Department of Signal Processing and Acoustics

Interference Management Techniques for Cellular Wireless Communication Systems

Pekka Jänis

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DOCTORAL DISSERTATIONS

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Interference Management Techniques for Cellular Wireless Communication Systems

Pekka Jänis

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Abstract

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Abstract

The growing demand for higher capacity wireless networks can be met by increasing the frequency bandwidth, spectral efficiency, and base station density. Flexible spectrum access, multiantenna, and multicarrier techniques are key enablers in satisfying the demand. In addition, automation of tasks related to network planning, optimization, interference management, and maintenance are needed in order to ensure cost-efficiency. Effective, dynamic, and automated interference management tailored for bursty and local data traffic plays a central role in the task.

Adjacent channel interference (ACI) management is an enabler for flexible spectrum use and uncoordinated network deployments. In this thesis the impact of ACI in local area time division duplex (TDD) cellular systems is demonstrated. A method is proposed where the transmitters optimize their transmitted spectral shape on-line, such that constraints on ACI induced by power amplifier non-linearity are met. The proposed method increases the fairness among spectrum sharing transceivers when ACI is a limiting factor.

A novel interference-aware scheduling technique is proposed and analyzed. The technique manages co-channel interference (CCI) in a decentralized fashion, relying on beacon messages sent by data receivers. It is demonstrated that the proposed technique is an enabler for fair spectrum sharing among operators, independent adaptation of uplink/downlink switching points in TDD networks, and it provides overall more fair and spectrally efficient wireless access. Especially, the technique is able to improve the cell-edge throughput tremendously.

New services are emerging that generate local traffic among the users in addition to the data traffic between the users and the network. Such device-to-device (D2D) traffic is effectively served by direct transmissions. The thesis demonstrates the possibilities for allowing such direct D2D transmissions on a shared band together with the cellular communication. It is shown that interference management is needed in order to facilitate reliable and efficient shared band operation. For this purpose, three methods are proposed that provide interference aware power control, interference aware multiuser and multiband resource allocation, and interference avoiding spatial precoding. It is shown that enabling direct transmission itself provides most of the gains in system capacity, while the interference management schemes are more important in promoting fairness and reliability.

Keywords Interference management, adjacent channel interference, co-channel interference, device-to-device communication, interference-aware scheduling

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Tiivistelmä

Langattomien tietoliikenneverkkojen käyttö kasvaa erittäin nopeasti mobiilien internet-palvelujen ja älykkäiden päätelaitteiden suosion myötä. Järjestelmien tiedonsiirtokapasiteettiä voidaan lisätä kasvattamalla kaistanleveyttä, spektritehokkuutta ja tukiasemaverkon tiheyttä. Kehityksen mahdollistaa mm. joustava taajuuksien käyttö ja moniantenni- ja monikantoaaltotekniikat. Lisäksi radioverkkojen suunnitteluun, optimointiin, ylläpitoon ja interferenssinhallintaan liittyvien tehtävien automatisoinnilla voidaan pienentää verkko-operaattoreiden kustannuksia. Tässä hetkellisen ja paikallisen tietoliikenteen tehokas, dynaaminen ja automatisoitu interferenssinhallinta on keskeisessä asemassa.

Viereisen kanavan interferenssin hallinta mahdollistaa osaltaan joustavan spektrinkäytön ja koordinoimattoman verkkojen asennuksen. Väitöskirjassa on analysoitu viereisen kanavan interferenssin vaikutusta aikajakoiseen dupleksilähetykseen perustuvien paikallisten radioverkkojen toimintaan. Lisäksi väitöskirjassa on kehitetty menetelmä, jolla voidaan hallita interferenssiä reaaliaikaisesti. Menetelmä maksimoi lähetetyn signaalin spektritehokkuuden siten, että tehovahvistimen epälineaarisuuden aiheuttama viereisen kanavan interferenssi on rajoitettu.

