication is generically for short range communication. To prioritize the cellular services, the D2D transmit power is reduced to maintain a 3-dB SINR degradation of the cellular user at 0.05 outage probability. The results show that a dynamic power control based on the position of the D2D pair i.e., distance $D$, is more needed in the cellular UL phases. This is because in the cellular UL phases, the interference generated from the D2D transmission is only related to the distance $D$, but not the position of the cellular users. With such a power control scheme which admits only a small amount of D2D transmit power compared to the cellular transmit power, we observe that the realized D2D SINR is comparable or higher than the cellular SINR in most of the cell area.
Figure 4.5  System settings in [44].
5 Radio Resource and Interference Management in D2D Underlay via Clustering and Interference Alignment

Enabling underlay direct Device-to-Device (D2D) communication mode in future cellular networks has good potential for spectrally-efficient and low-latency support of local media services. Recently, it has become evident that shrinking the reuse distance over which wireless resources are reused is a key enabler for achieving high spectral efficiency. Moreover, as discussed in chapter 2, IA based transmission can enhance the capacity of a wireless network by providing more degrees of freedom. In this work, we propose a framework for radio resource management in D2D underlay network based on reusing radio resources over smaller distances as defined by constructing groups of the D2D pairs and using IA to manage interference. Firstly, we explore using IA techniques in a D2D as an effective means to manage interference in order to enhance spectral efficiency. We compare IA transmission and traditional point-to-point (P2P) transmission from the Bit-Error-Rate (BER) and sum-rate points of view. We also propose three grouping schemes for the D2D users into groups of 3-pairs such that IA can be applied using a limited number of signal extensions. Secondly, we propose clustering of D2D users, reuse radio channels over the clusters and then using IA within each group in the cluster enhance the sum rate. Specifically, we show that in a D2D environment, it is possible to achieve significant gains in attainable rates by constructing clusters of D2D pairs and reuse the available radio resources over the clusters. Additionally, within a cluster, it is possible to further enhance the spectral efficiency by constructing small-sized groups of D2D pairs over which IA is applied to offer additional degrees of freedom. Results demonstrate
that although traditional P2P transmission can achieve better BER performance; IA transmission is still able to achieve gains in the sum rate. We also show that resource reuse over the clusters offer overall rate increase proportional to the number of formed clusters. In addition, interference alignment offers up to 33% increase in the overall rates in the high transmission power regimes compared to the normal Point-to-Point (P2P) communication.

5.1 Introduction

Wireless communication systems are in continuous evolution as a result of the ever increasing demand for higher data rate services. Recently, direct device-to-device communication (D2D) as an underlay network to IMT-Advanced cellular networks [1] has been proposed which represents a promising technique that is expected to provide efficient utilization of the available wireless spectrum. This technique has been proposed as a new technology component for LTE-Advanced that is expected to provide access to the Internet and local services using licensed bands that can guarantee a planned environment. There are many advantages for enabling D2D communication: offloading the cellular system, reducing battery consumption, increasing bit-rate, increasing robustness to infrastructure failures as well as enabling new services.

On another front, recently, a new paradigm shift in the design of wireless systems has occurred where it has become evident that enhancing the proximity between the access network and the end users has the potential to provide the next performance leap in attainable rates via spatial spectrum reuse and to enhance indoor coverage as well [18]. LTE-Advanced provides means for deployment and planning of pico- and femto-cells, which are characterized by small transmission power and coverage radius thus enabling reuse of spectrum resources over a smaller area.
Additionally, IA which has the potential to boost the overall cellular spectral efficiency, as discussed in chapter 2, allows signal vectors to be aligned in such a manner that they cast overlapping shadows at the receivers where they constitute interference while they continue to be distinct at the intended receivers [2]. Using IA, the interference channel is shown not to be essentially interference limited. In contrast, IA offers the wireless interference channel with $K$ transmitter–receiver pairs the ability to simultaneously provide each user the opportunity to send at a data rate equal to half of his interference-free channel capacity to his desired receiver, even though the number of users $K$ can be arbitrarily large. Usually, calculation of precoding vectors required to apply IA becomes more complex as the number of users $K$ and correspondingly the number of symbol (channel) extensions increases. Thus, a good mass of previous research work focused on the 3-user interference channel.

Motivated by the above, in this work, we focus on how to benefit from the extra degrees of freedom that IA offers to further boost the capacity of macrocells, which enable underlay D2D communication. Towards that end, we will first compare the traditional point-to-point (P2P) transmission and two schemes that are used to apply IA technique from the Bit Error Rate (BER) and sum rate points of view. We will then propose a setup where we can use IA to boost the overall cellular network capacity in a D2D enabled network. Moreover, we propose and compare three different algorithms that group D2D pairs considering transmitting nodes positions, channel gains, and distance between transmitting and receiving nodes as criteria for grouping such that IA can be efficiently applied. Then, we show that in a D2D environment, it is possible to achieve significant gains in attainable rates by constructing clusters of D2D pairs and reusing the available radio resources over the clusters. Additionally, within a cluster, it is possible to further enhance the spectral efficiency by constructing small-sized groups of D2D pairs over which IA is
applied to offer additional degrees of freedom. We show that resource reuse over the clusters can provide an overall rate increase that is proportional to the number of formed clusters. In addition, interference alignment offers up to 33% increase in the overall rates in the high transmission power regimes.

5.2 Interference Alignment Versus Point-to-Point

5.2.1 IA Precoding Vectors Design

In calculating the interference alignment precoding vectors, we consider the case of 3-user Single-Input-Single-Output (SISO) interference channel shown in Figure 5.1. The three precoding matrices are defined as

\[ V_i(\omega) = \Omega(\omega) \Gamma_i, \quad (5.1) \]

where the \( N \) by \( N \) diagonal matrix, \( \Omega(\omega) \), is defined as a function of the \( N \) by 1 vector \( \omega = [\omega_1 \quad \omega_2 \quad \cdots \quad \omega_N]^T \), such that

\[ \Omega(\omega) = \begin{bmatrix} \omega_1 & 0 & 0 & 0 \\ 0 & \omega_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \omega_N \end{bmatrix}, \quad (5.2) \]

where \( N \) represents the number of channel extensions (frequency slots) and is related to \( n \) by \( N = 2n + 1, n \in \{1, 2, 3, \ldots\} \).

The elements of \( \omega \) are constrained to be within the set of all positive and real numbers excluding zero, i.e. \( \omega_i \in \mathbb{R}^+ \) for all \( i \).

The \( N \) by \( n+1 \) matrix \( \Gamma_1 \) is defined as

\[ \Gamma_1 = \begin{bmatrix} 1 & t_1 & \cdots & t_n \end{bmatrix}, \quad (5.3) \]

and the \( N \) by \( n \) matrices \( \Gamma_2 \) and \( \Gamma_3 \) are respectively defined as

\[ \Gamma_2 = (H_{32})^{-1}H_{31}\begin{bmatrix} 1 & t_1 & \cdots & t_{n-1} \end{bmatrix}, \quad (5.4) \]

\[ \Gamma_3 = (H_{23})^{-1}H_{21}\begin{bmatrix} t_1 & t_2 & \cdots & t_n \end{bmatrix}, \quad (5.5) \]
\[ T = H_{12}(H_{21})^{-1}H_{23}(H_{32})^{-1}H_{31}(H_{13})^{-1}, \]  
\[ (5.6) \]
where \( t_m = \text{diag}(T^m) \) for \( m = \{1, \ldots, n\} \). The function \( \text{diag}(.) \) creates a column vector comprised of the diagonal elements of its matrix input. \( H_{jk} \) represents the channel coefficients between transmitter \( k \) and receiver \( j \). By setting \( \omega \) equal to 1, the expression for the precoding matrices in (5.1) is equivalent to the set of precoders proposed by CJ scheme in [2]. But by factoring out the diagonal elements of \( \Omega \) from \( V_i \) and defining them as variable, a new \( \omega \) can be found that improves the sum rate which is the scheme proposed by DM in [32].

### 5.2.2 Receiver Design for the P2P and IA Models

Considering the 3-user interference channel shown in Figure 5.1, for the case of IA transmission, user 1 is allocated \( n + 1 \) streams of data while users 2 and 3 are both allocated \( n \) streams; and all three users transmit over an \( N \)-symbol extension of the channel. On the other hand, for the case of P2P transmission, all the three users are allocated \( N/3 \) streams of data each; and each user transmits over \( N/3 \) of the resources. Thus, in IA transmission, the three pairs will cause interference on each other. Using IA will allow receivers to eliminate interference, but due to the interference suppression filter, noise will be enhanced which will cause degradation in Signal-to-Noise Ratio (SNR).

The received signal at the \( i^{\text{th}} \) receiver for the case of P2P transmission and IA transmission are given respectively by

\[ \bar{Y}_i = \bar{H}_{ii} \bar{x}_i + \bar{Z}_i, \forall i \in \{1, 2, 3\}, \]  
\[ (5.7) \]
\[ Y_i = H_{i1}V_1x_1 + H_{i2}V_2x_2 + H_{i3}V_3x_3 + Z_i, \]  
\[ (5.8) \]
where \( \bar{H}_{jk} \) and \( H_{jk} \) represent the channel coefficients from transmitter \( k \) to receiver \( j \), \( \bar{x}_i \) and \( x_i \) represent the input signal of the \( i^{\text{th}} \) transmitter, and \( \bar{Z}_i \) and
\( Z_i \) represent the additive white Gaussian noise (AWGN) at the \( i^{th} \) receiver, in case of P2P transmission and IA transmission, respectively. \( \bar{Z}_i \) and \( Z_i \) are modeled as an independent and identically distributed, i.i.d., complex Gaussian vectors with zero mean and covariance matrix \( E[Z_i^H Z_i] = I_N \). \( \bar{H}_{jk} \) and \( H_{jk} \) are assumed to be drawn i.i.d. from a continuous distribution with absolute values assumed to be bounded between a non-zero minimum value and a finite maximum value. The signal power at the \( i^{th} \) transmitter is given by \( E[x_i^H x_i] = P_i \) where we assume that the transmit filter is normalized to unit power such that \( E[V_i^H V_i] = 1 \), where \( P_i \) indicates the available power at the \( i^{th} \) transmitter. The same value of transmit power is assumed for both transmission schemes.