Väitöskirjassa on kehitetty ja analysoitu uudenlainen interferenssitietoinen lähetysten ajoitustekniikka. Tekniikka hallitsee reaaliaikaisesti ja hajautetusti saman kanavan interferenssiä vastaanottimien lähettämien majakkasignaalien avulla. Esitetyt simulaatiot osoittavat, että tämä mahdollistaa operaattoreiden välisen taajuuskaistojen jaon, ja alas- ja yloslinkkien aikajaon joustavan säädön. Tämän lisäksi on mahdollista saavuttaa korkeampi yleinen spektritehokkuus. Erityisesti tiedonsiirtonopeus solujen reunoille kasvaa esitetyn tekniikan avulla huomattavasti.

Uudenlaiset tietoliikennepalvelut lisäävät laitteidenvälisen paikallisen tietoliikenteen määrää. Spektrinkäytön kannalta tämä liikenne on tehokkainta lähettää suoraan laitteesta toiseen. Väitöskirjassa on tutkittu joustavaa spektrinkäyttöä suorien laitteidenvälisten lähetysten ja soluverkon välillä. Interferenssin hallinta takaa luotettavan ja tehokkaan spektrin yhteiskäytön. Tätä varten väitöskirjassa on kehitetty kolme menetelmää, jotka perustuvat tehonsäätöön, lähetysten ajoitukseen ja moniantennilähetykseen.

Avainsanat Interferenssin hallinta, soluverkko, interferenssitietoinen aikataulutus

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Preface

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Espoo, June 11, 2013,

Pekka Jänis

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I P. Jänis, V. Koivunen, O. Tirkkonen, and K. Hugl. Adjacent channel interference between asynchronous TDD cellular networks. In *IEEE Vehicular Technology Conference, VTC Spring 2009*, Barcelona, Spain, pp. 1–5, April 2009.

II P. Jänis, V. Koivunen, and M. Nentwig. Optimizing spectral shape under general spectrum emission mask constraints. In *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2009*, Tokyo, Japan, pp. 107-111, September 2009.

III P. Jänis, C. Ribeiro, and V. Koivunen. Interference Aware Radio Resource Management for Local Area Wireless Networks. *EURASIP Journal on Wireless Communications and Networking*, vol. 2011, article ID 921623, pp. 1–15, 2011.

IV P. Jänis, C. Ribeiro, and V. Koivunen. On the Performance of Flexible UL-DL Switching Point in TDD Wireless Networks. In *IEEE GLOBECOM Workshop on Femtocell Networks, FEMnet 2011*, Houston, USA, pp. 1–5, December 2011.

V P. Jänis, C. Ribeiro, and V. Koivunen. Flexible UL-DL Switching Point in TDD Cellular Local Area Wireless Networks. *ACM / Springer Journal on Mobile Networks and Applications (MONET)*, vol. 17, no. 5, pp. 695–

707, October 2012.

VI P. Jänis, C.-H. Yu, K. Doppler, C. Ribeiro, C. Wijting, K. Hugl, O. Tirkkonen, and V. Koivunen. Device-to-device communication underlaying cellular communications systems. *International Journal of Communications, Network and System Sciences*, vol. 2, no. 3, pp. 169–178, June 2009.

VII P. Jänis, V. Koivunen, C. Ribeiro, J. Korhonen, K. Doppler, and K. Hugl. Interference-aware resource allocation for device-to-device radio underlaying cellular networks. In *IEEE Vehicular Technology Conference, VTC Spring 2009*, Barcelona, Spain, pp. 1–5, April 2009.

VIII P. Jänis, V. Koivunen, C. Ribeiro, K. Doppler, and K. Hugl. Interference-avoiding MIMO schemes for device-to-device radio underlaying cellular networks. In *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2009*, Tokyo, Japan, pp. 2385-2389, September 2009.

List of Abbreviations

ACI	Adjacent channel interference
ACPR	Adjacent channel power ratio
ACS	Adjacent channel selectivity
AM	Amplitude modulation
AMC	Adaptive modulation and coding
AP	Access point
ARQ	Automated repeat request
BS	Base station
CCI	Co-channel interference
CDF	Cumulative distribution function
CDMA	Code division multiple access
CoMP	Co-operative multi-point transmission
CSG	Closed subscriber group
CSI	Channel state information
CSMA/CA	Channel sense multiple access / collision avoidance
D2D	Device to device
DL	Downlink
EVM	Error vector magnitude
FDD	Frequency division duplex
FDMA	Frequency division multiple access
GSM	Global system for mobile communications
HARQ	Hybrid automated repeat request
IA	Interference aware
IAS	Interference aware scheduler
IQ	In-phase / quadrature
ISI	Inter symbol interference
ITU	International telecommunications union

LMMSE	Linear minimum mean square error
LOS	Line of sight
LTE	Long term evolution
LTE-A	Long term evolution advanced
MAC	Multiple access
MAI	Multiple access interference
MCS	Modulation and coding scheme
MIMO	Multiple-input multiple-output
MUD	Multi-user detection
MU-MIMO	Multi-user multiple-input multiple-output
OFDMA	Orthogonal frequency division multiplexing
OSG	Open subscriber group
PA	Power amplifier
PAPR	Peak to average power ratio
PF	Proportional fair
PSD	Power spectral density
RAT	Radio access technology
RF	Radio frequency
RRM	Radio resource management
RTS/CTS	Request-to-send / clear-to-send
RX	Receiver
SC-FDMA	Single-carrier frequency division multiple access
SDMA	Spatial division multiple access
SIC	Successive interference cancellation
SINR	Signal to interference and noise ratio
SNR	Signal to noise ratio
TDD	Time domain duplexing
TDMA	Time domain multiple access
TETRA	Terrestrial trunked radio
TX	Transmitter
UE	User equipment
UL	Uplink
WCDMA	Wide-band code division multiple access
WLAN	Wireless local area network

List of Symbols

$\star$	Convolution operation
$\lvert\mathcal{S}\rvert$	Cardinality of set $\mathcal{S}$
α_i	i-th coefficient of polynomial PA model
$\mathcal{D}$	Function representing distortion
f	Frequency
f_{high}	Higher band edge
f_{low}	Lower band edge
$h(f)$	Frequency dependent channel gain
$\mathcal{L}_s$	The set of links served by scheduler s
N_0	White noise power spectral density
p_n	Power constraint on n-th rejection band
Q^+	Interfered link throughput under positive scheduling decision
Q^-	Interfered link throughput under negative scheduling decision
$\mathcal{R}_n$	n-th rejection band
$S_x(f)$	Power spectral density of signal x
$S(f)^{\star(m)}$	m-fold convolution of $S(f)$ with itself: $S(f) \star \ldots \star S(f)$
T^+	Desired link throughput under positive scheduling decision
T^-	Desired link throughput under negative scheduling decision

1. Introduction

1.1 Motivation

Wireless communication has witnessed a tremendous growth in the amount of transmitted information as a result of mobile internet, new wireless services, and smart phones. New radio access technologies (RAT) facilitate providing new services and high data rate everywhere. In the wireless communication systems the information is sent over radio frequency bands that may be characterized by their carrier frequency, bandwidth, propagation conditions, and interference conditions. The radio spectrum is a common resource and hence the use of it is strictly regulated by national governments and agencies like the International Telecommunication Union (ITU). The regulation is needed to ensure that the different systems may coexist without interfering with each other. The downside of such regulation is that spectrum allocations are rigid. Regulation is done over large geographical areas and over long time periods, whereas spectrum is accessed locally and over short time periods. The cost of obtaining new frequency bands to exclusive use is high. However, most of the existing frequency allocations are not fully utilized [87, 127]. If the rules of accessing radio spectrum would be more flexible such bands could taken into secondary use locally. Such secondary use could coexist with the system that is the primary user of the band if the interference among the two is managed dynamically and locally. Thus, spectrum is not necessarily a scarce resource, but obtaining exclusive rights to suitable bands is very expensive.