The Zero Forcing (ZF) equalizer used to retrieve data from the received signal of (5.7) for the \( i^{th} \) receiver is given by

\[
\mathbf{C}_i = (\bar{H}^H_{ii} \mathbf{H}_{ii})^{-1} \bar{H}^H_{ii}. \tag{5.9}
\]

The interference suppression matrix for the received signal of (5.8) for the \( i^{th} \) receiver is given by

\[
\mathbf{U}_i = \text{null}\left( [H_{ij} V_j]^H \right) = \text{null}\left( [H_{ik} V_k]^H \right), i \neq j \neq k, \tag{5.10}
\]

where \( \text{null}(A) \) indicates the null space of the matrix \( A \) and \( [B]^H \) is the conjugate transpose of \( B \). The ZF equalizer in (5.9) is then used to retrieve data for the \( i^{th} \) receiver where \( \bar{H}_{ii} \) is the effective channel, \( \bar{H}_{ii} = U_i^H H_{ii} V_i \).
5.3 System Model

We consider an LTE-Advanced environment with a single sector hexagonal cell in isolation with radius $R$ with $N_{D2D}^{Users}$ D2D users uniformly distributed over the cell and that all of these users are in active mode. There are $N_{D2D}^{Pairs}$ (equal to $N_{D2D}^{Users}/2$) transmitters that need to communicate with $N_{D2D}^{Pairs}$ receivers, where $N_{D2D}^{Pairs}$ represents the number of D2D pairs. We also assume that the maximum distance between the transmitter and receiver of each pair is constrained to $L_{Max}$. Moreover, we assume a single omni-directional antenna per user. Additionally, we will only consider the D2D communication links, and we will consider scenarios such as airports, malls, or sports events, where

---

**Figure 5.1** Example of 3-user SISO interference alignment channel.
D2D communication is expected viable. We assume that the D2D and macro-cell users are assigned orthogonal resources. Hence, no interference is experienced among them. We also assume the availability of $N^{RB}$ resource blocks (RBs), which are divided into $N^{RB}_{Macro}$ RBs dedicated to macro-cell users, and $N^{RB}_{D2D}$ RBs dedicated to D2D communication.

We propose a resource management scheme mainly based on shrinking the resource reuse distance by forming “clusters” of D2D pairs and fully reuse the available resource blocks over these clusters. In addition, within each cluster we assemble the D2D pairs into “IA groups” where each group is comprised of three D2D pairs. The reason for the choice of the group size to be three is to reduce the complexity of IA precoding calculations. IA is then applied to the D2D links where resources are shared between pairs of the same IA group to further boost the cellular network spectral efficiency.

The example in Figure 5.2 illustrates the main idea of the proposed scheme. Firstly, clusters of D2D pairs are formed. The formation of clusters is based on transmitting nodes positions and is done using what we refer to as the position-based scheme (PBS) that is based on the Fuzzy C-Means Clustering algorithm [45], which will be explained later in the sequel. Secondly, IA groups within each cluster are formed using channel gains and distances between transmitting and receiving nodes. We propose three schemes for forming the IA groups:

1) The position-based scheme (PBS) that is based on the Fuzzy C-Means Clustering algorithm and which attempts to group D2D pairs such that groups are characterized by a small containing area.

2) The channel-based scheme (CBS) that is also based on the Fuzzy C-Means Clustering algorithm and which attempts to group D2D pairs such that in each group there is a pair with high, intermediate, and low direct channel gain.
3) A simple distance-based scheme (DBS) that combines the benefits of ensuring both small containing areas for the IA groups and the existence of at least one pair of high channel gain in each of the IA groups.

Since both the clusters and IA group formations use the Fuzzy C-Means clustering mechanism, we provide some background and the motivation for using this concept in the following section.

Define \( N^{Cl} \) as the number of clusters of D2D pairs to be formed and \( N_u^{Cl} \) as the number of D2D pairs per cluster where \( N_u^{Cl} = \frac{N_{pairs}}{N^{Cl}} \). Furthermore, let \( C \) be an \( N_u^{Cl} \times N^{Cl} \) matrix that contains the indices of the \( N_u^{Cl} \) pairs that belong to each of the \( N^{Cl} \) clusters. Also, let the matrix \( G \) be a \( 3 \times N_G \) matrix containing the indices of the 3 pairs that form each IA group where \( N_G = \text{floor} \left( \frac{N_{pairs}}{3} \right) \) is the number of IA groups. Note that if \( N_{pairs} \) is not an exact multiple of 3, the remainder of the users will simply use point-to-point (P2P) transmission. We also define a group of matrices \( \{ D_n, n = 1, 2, \ldots, N^{Cl} \} \), each of which is an \( N_u^{Cl} \times N_u^{Cl} \) matrix that contains the distances between different D2D users within cluster \( n \), i.e., \( d_{jk}^n \) represents the distance between transmitter \( j \) and receiver \( k, j, k \in [1, N_u^{Cl}] \), located in cluster \( n \).
Figure 5.2 An illustrative example on the clustering and IA grouping steps.
5.4 Fuzzy Clustering Schemes

Cluster analysis divides data into groups (clusters) such that similar data objects belong to the same cluster and dissimilar data objects to different clusters. It has been used in Wireless Sensor Networks (WSN) by dividing the sensor networks into small manageable units to facilitate energy efficient routing and data reduction techniques. Moreover, it has advantages like conserving communication bandwidth within the clusters, avoiding redundant message transfer between the sensor nodes, and localizing energy efficient route setup within the clusters. Clustering sensor nodes and organizing them hierarchically in a WSN environment have proven to be an effective method to provide better data aggregation and scalability for the sensor network while conserving limited energy. Some of the energy efficient routing protocols in WSN are LEACH, HEED, DECA, among others [46]. However, in this chapter, clustering is used to enable radio resources reuse over smaller areas and also to facilitate precoding for interference alignment at receivers when radio resources are shared to further enhance the overall system sum rate.

Fuzzy clustering provides a flexible and robust method for handling natural data with vagueness and uncertainty. In fuzzy clustering, each data point will have an associated degree of membership for each cluster. The membership value indicates the strength of its association to that cluster. The most prominent fuzzy clustering algorithm is the Fuzzy C-Means [45], which involves two processes: the calculation of cluster centroids as being the mean of all points, weighed by their degree of belonging to the cluster and the assignment of points to these centers using a form of Euclidian distance. This process is repeated until the cluster centers stabilize. The algorithm results in clusters of spherical shape and approximately the same size. In [45], performance comparison of Fuzzy K-Means, Fuzzy C-Means, Gaussian Mixture and Single-Link hierarchical clustering algorithms for different data
sets is presented. The Fuzzy C-Means algorithm is shown to perform very well; in all datasets. The degree of correctness obtained in the categorization was comparable to the best ones achieved. Moreover, the performance speed was very acceptable. More specifically, for a data set with \( N \) input patterns, the computational complexity of the Fuzzy C-Means clustering algorithm is near \( O(N) \). The Fuzzy C-Means Clustering algorithm is shown in Figure 5.3. In this algorithm, centroids represent the center of each cluster and each data point has a feature vector that represents the feature of the data point upon which we take the clustering decisions. This algorithm will be used for both cluster formations and IA group formations as explained in the following subsections.

5.4.1 The D2D Clusters Formation

To attain increasing data rates for the system, we aim at reducing the frequency reuse distance. Hence, to reuse the available \( N_{RB}^{D2D} \) RBs, we cluster all the active D2D links depending on their positions in order to isolate them spatially and then explore the potential of boosting the spectral efficiency via decreasing the spatial-reuse distance in D2D environment. Hence, we propose to use a Position Based Scheme (PBS) for the clustering process as it offers the ability to cluster D2D pairs in small containing areas. PBS is based on Fuzzy C-Means scheme by setting the feature vector to contain the positions of the D2D transmitting nodes. Here, the parameters \( N_c \) and \( N_p \) of Algorithm 1 are set to \( N_c^{CI} \) and \( N_p^{CI} \), respectively, where \( N_c \) represents the final total number of centroids defined in the algorithm [45]. The \( N_{u}^{CI} \times N_c^{CI} \) matrix \( C \) is updated column by column. The scheme is shown in Figure 5.3, where the feature vector \( F \) values are the positions of the transmitting nodes whose indices are initially available in the set \( \{1, 2, ..., N_{pairs}^{D2D}\} \), and is updated for each of the algorithm iterations. The modification of the C-Means clustering algorithm is to allow for an equal number of D2D pairs to be grouped in each of the clusters.
where in each of the iterations a number of \( N_p \) pairs that have the highest degree of membership to the same centroid are chosen to form a cluster. This mechanism shows the ability to group D2D pairs in clusters characterized by nearly-separate small containing areas.