As the usage of wireless systems keeps increasing at a rapid rate both in terms of the data rate per user and in number of users, the wireless systems need to be continuously developed further to keep up with capacity demand. The operators need to keep the cost per transmitted bit low to ensure profitable business. In general, higher system capacity may be achieved by improving the spectral efficiency, increasing the bandwidth, and deploying more base stations. New frequency bands are searched for in higher frequencies as well. However, these improvements come with a cost. Higher spectral efficiency at the physical layer through e.g. use of multiple antenna techniques and spectrally efficient waveforms increases the cost of the devices. The same is true for increasing the bandwidth. Supporting multiple frequency bands (also called carrier aggregation) in a device requires careful RF design and is expensive. Limited availability of new paired frequency bands hinders deployment of new frequency division duplex (FDD) systems. Decreasing reuse factor means that the interference among the reusing radio links increases. Therefore, more intricate and complex interference management techniques for ensuring reliability are needed. Finally, although essential, making the network deployments denser is only feasible if the cost of base stations, network planning, and the associated infrastructure is kept low. This calls for automation of tasks related to network deployment, optimization, interference management, and maintenance. From the physical layer point of view, dynamic methods that allow adapting to interference by avoiding, suppressing, and coordinating it are central. This involves agile use of different degrees of freedom and sources of diversity in the system.

An important consequence of the tendency toward denser network deployments and smaller cells is that the number of users served by each cell gets smaller. At the same time, the internet traffic consumed by smartphones and new services is more bursty than e.g. traditional voice traffic. Moreover, new services are emerging that generate local data traffic among users and machines connected wirelessly. This trend implies that the spectrum demand becomes very local and intermittent, which is in contrast with the spectrum needs of macrocellular base stations. Novel methods for spectrum access and interference management are needed in order to enable efficient and reliable wireless access in this scenario.

1.2 Scope

Supporting the growth of the wireless systems' capacity demand requires tremendous effort in all aspects of improving area spectral efficiency. In this thesis the emphasis is on developing low level interference management schemes for future cellular systems. The goal of such schemes include higher spectral efficiency, lower frequency reuse factors, and reduced costs through lighter infrastructure and network planning.

Three different sub-topics in interference management considered in this thesis. The first one is about managing adjacent channel interference (ACI). The ACI manifests between radio systems that operate on adjacent frequency bands. As such, ACI dictates the rules by which the frequency bands may be allocated to different radio systems. In order to manage ACI one has to consider e.g the locations of the devices, transmission powers, resiliency toward interference, and properties of the RF transceivers. In this respect, the goal is to investigate how ACI arises in wireless communication systems, and how it could be managed in an on-line fashion. Developments in this field could eventually enable more flexible utilization of frequency bands (therefore, increased spectrum availability), reduced energy consumption, and increased flexibility in network deployments (therefore, reduced costs to the operators) to name a few.

The second sub-topic of the thesis is managing co-channel interference (CCI). CCI is interference among transmissions occurring on the same frequency band. The employed frequency reuse schemes dictate how close the devices that reuse the frequency resource are to each other. In addition to this, other factors that influence CCI are transmit power control schemes and multi-antenna techniques. An important trade-off involving CCI management relates to ensuring high total system capacity (i.e. sum rate), and on the other hand high fairness and reliability (i.e. individual user's instantaneous rate). The goal of the thesis is to develop techniques that enable dense reuse of radio resources while still providing fair and reliable access. This leads directly to higher system spectral efficiency and therefore possibilities to serve more users over the same frequency bands.

The third sub-topic of the thesis involves supporting direct device-to-device (D2D) communication in a wireless system. Specifically, enabling D2D (ad hoc) communication that reuses the same frequency bands as the communication between user terminals and base stations (infrastructure) is considered. In such a scenario there arises strong interference among the D2D and infrastructure communication links, which calls for advanced interference management schemes. This sub-topic may be viewed as a special case of CCI management. Here, the goal of the thesis is to investigate the opportunities for reusing the cellular frequency bands for

D2D communication and to develop interference management schemes that maximally exploit such opportunities. The D2D communication scenario is becoming more and more important as new wireless services are emerging that result in data traffic between devices that are located close to each other. As the amount of such local data traffic becomes large, supporting it in an efficient manner clearly improves the system capacity.