5.4.2 The IA Group Formation in Each Cluster

In a normal P2P D2D-enabled cell operation, each transmitter will be assigned dedicated resources, e.g., a set of RBs to communicate with its corresponding receiver. However, to enable the usage of IA technique, we need to define users that will be grouped together and who will intentionally use the same resources in the manner defined by IA, which allows the extra degrees of freedom offered to be attained. In this subsection, we present three different grouping schemes as mentioned previously. In our model, we will assume that the size of each of the formed clusters \( N_u^{\text{Cl}} \) is a multiple of three. Hence, all D2D pairs shall be grouped.

We assume a set \( \mathcal{P} \) that contains the indices of each D2D pair that has been assigned to an IA group, which is initialized as an empty set. We also define \( N_r^{\text{Pairs}} \) as the number of remaining ungrouped D2D pairs, which is first initialized as \( N_u^{\text{Cl}} \). Without loss of generality, and to simplify the discussion of the grouping schemes, we assume that all D2D pairs belong to a single cluster, i.e., \( N^{\text{Cl}} \) is equal to one and \( N_u^{\text{Cl}} \) is equal to \( N_{D2D}^{\text{Pairs}} \). Note that, in the case of multiple clusters, the steps are repeated per cluster with the proper definition of the parameters. The three proposed grouping schemes are described below.
Algorithm 1: Fuzzy C-Means Clustering Based Grouping Algorithm

01: **Initialize:** \( N_c = N_G, 3, \text{ or } N^{Cl}_G, \mathcal{P} = \emptyset, N_p = 3, N_G, \text{ or } N^{Cl}_u. \)

02: **for** \( n_{c} = N_{c} \) **to** 1

03: Find Feature Vector \( F \) for all users such that \( X_j \in F, j \in \{1, 2, \ldots, N^{Pairs}_{D2D}\} - \mathcal{P}. \)

04: Initialize: \( C_i, i = 1, 2, \ldots, n_{c}, \)

\( M: \) length of the feature Vector \( F. \)

05: Compute Degree of Membership \( u_{ij} \) between users' feature \( X_j \) and each centroid \( C_i, d^2(X_j, C_i) \) is an inner product metric (distance measure),

\[
u_{ij} = \frac{1}{\sum_{k=1}^{n_c} \frac{1}{d^2(X_j, C_k)}}, j \in \{1, 2, \ldots, N^{Pairs}_{D2D}\} - \mathcal{P}.
\]

06: **while** \( \max_{ij} \| u_{ij} - \hat{u}_{ij} \| > \text{ tolerance} \)

07: Compute new centroids \( \hat{C}_i \) such that \( \hat{C}_i = \frac{\sum_{j=1}^{M} u_{ij} X_j}{\sum_{j=1}^{M} u_{ij}}. \)

08: Update degrees of membership \( \hat{u}_{ij}. \)

09: **end while**

10: Find the first \( N_p \) pairs that have the highest Degrees of Membership to the same centroid.

11: Update the matrix \( C \) by column (when applied for clustering) OR the matrix \( G \) by row (CBS grouping method) or column (PBS grouping method) with the indices of pairs obtained from the previous step.

12: Update the set \( \mathcal{P} \) with the pairs indices obtained.

13: **end for**

**Figure 5. 3** Fuzzy C-Means Clustering Algorithm

5.4.2.1 Position-Based Grouping Scheme (PBS)

The first scheme, PBS, is based on the D2D transmitting nodes positions in which the variable \( N_c \) is initialized as \( N_G \), and \( N_p \) is set to three. The matrix of IA Groups \( G \) is updated column by column. In this scheme, we study the effect of grouping users so that they have the minimum containing area. The scheme is described in Algorithm 1 shown in Figure 5. 3, where the feature vector \( F \) values are the positions of the transmitting nodes whose indices are available in
the set \( \{1, 2, \ldots, N_{D2D}^{\text{pairs}} \} - \mathcal{P} \). This grouping mechanism results in groups characterized by small containing areas.

5.4.2.2 Channel-Based Grouping Scheme (CBS)

The second scheme, CBS, follows the same steps as those of Algorithm 1 shown in Figure 5.3. The only difference from PBS is that the feature vector \( \mathbf{F} \) now contains the gains of the direct channel between each D2D pair transmitter and receiver. The variable \( N_c \) is initialized to three, and \( N_p \) is set to \( N_g \). The matrix of IA Groups \( \mathbf{G} \) is updated row by row. Then, we calculate the average channel gain for all users existing in the same row of the matrix \( \mathbf{G} \). What CBS does is that it categorizes all the available D2D pairs into three categories: D2D pairs with high, intermediate, and low direct channel gain. It then chooses a pair from each category to form an IA group. In the CBS scheme, we do not take the positions of users into consideration, i.e., users in a single group can be distributed over the whole cell/cluster area as long as the distance between the transmitter and receiver is less than \( L_{\text{Max}} \), as mentioned before. The main drawback of this grouping mechanism is that it might result in groups characterized by dispersed distribution of users over the cell/cluster where each group contains at least one pair with high channel gain. To be able to define a group over a small area, the following simple scheme is proposed.

5.4.2.3 Distance-Based Grouping Scheme (DBS)

The grouping criterion in DBS is based on attempting to select the D2D pairs in a group that are likely to cause large mutual interference on each other. When IA is applied, this mutual interference should be eliminated and thus, throughput gains can be achieved. The DBS assumes that the distance between the transmitter and receiver of each pair is a good measure of the channel path loss, which is the parameter that has the largest effect on the channel gain. Hence, we can say that DBS takes into account the channel conditions between
the IA group lead pair’s transmitter and receiver; and at the same time tries to contain each IA group in a small area, where we define a lead pair as the pair that will be assigned the extra degrees of freedom offered by applying IA.

Algorithm 2 shown in Figure 5.4 summarizes the procedure. We first choose a pair that has the minimum distance between its transmitter and receiver from the \( \{D_n, n = 1,2,\ldots,N^{CI}\} \) group of matrices and set it as the lead pair in an IA group. Then, we choose two other pairs that have a minimum distance between their transmitters and the lead pair receiver.

<table>
<thead>
<tr>
<th>Algorithm 2: DBS Grouping Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:  for ( n = 1 ) to ( N^{CI} )</td>
</tr>
<tr>
<td>2:  Initialize: ( N^P_{\text{pairs}} = N_u^{CI}, P = \emptyset ).</td>
</tr>
<tr>
<td>3:  while ( N^P_{\text{pairs}} \geq 3 )</td>
</tr>
<tr>
<td>4:  Find pair index with minimum ( d_{ii}^n, i \in {1,2,\ldots,N_u^{CI}} - P ), which is then chosen as the first pair of the IA group.</td>
</tr>
<tr>
<td>5:  Find two pair indices with minimum ( d_{ki}^n, k \in {1,2,\ldots,N_u^{CI}} - P, k \neq i ) which are then chosen as the second and third pairs of the IA group.</td>
</tr>
<tr>
<td>6:  Update the matrix ( G ) with the obtained pair indices to form an IA group, and the set ( P ) with the pairs indices assigned to the IA group.</td>
</tr>
<tr>
<td>7:  Update ( N^P_{\text{pairs}} = N^P_{\text{pairs}} - 3 ).</td>
</tr>
<tr>
<td>8:  end while</td>
</tr>
<tr>
<td>9:  end for</td>
</tr>
</tbody>
</table>

Figure 5.4 The DBS Grouping Algorithm

5.5 The Proposed IA-based Transmission and the Associated Resource Block Allocation Scheme

Once the clusters are formed, all the resource blocks dedicated to D2D communication are fully reused in each cluster. The next problem to tackle would be how to apply IA in the formed IA groups within each cluster and which RBs will be allocated to members of the different IA groups. These two problems are discussed in the next two subsections.
5.5.1 The Overall D2D IA-Based Transmission Scheme

In general, IA-based transmission schemes allow users to share their resources and align the interference caused by the sharing process through precoding. We group the D2D pairs, assign each group multiple RBs, and use IA to precode transmissions. Although the scheme is not limited to a group size of three pairs, we consider only the 3-user interference channel with limited resources, $3n_r$ RBs in each group, $n_r \in \{1, 2, 3, \ldots \}$. This allows $4n_r$ simultaneous transmissions over the $3n_r$ RBs. The limitation of 3-users per groups is imposed in order to cope with the practical limitations discussed in earlier precoding design works [2], which shows that the complexity of IA precoding calculations tremendously increases as the number of users and the required symbol extensions increase. The calculations of the precoding vectors are based on [2] and are discussed in section 5.2 along with the design of the receivers decoders.

Afterwards, we choose the lead pair in each IA group to be the pair that has the highest average gain.

The system proposed so far depends on the centralized calculations of the precoding vectors. However, the results shown are encouraging to further evaluate the system performance when users are equipped with multiple antennas and distributed algorithms for precoding vectors calculations are considered such as that proposed in [47].

5.5.2 Resource Block Allocation for the D2D Links

We focus on the overall sum rate assuming no QoS or minimum rate requirements. Hence, we assume equal resource sharing between links, i.e., each link is assigned the same amount of RBs. In our model, each active link is assigned at least one RB. For a single cluster, each user will be assigned a number of RBs that is equal to $N^{RB}_{D2D}/N^{pairs}_{D2D}$. For multiple clusters, the resource
allocation process is performed for each cluster individually and all $N_{D2D}^{RB}$ RBs are allocated for each cluster allowing each user to be allocated a number of $(N_{D2D}^{RB} \times N_{CL}) / N_{D2D}^{Pairs}$ RBs.