A cellular communication system is assumed throughout the thesis. The research is not specific to a certain standard as a lot of the functionalities in a cellular network are modeled in a simplified manner. Moreover, the developed interference management schemes are partly rather disruptive with respect to the current standards. However, the assumptions made on the cellular system resemble e.g. the Evolved Universal Terrestrial Radio Access (E-UTRA) system [2]. E-UTRA is referred to as LTE (Long Term Evolution) in the sequel. In particular, the assumed physical layer is intended to be functionally similar to that of LTE. The results may therefore find applications in most emerging and current wireless systems. In addition, the thesis assumes a local area communication scenario as e.g. the simulations are performed assuming an indoor propagation environment. It may be further mentioned that system simulations play a central role in this thesis in addition to the analytical results. Simulations are essential in studying effects that manifest themselves in networks with multiple base stations and terminals. Applying analytical tools may become too tedious and impractical, or require oversimplification of large scale problems. In this respect the primary goal of the thesis is to develop solutions of practical relevance, in addition to merely satisfying academic interest.

1.3 Contributions

This thesis provides an overview of different aspects of interference in local area cellular systems. It proposes methods for performing low-level management of different types of interference in such systems. The individual contributions of the thesis are the following:

1. The manifestation of ACI among local area TDD cellular systems is investigated.

2. A method for on-line optimization of the spectral shape of the transmitted signal is proposed. The optimization aims at maximizing the desired

link capacity under constraints on power amplifier induced ACI.

3. A novel multiple access technique that enables decentralized interference-aware scheduling (IAS) is developed. The technique enables making scheduling decisions that improve system-wide performance. The convergence of IAS is proven analytically.

4. The benefits from spectrum sharing between two networks are demonstrated. The spectrum sharing is facilitated through applying IAS for interference management among the networks.

5. The performance of flexible TDD switching point in local area cellular networks is characterized analytically and in system simulations. The role of cross-link interference management in such a scenario is demonstrated.

6. A power control based interference management method for D2D communication reusing cellular uplink radio resources is developed.

7. An interference aware resource allocation method for D2D communication reusing cellular radio resources is developed.

8. An interference aware MIMO precoding technique for the scenario of D2D communication reusing cellular downlink radio resources is developed.

1.4 Structure of the thesis and summary of the publications

This thesis consists of a compendium and eight original publications. First, an overview of interference management in wireless networks is given in Chapter 2. Then, Chapters 3, 4, and 5 deal with adjacent channel interference, co-channel interference, and device-to-device communications, respectively. The main contributions of the thesis are described as well. Finally, Chapter 6 concludes the thesis.

In all of the original publications, except for sections 1, 2, 5, 6, and 7 in Publication VI, the author of this thesis has written the first draft, and conducted all the simulations and the associated theoretical analysis.

Also the simulation tools used in obtaining the system simulation results have been developed mainly by the author of the thesis. The co-authors have helped in writing of the publications and provided with ideas on the proposed interference management schemes. In addition, in Publication II, the measurements on the actual power amplifier are were carried out by Mr. Markus Nentwig. The original publications are briefly summarized as follows:

- Publication I investigates how ACI impacts to the SINR distributions in local area TDD cellular systems. The paper assumes that the multiple access is partly divided in frequency (i.e. FDMA, or OFDMA), and that there are two networks operating on the same geographical area. The paper presents simulation results on the uplink and downlink SINR distributions in case the two networks deploy their base stations either co-located or not, and for the cases when the networks are synchronous or not. The paper concludes that the adjacent channel base station is the most severe source of interference in such a scenario.

- Publication II proposes a technique where the devices optimize the spectral shape of their transmitted signal such that the desired link capacity is maximized and adjacent channel emissions are minimized. The paper assumes that the dominant source of the adjacent channel leakage is due to non-linearity of the power amplifier. The optimization is facilitated by fitting a polynomial model to the power amplifier AM/AM curve and assuming that the driving signal is Gaussian. A numerical example together with measurement results is given that demonstrates the method in practice. The proposed approach may be considered as one key component in a system that controls adjacent channel interference in and on-line fashion instead of through specifications and regulations.