A resource allocation optimization problem that aims at maximizing the sum of SINRs (which can be a good indication for realizable rates) for the D2D pairs in the formed clusters can be formulated as follows:

$$
\text{max} \sum_{k=1}^{N_{D2D}^{RB}} \sum_{n=1}^{N_{CL}} \sum_{i=1}^{N_{u}^{Cl}} \left( \frac{\alpha_{i,k}^{n} P |H_{i,i}^{k,n,n}|^2}{\sigma^2 + \sum_{l=1, l \neq n}^{N_{CL}} \sum_{j=1}^{N_{u}^{Cl}} \alpha_{j,k}^{l} P |H_{i,j}^{k,n,l}|^2} \right)
$$

Subject to:

$$
\alpha_{i,k}^{n}, \alpha_{j,k}^{l} = \begin{cases} 
1 & , \\
0 & , 
\end{cases}
$$

$$
\sum_{i \in G_{s}} \alpha_{i,k}^{n} = \begin{cases} 
3 & , n = 1, 2, ..., N_{CL}; k = 1, 2, ..., N_{D2D}^{RB}, s = 1, 2, ..., N_{G}, \\
0 & , 
\end{cases}
$$

$$
\sum_{k=1}^{N_{RB}} \alpha_{i,k}^{n} \geq 3, n = 1, 2, ..., N_{CL}; i = 1, 2, ..., N_{u}^{Cl}.
$$

We assume that all D2D pairs are grouped in IA groups of three each. Moreover, we assume that $N_{D2D}^{RB} \geq N_{u}^{Cl}$. In the above formulation, $\alpha_{i,k}^{n}$ is the selection variable that indicates the allocation of RB $k$ for pair $i$ in cluster $n$, $H_{i,j}^{k,n,l}$ is the channel matrix between pair $j$ transmitter in cluster $l$ and pair $i$ receiver in cluster $n$, $G_{s}$ is the $s^{th}$ column of the matrix $G$, and $\sigma^2$ is the noise variance. We also assume equal power sharing $P$ at all transmitters. The constraints ensure that all pairs in the same IA group are assigned the same RB and that each IA group shares at least three RBs. The aforementioned problem is very complex and methods for its efficient solution are left for future work. However, in a D2D setup it will be required to have simple and efficient methods due to the nature of the decision making process in such environment. We propose below reasonable allocation methods that can work in practice.
The first method distributes the $N_{D2D}^{RB}$ RBs over users in such a way that the users that have the best channel conditions are allocated resources first, which we call the "greedy best channel allocation". The second allocation method is based on proportional fair resource allocation in which we multiply the channel matrices by a metric and then allocate resources in the same way as the greedy allocation. The metric $m_{ik}$ is calculated as

$$m_{ik} = \frac{C_{ik}}{R_i},$$

where $R_i$ represents the average rate realized for the D2D pair $i$, and $C_{ik}$ represents the capacity of RB $k$ for the pair $i$ and is calculated as

$$C_{ik} = \lambda_i B \log_2 \left( 1 + \frac{|H_i^k|^2}{\sigma^2 + I_{ik}} \right),$$

where $\lambda_i$ represents the degrees of freedom available for the pair $i$, which is equal to 1 for a normal pair and 2 for a lead pair, $B$ represents the bandwidth of a single RB, $H_i^k$ represents the channel coefficient for pair $i$ at RB $k$, $\sigma^2$ represents the noise variance, and $I_{ik}$ represents the last reported interference gain that pair $i$ suffered from at RB $k$.

It is worth mentioning here that in P2P transmission, each link uses the assigned RBs exclusively to transmit its message and in that case the grouping schemes are irrelevant.

5.6  Performance Evaluation

5.6.1  Point-to-Point vs. Interference Alignment

In Figure 5. 5, we compare direct P2P transmission and IA transmission in the 3-user SISO interference channel setup from the BER point of view. We represent the results of IA transmission by the average BER of the three
grouped pairs. From Figure 5.5, it is clear that CJ IA scheme has a worse performance than that of the traditional P2P transmission from the BER point of view. The same observation applies to DM IA scheme. It can also be seen that DM IA scheme has better BER performance than CJ IA scheme. This degradation in BER performance in IA schemes is due to the noise enhancement caused by the interference suppression filter in Eq. (5.10).

The sum rate performance of all schemes is then compared in Figure 5.6. It is observed that both IA schemes have better sum rate performance than the traditional P2P transmission. In particular, at 5 dB SNR, CJ scheme achieves a sum rate gain of about 1.3% and DM schemes achieves a gain of about 8% over the traditional P2P transmission. At 15 dB, CJ scheme achieves a sum rate gain of about 16% and DM scheme achieves a gain of about 23.9% over the traditional P2P transmission. We notice that despite the degradation in BER for IA schemes, they are still able to achieve higher sum rates than P2P transmission scheme. This result is made possible by the fact that IA technique provides users with more degrees of freedom than those available from P2P transmission.

5.6.2 System Level Results

For the implemented simulation model, large indoor hall (WINNER B3 hotspot [5]) scenario is assumed for all direct and interfering links that have a maximum distance between the transmitting (interfering) node and the receiver of $L_{\text{Max}}$. Furthermore, outdoor to indoor (WINNER B4) scenario is assumed for all interfering links with link distance greater than $L_{\text{Max}}$. The preceding assumptions are typical for large hall scenarios such as: airports, malls, libraries, and bookstores. Other simulation parameters are summarized in Table 5.1. Furthermore, the simulation results shown are the average of multiple simulation runs; each run is 1 second long. Users are distributed randomly over
the cell. The users have very low mobility, which further complies with the assumed scenarios and the proposed applications such as providing internet services in public places. With these realistic assumptions, the clustering and grouping remain constant during each run. We believe that high mobility users should not be part of D2D and should rather be switched to normal cellular operation. The result of the CBS grouping scheme is depicted in Figure 5.7, and of the DBS grouping scheme in Figure 5.8. Members of the same group are represented by the same marker. We can note that in DBA group members are close to each other while that is not the case in CBA.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of D2D pairs</td>
<td>24</td>
</tr>
<tr>
<td>Cell radius – $R$ (m)</td>
<td>500</td>
</tr>
<tr>
<td>Noise power per RB (dBm)</td>
<td>-121</td>
</tr>
<tr>
<td>Number of D2D RBs - $N_{D2D}^{RB}$</td>
<td>24</td>
</tr>
<tr>
<td>$L_{\text{Max}}$ (m)</td>
<td>80</td>
</tr>
<tr>
<td>Modulation Scheme</td>
<td>QPSK</td>
</tr>
<tr>
<td>Number of Clusters $N_{C}^{CI}$</td>
<td>1, 2, 4</td>
</tr>
<tr>
<td>Number of Users per Cluster $N_{u}^{CI}$</td>
<td>24, 12, 6</td>
</tr>
</tbody>
</table>

5.6.2.1 Single Cluster Per Cell

For the D2D setup assuming a single cluster, comparison between the total cell D2D sum rate, when using P2P transmission and IA transmission, is shown in Figure 5.9. The results reveal that the CJ-IA scheme provides opportunities for boosting D2D network spectral efficiency. The CBS is shown to have the best performance for the CJ-IA scheme over P2P transmission for all transmit signal power values. The DBS has a close performance to CBS performance. The maximum D2D sum rate achieved by the P2P transmission is about 8.03 Mbps while the IA transmission is able to achieve sum rate of about 10.59 Mbps; a gain of about 31.8%. The PBS is shown to have the worst performance of the three proposed algorithms, the D2D sum rate of CJ IA scheme is shown
to be lower than that of the P2P transmission for transmit signal power from about -40 dBm to -31 dBm.

In Figure 5.10, we plot the Jain’s fairness index for P2P transmission and CJ-IA schemes when using the different grouping algorithms. The Jain’s Fairness Index (FI) [48] is formulated as:

$$\text{FI} = \frac{(\sum \hat{x}_i)^2}{n \sum \hat{x}_i^2},$$  

(5.11)

where $\hat{x}_i$ represents throughput for the $i^{\text{th}}$ user, and $n$ represents the number of users. The figure shows that the gains in achievable rates provided by IA, typically associated with the high SNR regime, result in little penalty in the fairness performance. We note that the rates achieved by the lead pairs are normalized by the increase in offered degrees of freedom to have a meaningful comparison.

5.6.2.2 Multiple Clusters Per Cell

In the case when multiple clusters are formed, a comparison between the total cell D2D sum rate for the different cluster sizes is shown in Figure 5.11. The DBS grouping scheme is used for the IA grouping in all the formed clusters. The results in Figure 5.11 show the large gains in overall rates that can be achieved by the reuse of resource blocks in the clusters. It is to be noted that if we normalize the total sum rates by the number of clusters $N^{CI}$, we can observe the effect of interference when resources are being reused among clusters as shown in Figure 5.12. As the number of clusters increases, the effect of interference increases, but it is only effective for transmit signal powers greater than -15 dBm/user/RB for the scenario considered.

The results shown so far present the allocation based on greedy (Gr) best channel allocation for the RBs among the pairs. Figure 5.13 and Figure 5.14 show the comparison of sum rate and fairness index when using the greedy and
the proportional fair resources allocation in the case where we assume 4 clusters per cell, each containing 6 D2D pairs, where (PF) denotes the proportional fair allocation results. We notice in Figure 5.13 that there is a slight reduction in sum rate when using PF resource allocation. But, we can also see that fairness is improved for transmit powers less than -15 dBm in Figure 5.14. The lack of improvement in fairness when using PF for transmit powers greater than -15 dBm is mostly due to the effect of interference between clusters that becomes more prominent when transmit power levels increase.

![Figure 5.5 BER comparison between traditional P2P transmission and IA transmission using a) CJ scheme. b) DM scheme.](image-url)
Figure 5.6  Sum rate comparison between traditional P2P transmission and IA transmission using a) CJ scheme. b) DM scheme.
Figure 5.7  Example distribution of D2D transmitters after using CBA grouping.
Figure 5.8  Example distribution of D2D transmitters after using DBA grouping.
Figure 5.9  Total sum rate of a single cell enabling D2D communication for both P2P and IA transmission.

Figure 5.10  Fairness index results for both P2P and IA transmission when using a) CBS. b) DBS. c) PBS.
Figure 5.11  Total sum rate of a single cell enabling D2D communication with IA transmission for different cluster sizes.

Figure 5.12  Total sum rate of a single cell enabling D2D communication with IA transmission for different cluster sizes normalized by the number of clusters $N^C$. 

- 90 -
Figure 5.13 Comparing total sum rate per cluster for greedy and proportional fair resources allocation.

Figure 5.14 Comparing fairness index for greedy and proportional fair resources allocation.
6 Low-Complexity Limited Feedback Strategy in 3-User Interference Channel Exploiting Interference Alignment

IA schemes have been employed to realize the full multiplexing gain of $K$-user interference channels (IC) under the assumption that channel state information (CSI) is ideally known at each transmitter. However, the assumption of perfect CSI is almost impossible to realize at the transmitters, especially for quantized feedback systems using feedback links with finite bandwidth. When the CSI is fed back from receivers using the limited number of feedback bits, a significant performance loss is inevitable in IA due to quantized channel knowledge. A new feedback strategy is proposed in [3] to minimize the quantization error by considering an additional receive filter. In this chapter, we propose new strategies that aim at minimizing the quantization error through partial processing at receivers and reduction of the amount of feedback data to send to the transmitters in the special case of 3-user IC. The proposed limited feedback strategies significantly reduces the processing complexity required for minimizing quantization errors at the receivers compared to the scheme proposed in [1] and interestingly improves spectral efficiency performance as well.

6.1 Introduction

CSI makes it possible to adapt transmissions to current channel conditions, which is crucial for achieving reliable communication with high data rates in MIMO systems. CSI can be obtained via sending training symbols in the time domain or pilots in the frequency domain (if OFDM is used) that could be used to estimate the channel at the receiver side. The receiver then feeds back the
channel estimates to the transmitter. In time division duplex (TDD) systems, assuming reciprocal channels feedback from the receiver is not needed. Usually, the channel state information needs to be quantized since they will be sent to the transmitter over a limited-rate feedback channel. Unfortunately, the feedback requirements in a MIMO system generally grow with the product of the number of transmit antennas, the number of receive antennas, the delay spread, and the number of users, while the capacity only grows linearly. Performance results in MIMO channels show that even a few bits of feedback can provide performance close to that with full channel knowledge at the transmitter [29].

In situations where the feedback is severely limited, a challenging issue is how to quantize the information needed at the transmitter and then how much improvement in the associated performance can be obtained as a function of the amount of feedback available.

In limited feedback communication, the goal is to maximize capacity or minimize bit error rate with a few bits of feedback information. A pure Vector Quantization (VQ) approach would attempt to obtain a good approximation of a given channel realization. However, it is not the reconstruction of the channel that is of interest, but rather, achieving a good approximation of what might be done with that channel. Thus, there are two main approaches to implement channel state feedback: quantizing the channel or quantizing properties of the transmitted signal. It is apparent, however, that channel quantization offers an intuitively simple approach to closed-loop MIMO, but lacks the performance of more specialized feedback methods [29].

The channel quantization problem is reformulated as a VQ problem by stacking the columns of the channel matrix $\mathbf{H}$ into an $N_r \times N_t$ dimensional complex vector $\mathbf{h}_{vec}$ where $N_r, N_t$ represent the number of receive and transmit antennas, respectively. The vector $\mathbf{h}_{vec}$ is then quantized using a VQ algorithm. A vector quantizer works by mapping a real or complex valued vector into one
of a finite number of vector realizations. The mapping is usually designed to minimize some sort of distortion function such as the average mean squared error (MSE) between the input vector and the quantized vector [29].

A drawback of VQ schemes is complexity. Namely, in general, the receiver must select a quantized channel or a precoding matrix from among the $2^B$ possibilities via an exhaustive search, where $B$ is the number of feedback bits. This clearly becomes a large computational burden as $B$ increases [29].

Interestingly, it is shown in [2] that interference alignment does for SISO wireless networks what MIMO technology has done for the point to point wireless channel. In both cases, the capacity, originally limited to $\log(1 + SNR)$, where $SNR$ is the signal-to-noise ratio, is shown to be capable of linearly increasing with the number of antennas. While MIMO technology requires nodes equipped with multiple antennas, interference alignment works with the distributed antennas naturally available in a network across the interfering transmitters and receivers.

Interference alignment schemes have been employed to realize the full multiplexing gain of $K$-user interference channels under the assumption that CSI is ideally known at each transmitter. However, the assumption of the perfect CSI is almost impossible to realize at the transmitters, especially for quantized feedback systems using feedback links with finite bandwidth.

In this chapter, we review some of the work that considers the problem where each receiver knows its channels from all the transmitters and feeds back this information using a limited number of bits to all other terminals. Then, we consider the case of the 3-user IC where closed-form solutions for IA precoding have been proposed for both SISO and MIMO channels. We propose a simple limited feedback strategy that employs partial processing at the receivers and
leads to a reduction of the amount of information needed to be fed back to the transmitters.

The following notations are used for description throughout this chapter. Normal letters represent scalar quantities, boldface letters indicate vectors and boldface uppercase letters designate matrices. Also, \((\cdot)^*, (\cdot)^\dagger\) and \(\mathbb{E}[\cdot]\) stand for conjugate, conjugate transpose and expectation, respectively. In addition, \(\mathbb{R}^{m\times n}\) and \(\mathbb{C}^{m\times n}\) denote \(m \times n\) real and complex matrix spaces, respectively. An identity matrix with size \(m \times m\) is represented as \(I_m\), and \(\otimes\) indicates Kronecker product.

### 6.2 System Description and Background

Figure 6.1 illustrates the \(K\)-user interference channel where each transmitter \(i\) communicates with its corresponding receiver \(i\) and interferes with all other receivers \(j \neq i\). In this system and throughout this chapter, each transmitter and receiver pair \(i\) is equipped with either a single antenna or \(N\) transmit and receive antennas. In case of a single antenna equipped system, \(N\) will represent the number of symbol extensions in time or frequency slots to support \(d_i\) data streams for all \(d_i \leq N\).

In the discrete-time complex baseband MIMO case, the frequency-flat channel from transmitter \(i\) to receiver \(j\) is modeled by the matrix \(H_{ji} = [h_{ji}^1 \ldots h_{ji}^N] \in \mathbb{C}^{N\times N}\) where \(h_{ji}^l \in \mathbb{C}^{N\times 1}\) represents the \(l^{th}\) column vector for \(i,j = 1,\ldots,K\). The entries of \(H_{ji}\) are assumed to be independently and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance \(\mathcal{CN}(0,1)\). Noting that in SISO case, \(H_{ji}\) is a diagonal matrix and \(h_{ji}^l\) is a column vector with a single non-zero element that is assumed as i.i.d \(\mathcal{CN}(0,1)\).

At the \(i^{th}\) receiver, the received signal vector \(y_i \in \mathbb{C}^{N\times 1}\) is given as
\[ \mathbf{y}_i = \mathbf{H}_{ii} \mathbf{V}_i \mathbf{x}_i + \sum_{j=1,j\neq i}^{K} \mathbf{H}_{ij} \mathbf{V}_j \mathbf{x}_j + \mathbf{n}_i \]  

(6.1)

where \( \mathbf{V}_i \in \mathbb{C}^{N \times d_i} \) indicates the transmit precoder at transmitter \( i \) with unit-norm columns, \( \mathbf{x}_i \in \mathbb{C}^{d_i \times 1} \) denotes the transmit symbol vector from transmitter \( i \), and \( \mathbf{n}_i \in \mathbb{C}^{N \times 1} \) is the additive white Gaussian noise vector observed at receiver \( i \). Here the symbols in \( \mathbf{x}_i \) are assumed to be independently generated with unit variance and the entries of \( \mathbf{n}_i \) are i.i.d. with zero mean and variance \( \sigma_n^2 \).

Defining \( \mathbf{R}_i \in \mathbb{C}^{N \times d_i} \) as the receive combining matrix for the \( i^{th} \) receiver, the received signal vector \( \mathbf{\hat{x}}_i \) after the receiver combining is expressed as

\[ \mathbf{\hat{x}}_i = \mathbf{R}_i^\dagger \mathbf{y}_i = \mathbf{R}_i^\dagger \mathbf{H}_{ii} \mathbf{V}_i \mathbf{x}_i + \mathbf{R}_i^\dagger \sum_{j=1,j\neq i}^{K} \mathbf{H}_{ij} \mathbf{V}_j \mathbf{x}_j + \mathbf{R}_i^\dagger \mathbf{n}_i \]  

(6.2)

We assume that each receiver \( i \) knows its channels \( \mathbf{H}_{i1}, \ldots, \mathbf{H}_{iK} \) perfectly based on separate pilot signals transmitted by each of \( K \) transmitters. Also, error-free dedicated broadcast links are assumed from each receiver to other transmitters \( j (\forall j \neq i) \) in the network. During the channel feedback phase, receiver \( i \) broadcasts its CSI using \( B \) bits.

Under the assumption of the perfect CSI at the transmitters, one can achieve the maximum multiplexing gain or the maximum DoF by utilizing the IA technique. This implies that the transmit precoding matrix \( \mathbf{V}_i \) is chosen in the null space of \( \mathbf{R}_j^\dagger \mathbf{H}_{ji} \) such that \( \mathbf{R}_j^\dagger \mathbf{H}_{ji} \mathbf{V}_i = 0 (\forall j \neq i) \). Consequently, \( \mathbf{V}_i \) causes no interference to receiver \( j \) by completely removing the interference term in eq. (6.2). Also, the total number of the transmitted data streams \( \sum d_i \) is set to attain a full spatial multiplexing gain, i.e., \( \sum d_i = \frac{KN}{2} \) in case of MIMO and \( \sum d_i \leq \frac{K}{2} \) in case of SISO where the equality condition is only achieved as the number of channel extensions reaches infinity \([2]\). However, when the CSI is fed back through the limited feedback channel, it is difficult to obtain such
theoretical bound, which satisfies zero interference. That is, a significant loss of performance is inevitable due to the imperfect CSI.

In this chapter, we only consider the case of the 3-user IC shown in Figure 6.2 where a closed-form solution to both SISO and MIMO cases is made available by the work of Cadambe and Jafar (CJ) in [2], Shen, Host-Madsen, and Vidal (SHV) in [31], and Douglas and Murat (DM) in [32].

Moreover and as discussed earlier, it is shown in [2], [31] and [32] that the design of the precoding vector for the proposed interference alignment scheme becomes more complex as the number of users and channel extensions increase which led to the result that much of the following work on IA precoding design focuses on the case of 3-user IC and with limited channel extensions.

![Diagram of K-user Interference Channel with Direct and Interfering Links Clarification.](image)

**Figure 6.1** K-User Interference Channel with Direct and Interfering Links Clarification.
6.3 Previous Work

The requirement of perfect channel state information at the transmitters (CSIT) by the IA scheme in [2] is, of course, practically unrealizable for a time-variant or frequency-selective system and this issue has recently begun to receive considerable attention (see for example, [49], [50] and [51]). In particular, [49] analyzed the impact of imperfect channel knowledge on the sum mutual information achieved by interference alignment, when applied to the downlink of a cellular network using Orthogonal Frequency Division Multiplexing Access (OFDMA), and compared the case where the base stations share their information about the channel to the case where they do not cooperate. It is also shown in [50] that for a frequency-selective SISO setup, the full spatial multiplexing gain of $K/2$ can be obtained even under conditions of limited feedback as long as the feedback rate exceeds $K(L-1)\log P$ bits per receiver, where $L$ is the number of taps in the channel between any pair of
nodes and $P$ is the total power available for the transmitting sources. Moreover, in [51] channel quantization over the composite Grassmann manifold is considered for MIMO interference channels where it is shown that the full sum DoFs of the interference channel can be achieved as long as the feedback bit rate scales sufficiently fast with the SNR. More specifically, the proposed IA scheme with limited feedback can attain the same DoF as the original IA scheme with perfect CSI as long as each receiver uses no less than $B = \min\{N_t,N_r\}^2 K(ZL - 1) \log P$ bits, where $Z = \left\lceil \frac{\max\{N_t,N_r\}}{\min\{N_t,N_r\}} \right\rceil$. It is also shown that a continuous tradeoff, whereby an individual user can opt for a slower scaling of feedback bits and obtain proportionally lower DoFs, exists.

### 6.4 Low-Complexity Limited Feedback Strategy in a 3-User Interference Alignment System

In this section, we briefly describe the conventional limited feedback strategy proposed in [51] and the limited feedback strategy that is based on channel transformation proposed in [3]. Then, we propose new limited feedback strategies for both SISO and MIMO systems in the special case of the 3-user IC. For SISO systems, we propose two limited feedback strategies: one that combines partial IA precoding vectors processing at the receivers with the conventional scheme, and the other combines partial processing with the channel transformation scheme. For MIMO systems with even number of antennas $N$, only the partial processing at receiver is employed.

#### 6.4.1 Quantization over Composite Grassmann Manifold (CS)

The Grassmann and Stiefel manifolds are geometric objects relevant to the beamforming codebook design. The Grassmann manifold $G_{n,p}(\mathbb{L})$ is the set of all $p$-dimensional planes (through the origin) in the $n$-dimensional Euclidean space $\mathbb{L}^R$, where $\mathbb{L}$ is either $\mathbb{R}$ or $\mathbb{C}$, i.e., the set of all one-dimensional
subspaces of $\mathbb{L}^2$, $G_{2,1}$, is simply the set of all lines passing through the origin, and the set of all two-dimensional subspaces of $\mathbb{L}^3$, $G_{3,2}$ can be thought of as the set of all planes. It forms a compact Riemann manifold of real dimension $\beta p(n - p)$, where $\beta = 1$ when $\mathbb{L} = \mathbb{R}$ and $\beta = 2$ when $\mathbb{L} = \mathbb{C}$. The Grassmann manifold provides a useful analysis tool for multi-antenna communications (MIMO communication systems). For non-coherent MIMO systems, sphere packings of $G_{n,p}(\mathbb{L})$ can be viewed as a generalization of spherical codes.

The **Stiefel manifold** $S_{n,p}(\mathbb{C})$ (where $n \geq p$) is the set of all complex unitary $n \times p$ matrices $S_{n,p}(\mathbb{C}) = \{ \mathbf{Q} \in \mathbb{C}^{n \times p}: \mathbf{Q}^\dagger \mathbf{Q} = \mathbf{I}_p \}$. Now define an equivalence relation on the Stiefel manifold, two matrices $\mathbf{P}, \mathbf{Q} \in S_{n,p}(\mathbb{C})$ being equivalent if their column vectors span the same subspace. The Grassmann manifold $G_{n,p}(\mathbb{C})$ is thus simply the quotient space of $S_{n,p}(\mathbb{C})$ with respect to this equivalence relation. A generator matrix of $\mathbf{Q} \in G_{n,p}(\mathbb{C})$ is any matrix $\mathbf{Q} \in S_{n,p}(\mathbb{C})$ whose columns span $\mathbf{Q}$. Given a $\mathbf{Q} \in G_{n,p}(\mathbb{C})$, the corresponding generator matrix is not unique: if $\mathbf{Q}$ generates $\mathbf{Q} \in G_{n,p}(\mathbb{C})$, then $\mathbf{QU}$ with $\mathbf{U} \in S_{p,p}$ also generates the same plane $\mathbf{Q}$ [52]. Hence, Multidimensional Grassmann analysis (i.e., on $G_{n,k}$, for $k > 1$) cannot be directed in the current interference alignment scheme for a 3-user system, since if all that the users know is the subspace spanned by $\{ h_{11}, h_{12}, h_{13}, h_{21}, h_{22}, h_{23}, h_{31}, h_{32}, h_{33} \}$, they would not be able to align their vectors such that they are separable at receiver one. A more precise characterization in terms of the actual channel directions is indispensable here for the accomplishment of the full spatial multiplexing gain. Such a representation is precisely what is provided via procedures on the composite Grassmann manifold [51].

The composite Grassmann manifold $G_{n,k}^m$ is formed by taking the direct sum of $m$ copies of the Grassmann manifold $G_{n,k}$, i.e.
\[ G_{n,k}^m = \bigoplus_{m \text{ copies}} G_{n,k} \]

On the Grassmann manifold, a commonly used distance metric is the chordal distance \( d_c \). For the particular case of \( k = 1 \), it reduces to \( d_c^2(v_1, v_2) = 1 - |v_1^H v_2|^2 \). One can extend this distance to \( G_{n,1}^m \) as follows: If \( P, Q \in G_{n,1}^m \), then \( P = [p_1, ..., p_m], Q = [q_1, ..., q_m] \), where \( p_i, q_i \in G_{n,1} \forall \ i \in \{1, 2, ..., m\} \), then the chordal distance between \( P \) and \( Q \) is given by:

\[
\mathcal{D}(P, Q) = \sum_{i=1}^{m} d_c^2(p_i, q_i)
\]

To study how each receiver quantizes its respective channels \( H_{ij} (\forall j \neq i) \) for implementing IA, the aggregated channel matrix \( W_i \in \mathbb{C}^{N^2 \times (K-1)} \) fed back from the \( i^{th} \) receiver is expressed as

\[
W_i = [\hat{h}_{i,1} ... \hat{h}_{i,i-1} \hat{h}_{i,i+1} ... \hat{h}_{i,K}]
\]

where a unit-norm vector \( \hat{h}_{i,j} \in \mathbb{C}^{N^2 \times 1} \) is obtained by stacking the columns of \( H_{ij} \). Note that the vector \( \hat{h}_{i,i} \) corresponding to \( H_{ii} \) is excluded in eq. (6.3), because it is not mandatory for the transmitters to calculate the precoders for the IA.

Using the concept of the composite Grassmann manifold [51], the matrix \( W_i = [w_i^1 ... w_i^{K-1}] \) can be quantized with a codebook \( \mathcal{C} = \{c_1, ..., c_{2^K}\} \) where each codeword \( c_j = [c_j^1 ... c_j^{K-1}] \in \mathbb{C}^{N^2 \times (K-1)} \) with \( \|c_j^m\| = 1 \) \( \forall j, m \), \( c_j \) has the same size of \( W_i \). Specifically, we can represent the chordal distance between these two matrices as

\[
\mathcal{D}(W_i, c_j) = \sum_{l=1}^{K-1} \left( 1 - |w_i^l c_j^l|^2 \right)
\]
Then, receiver $i$ computes the chordal distance from $W_i$ to each codeword in $C$, and feeds back the index of the codeword which shows the minimum chordal distance. This is because the chordal distance accounts for the quantization error on the Grassmann manifold. Based on these indices fed back from all receivers, each transmitter can obtain the CSI for $H_{ij}$ ($i, j = 1, \ldots, K, i \neq j$) from the corresponding codewords and the IA becomes feasible.

6.4.2 Limited Feedback Through Receive Channel Transformation (RCT)

A channel quantization strategy that optimizes the performance of the IA with limited feedback is proposed in [3]. In the proposed scheme, an additional receive filter is introduced to minimize the chordal distance, which accounts for the quantization error on the Grassmann manifold. The quantization error is shown to be substantially reduced in the proposed scheme and significant performance improvements is exhibited for the whole SNR region regardless of the number of the feedback bits compared to the conventional one in [51].

In [3], an additional receive filter $G_i \in \mathbb{C}^{N \times N}$ is introduced at the $i^{th}$ receiver before quantizing the channels. We assume that $G_i$ is a unitary matrix so that the noise remains uncorrelated, i.e., $\mathbb{E}[G_i n_i G_i^\dagger] = \sigma_n^2 I_N$. Denoting $\bar{H}_{ij} = [\bar{h}_{i,j} \ldots \bar{h}_{i,j}^N]$ as the effective channels, we can feed back $\bar{H}_{ij}$ as the actual channel matrix instead of $H_{ij}$. The new aggregated channel matrix becomes $\bar{W}_i = [\bar{h}_{i,1} \ldots \bar{h}_{i,i-1} \bar{h}_{i,i+1} \ldots \bar{h}_{i,K}]$ in which $\bar{h}_{i,j}$ represents the stacking of the columns of $\bar{H}_{ij}$ and is presented as

$$\bar{h}_{i,j} = \frac{(I_N \otimes G_i) \left( [h_{i,j}^1 \ldots h_{i,j}^N] \right)^\dagger}{\| (I_N \otimes G_i) \left( [h_{i,j}^1 \ldots h_{i,j}^N] \right) \|} = \frac{(I_N \otimes G_i) \bar{h}_{i,j}}{\| (I_N \otimes G_i) \bar{h}_{i,j} \|} = (I_N \otimes G_i) \hat{h}_{i,j}$$

(6.4)
where the last equality holds since \( \| (I_N \otimes G_i) \tilde{h}_{ij} \| = 1 \) with the unitary matrix \( G_i \) and the unit-norm vector \( \tilde{h}_{ij} \). By judiciously designing \( G_i \) in eq. (6.4), which determines \( \tilde{W}_i \), the minimum chordal distance for the given codebook \( \mathcal{C} \) becomes smaller than that from quantizing the original \( W_i \).

Using the relation in (4), the chordal distance between \( \tilde{W}_i \) and a given arbitrary codeword \( c_m \in \mathcal{C} \) is developed as

\[
\mathcal{D}(\tilde{W}_i, c_m) = \sum_{l=1}^{K-1} \left( 1 - \left| c_m^{(l)} (I_N \otimes G_i) w_i^l \right|^2 \right)
\]  

(6.5)

where \( w_{i,n}^l \in \mathbb{C}^{N \times 1} \) and \( c_{m,n}^{(l)} \in \mathbb{C}^{N \times 1} \) denote the \( n^{th} \) block of \( w_i^l \) and \( c_m^{(l)} \), respectively (i.e., \( w_i^l = [w_{i,1}^{(l)} \ldots w_{i,N}^{(l)}]^{\dagger} \) and \( c_m^{(l)} = [c_{m,1}^{(l)} \ldots c_{m,N}^{(l)}]^{\dagger} \)). To reduce the chordal distance in eq. (6.5), a lower bound is presented and minimized instead in [3].

The limited feedback strategy proposed in [3] is summarized in algorithm 3.

**Algorithm 3: Receive Channel Transformation Limited Feedback Strategy**

1. Initialize \( G_i = I_N \)
2. Set \( \theta_i \) to the phase of \( c_m^{(l)} (I_N \otimes G_i) w_i^l \)
3. Apply SVD to \( \sum_{l=1}^{K-1} \sum_{n=1}^{N} e^{-j \theta_i} w_{i,n}^{l(+)^{\dagger}} \mathcal{U} \Sigma \mathcal{V}^{\dagger} \)
4. \( G_i = \mathcal{V} \mathcal{U}^{\dagger} \)
5. Go back to (2) until convergence
6. The reduced chordal distance \( \mathcal{D}(\tilde{W}_i, c_m) \) is computed in eq. (6.5).
7. The index of the codeword \( m \) is chosen such that \( \min_{m \in \{1, 2, \ldots \}} \mathcal{D}(\tilde{W}_i, c_m) \) and the corresponding \( G_i \) is identified.
8. Then, the index \( m \) is fed back to the transmitter.

It is worth noting that the performance of this scheme becomes identical to that of the conventional method when the filter \( G_i = I_N \).

At the \( i^{th} \) transmitter, the quantized feedback information corresponding to \( \tilde{H}_{ij} \) is utilized to yield a solution for \( V_i \). In contrast, at receiver \( i' \), the filter \( R_i \) is
derived by using the actual (unquantized) values of $\tilde{H}_{ij}$ since $G_i$ and $H_{ij}$ are both known exactly at the receiver.

6.4.3 Closed Form Solution for Interference Alignment

Closed form solutions for IA in SISO case have been proposed by Cadambe and Jafar in [2] and improved by Douglas and Murat solution in [32] which can also be combined with the ortho-normalization procedure proposed by SHV in [31] to achieve further gains in sum rate. The calculations of IA precoders using these schemes are described in detail in 5.2.1.

Furthermore, it is shown in [2] as mentioned earlier in section 2.2.2.2 that for the 3-user MIMO IC with $N > 1$ antennas at each node, one can achieve exactly $3N/2$ degrees of freedom with constant channel matrices by zero forcing and interference alignment, which gives an $O(1)$ approximation to the $3N/2 \log(1 + \text{SNR}) + O(1)$ capacity of the 3-user MIMO IC with $N > 1$ antennas at all nodes. Thus, we can conclude that the 3-user interference network where all nodes are equipped with multiple antennas can achieve optimal degrees of freedom without the need for long channel extensions.

Two precoding design schemes have been proposed in [2], one is for the case when $N$ is even and the other is for the case when $N$ is odd. Both schemes are shown to provide a total of $3N/2$ degrees of freedom.

Here, we only consider the case when $N$ is even in IA precoders design. Precoding vectors $V_i, i \in \{1, 2, 3\}$ for such case are chosen according to the following equations so that IA Conditions are satisfied.

\[
E = (H_{3,1})^{-1} H_{3,2} (H_{1,2})^{-1} H_{1,3} (H_{2,3})^{-1} H_{2,1} \quad (6.6)
\]

\[
F = (H_{3,2})^{-1} H_{3,1} \quad (6.7)
\]

\[
G = (H_{2,3})^{-1} H_{2,1} \quad (6.8)
\]
Let \( \mathbf{e}_1, \mathbf{e}_2, \ldots, \mathbf{e}_N \) be the \( N \) eigenvectors of \( \mathbf{E} \). Then \( \mathbf{V}_1 \) is set to be

\[
\mathbf{V}_1 = [\mathbf{e}_1, \mathbf{e}_2, \ldots, \mathbf{e}_{(N/2)}] \tag{6.9}
\]

Then \( \mathbf{V}_2 \) and \( \mathbf{V}_3 \) are found using

\[
\mathbf{V}_2 = \mathbf{FV}_1 \tag{6.10}
\]
\[
\mathbf{V}_3 = \mathbf{GV}_1 \tag{6.11}
\]

### 6.4.4 Proposed Limited Feedback Strategies

In this section, we propose a new limited feedback strategy that offers a low-complexity solution to the calculation of the IA precoding vectors in a 3-user IC that is based on the closed-form solutions proposed in [2], [32] as reviewed in Section 6.4.3. The proposed strategy suggests partial calculation of the precoding vectors at receivers, which minimizes the enhancement in quantization error that results from processing quantized quantities. Moreover, the partial processing reduces the amount of information that is required to be feedback to the transmitters to complete the calculation of the IA precoding vectors.

We define the following matrices \( \mathbf{S}_i, i \in \{1, 2, 3\} \) as

\[
\mathbf{S}_1 = \left( \mathbf{H}_{1,2} \right)^{-1} \mathbf{H}_{1,3}, \tag{6.12}
\]
\[
\mathbf{S}_2 = \left( \mathbf{H}_{2,3} \right)^{-1} \mathbf{H}_{2,1}, \tag{6.13}
\]
\[
\mathbf{S}_3 = \left( \mathbf{H}_{3,1} \right)^{-1} \mathbf{H}_{3,2}, \tag{6.14}
\]

where it can be noticed that all the information needed to process \( \mathbf{S}_i \) is available at receiver \( i \) as indicated in Section 6.2.

#### 6.4.4.1 Proposed Limited Feedback Strategies for the 3-User SISO Channel

Now, we can use Eqs. (6.12)-(6.14) to rewrite the precoders designed for the SISO channel in Section 5.2.1 as
\[ V_i(\omega) = \Omega(\omega)\Gamma_i, \]

where the \( N \) by \( n + 1 \) matrix \( \Gamma_1 \) is defined as

\[ \Gamma_1 = \begin{bmatrix} 1 & t_1 & \cdots & t_n \end{bmatrix}, \]

and the \( N \) by \( n \) matrices \( \Gamma_2 \) and \( \Gamma_3 \) are respectively defined as

\[ \Gamma_2 = (S_3)^{-1}\begin{bmatrix} 1 & t_1 & \cdots & t_{n-1} \end{bmatrix}, \quad \Gamma_3 = S_2\begin{bmatrix} t_1 & t_2 & \cdots & t_n \end{bmatrix}, \]

\[ T = H_{1,2}(S_2)^{-1}(S_3)^{-1}(H_{1,3})^{-1}, \quad (6.15) \]

\[ (6.16) \]

From Eqs. (6.15)-(6.17), we can notice that only \( S_i, H_{1,i}, i \in \{2,3\} \) are required to be available at the transmitters to calculate the precoding vectors. Now, we propose two new limited feedback strategies based on those equations.

6.4.4.1.1 Conventional Scheme and Partial Receiver Processing Combination (CS-PRP)

In this scheme, we use the conventional method using the concept of Composite Grassmann Manifold in Section 6.4.1 only at receiver 1 where the aggregated channel matrix \( \hat{W}_1 \in \mathbb{C}^{N^2 \times 2} \) fed back is expressed as \( \hat{W}_1 = \begin{bmatrix} \hat{h}_{1,2} & \hat{h}_{1,3} \end{bmatrix} \) and is quantized with a codebook \( \hat{C} = \{ \hat{c}_1, \ldots, \hat{c}_{2^B} \} \) where each codeword \( \hat{c}_j = [c_j^1 \ c_j^2] \in \mathbb{C}^{N^2 \times 2} \) with \( \|c_j^m\| = 1 \ \forall j, m \), \( c_j \) has the same size of \( \hat{W}_1 \) and \( \hat{h}_{i,j} \) is obtained by stacking the diagonal elements of \( H_{i,j} \). Now, each receiver \( i, i \in \{2,3\} \) is required to feed back only a single unit-norm vector \( \hat{S}_i \in \mathbb{C}^{N^2 \times 1} \) that is obtained by stacking the diagonal elements of \( S_i \). \( \hat{S}_i \) is quantized with a codebook \( \hat{C}_1 = \{ c_1, \ldots, c_{2^B} \} \) where each codebook vector \( c_j \in \mathbb{C}^{N^2 \times 1} \) with \( \|c_j\| = 1 \ \forall j \), \( c_j \) has the same size of \( \hat{S}_i \).
6.4.4.1.2 Receive Channel Transformation and Partial Receiver Processing Combination (RCT-PRP)

Similarly, each receiver \( i, i \in \{2,3\} \) is required to feed back only a single unit-norm vector \( \hat{S}_i \in \mathbb{C}^{N \times 1} \) that is quantized with a codebook \( \hat{\mathbf{C}}_1 = \{c_1, \ldots, c_{2^B}\} \) where each codebook vector \( c_j \in \mathbb{C}^{N \times 1} \) with \( \|c_j\| = 1 \forall j \), \( c_j \) has the same size of \( \hat{S}_i \). In contrast, receiver 1 uses the RCT limited feedback strategy described in Section 6.4.2.

At receiver 1, the aggregated channel matrix \( \hat{\mathbf{W}}_1 \in \mathbb{C}^{N \times 2} \) fed back is expressed as \( \hat{\mathbf{W}}_1 = \left[ \hat{\mathbf{h}}_{1,2} \hat{\mathbf{h}}_{1,3} \right] \) and is quantized with a codebook \( \hat{\mathbf{C}} \) where \( \hat{\mathbf{h}}_{i,j} \) is obtained by stacking the diagonal elements of \( \overline{\mathbf{H}}_{i,j} \).

6.4.4.2 Proposed Limited Feedback Strategies for the 3-User MIMO Channel (PRP-MIMO)

We use Eqs. (6.12)-(6.14) to rewrite Eqs. (6.6)-(6.8) used in the design of the MIMO channel precoders \( \mathbf{V}_i, i \in \{1,2,3\} \) in Section 6.4.3 when \( N \) is even as

\[
\begin{align*}
\mathbf{E} &= \mathbf{S}_3 \mathbf{S}_1 \mathbf{S}_2, & (6.18) \\
\mathbf{F} &= (\mathbf{S}_3)^{-1}, & (6.19) \\
\mathbf{G} &= \mathbf{S}_2. & (6.20)
\end{align*}
\]

From Eqs. (6.9)-(6.11), (6.18)-(6.20), we can notice that only \( \mathbf{S}_i, i \in \{1,2,3\} \) are required to be available at the transmitters to calculate the precoding vectors. Hence, each receiver \( i, i \in \{1,2,3\} \) is required to feedback only a single unit-norm vector \( \tilde{S}_i \in \mathbb{C}^{N \times 1} \) that is quantized with a codebook \( \mathbf{C}_1 = \{c_1, \ldots, c_{2^B}\} \) where each codebook vector \( \mathbf{C}_j \in \mathbb{C}^{N \times 1} \) with \( \|\mathbf{C}_j\| = 1 \forall j \), \( \mathbf{C}_j \) has the same size of \( \tilde{S}_i \), and \( \tilde{S}_i \) is obtained by stacking the columns of \( \mathbf{S}_i \).
6.5 Performance Evaluation

In this section, we present the results of our proposed limited feedback strategies and compare it to both the pure conventional strategy based on Composite Grassmann Manifold (abbreviated CS) presented in Section 6.4.1 and the pure RCT strategy described in Section 6.4.2 through the Monte Carlo simulations. The same transmission power constraint $P$ is assumed for each transmitter, i.e., $\mathbb{E}[\mathbf{x}_i^H \mathbf{x}_i] = P$ for all $i$, and the SNR is defined as $P/\sigma_n^2$. The codewords in $\mathcal{C}$ are generated through RVQ in which the codebook is randomly generated and the $2^B$ codebook vectors are generated independently and identically distributed according to the stationary distribution of the optimal unquantized vector [53]. It is intuitive to think that as the number of bits $B$ used for quantization increases, performance improves. Hence, we will only present results for $B = 4$. SISO system results for a number of channel extensions $N = 3$ are shown in Figure 6. 3. We can notice that our proposed CS-PRP scheme achieves better performance than the conventional (CS) scheme due to the reduction of the number of feedback quantized vectors at 2 of the 3 receivers to 1 vector instead of 2 vectors. Also, it can be noticed that the proposed RCT-PRP scheme performs better than the original RCT scheme for low SNR values and both offer the same spectral efficiency for SNR values greater than 25 dB. Moreover, it is shown that both RCT and RCT-PRP schemes have better performance than both CS and CS-PRP schemes.

On the other hand, MIMO results for a number of antennas $N = 2$ and 4 are shown in Figure 6. 4 and Figure 6. 5, respectively. In the aforementioned figures, it is clear that our proposed PRP scheme outperforms both CS and RCT schemes over all SNR values while reducing the processing complexity at receivers presented by the RCT scheme.
Figure 6.3  Spectral efficiency results in case of SISO, $B = 4$, and $N = 3$.

Figure 6.4  Spectral efficiency results in case of MIMO, $B = 4$, and $N = 2$. 

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Figure 6.5  Spectral efficiency results in case of MIMO, $B = 4$, and $N = 4$. 
7 Conclusion

7.1 Evaluation

In chapter 5, we propose a new setup where IA can be applied to a cellular network enabling direct D2D communication. We have shown that despite the worse performance of IA schemes as compared with the P2P scheme from BER perspective, IA schemes are still able to achieve higher throughputs due to the excess degrees of freedom available in IA transmission schemes as compared to those available in the P2P transmission scheme. Additionally, we have shown that the overall capacity of a D2D enabled cellular network using the separate resource sharing mode can be improved by using the IA technique and it suffices to take channel conditions between each pair’s transmitter and receiver into account for grouping as in the CBS scheme to achieve the highest performance in a single cluster where interference is not an issue. Also, we have shown that for the proposed D2D scenarios, frequency reuse can achieve better sum rates that are proportional to the number of formed clusters. The interference induced by the reuse process is not very significant at signal transmit powers less than -15 dBm for the D2D setup provided.

On the other hand, chapter 6 proposes new limited feedback schemes for both SISO and MIMO systems that exploits IA for precoding and considering only the 3-user IC where a closed form solution for IA precoders exists. The proposed schemes simply depend on partial IA precoding processing depending on information that is already available at receivers. The limited feedback schemes proposed significantly reduces the processing complexity required to minimize quantization errors at the receivers, subsequently, minimize errors in the IA precoders calculation at transmitters compared to the scheme proposed in [3] and interestingly improves spectral efficiency performance as well.
7.2 Future Work

Future work suggested for the work conducted in chapter 5 includes the relaxation of the assumption of the availability of full channel state information at the transmitters and receivers and implementing practical schemes for IA using the minimalist information expected to exist in mobile handsets. Also, the study of the effect of the parameter $L_{\text{Max}}$ on the interference among clusters and the study of the relation between $L_{\text{Max}}$ and the number of clusters within a cell and its effect on sum rate are worth investigating.

As for the schemes proposed in chapter 6, a thorough study to the effect of increasing the number of channel extensions in SISO systems while increasing the number of feedback bits as well is suggested. Moreover, a comparison to the scheme proposed in [54] as the number of channel extensions increases when considering correlated channels is targeted.
References