- Publication III proposes a multiple access (MAC) technique that is a modification to the traditional frame based scheduled transmissions employed in cellular standards. The technique enhances the traditional MAC with broadcast beacon messages that are transmitted from the data receivers. The beacon messages contain information on the received power levels and throughput, which enables making system level optimal scheduling decisions. Hence decentralized and dynamic interference management is facilitated. The method is called interference aware scheduling (IAS). The paper proves that IAS is convergent by using analytical tools. The impact of several non-idealities to the beacon transmissions is investigated as well. Extensive system simulations are presented that show the tremendous potential from IAS. In the provided example, IAS is applied to the case where two operators serve their users on the same geographical area on a shared frequency band. It is shown that shared band operation is much more efficient than orthogonal band operation once interference awareness is incorporated to the MAC.

- Publication IV investigates the performance of local area TDD systems that employ flexible uplink/downlink switching points. In such systems each base station may independently decide how to split the available time slots between the uplink and downlink transmission. Such adaptation potentially doubles the peak data rates but at the same time may induce harsh interference among the different link directions. The paper presents theoretical analysis on the potential gains assuming a finite buffer traffic model. The analysis reveals that the throughput gain is available regardless of the interference (that is, both in an isolated link and in case of two interfering links). The practical throughput gains are also demonstrated through system simulations, where both non-interference aware scheduling and also IAS are applied. The preliminary results presented in Publication IV are extended and studied in more detail in Publication V. The paper concludes that the majority of the throughput gain comes from simply enabling the flexible switching points. Interference management through IAS provides robustness, reliability, and fairness to the system.

- Publication V is an extended version of Publication IV. While in Publication IV the UL and DL transmit power spectral densities were assumed to be identical, in Publication V UL power control was assumed. The paper demonstrates the impact of asymmetric transmit power in UL and DL through system simulations. The packet delay statistics of UL and DL show that selecting similar UL and DL transmit powers is beneficial in flexible switching point TDD systems, especially if the interference between the two link directions is not managed. Employing IAS makes the system more tolerant toward asymmetric UL and DL transmission powers.

- Publication VI gives a high-level introduction to a wireless system which supports both cellular communication and also direct device-to-device (D2D) communication on the same frequency band. The paper presents system simulation results on the SINR distributions arising in such a system. A method for interference aware power control is proposed for the case when the D2D communication shares radio resources with the uplink cellular transmissions. The paper also presents simulation results on how the optimal mode for D2D communication depends on the location of the D2D pair in the cell. It is concluded that despite the potentially harsh interference among the D2D and infrastructure communication, ample opportunities for reusing the radio resources between the two communication types exist. In order to exploit these opportunities to the full, the system has to rely on careful and dynamic interference management.

- Publication VII proposes to reduce the interference between the D2D and infrastructure communication by exploiting multi-user diversity. In the proposed method, the base station allocates the radio resources within the cell such that the distances between the devices reusing the same radio resource is maximized. In addition, a method for obtaining the necessary knowledge on the interference links is proposed. The method relies on measurements made by the D2D devices and it may be facilitated without need for modifications to the legacy non-D2D devices. The paper demonstrates through system simulations the benefits from the proposed technique. It is concluded that the vast majority of system capacity gain comes from simply allowing the direct D2D communication (instead of routing the traffic through the base station). Although the additional gain from the interference aware resource allocation is small in comparison, it is envisioned to have in practice a higher impact on the reliability of the communication.

- Publication VIII deals with spatial domain techniques in suppressing the interference among the D2D and infrastructure communication. A technique for interference aware MIMO precoding of the downlink transmissions is proposed. The technique optimizes the downlink capacity under the constraint of minimizing the interference toward the D2D receivers that are active on the same radio resource. The performance of the technique is studied through system simulation. It is concluded that the additional gain from interference aware MIMO precoding is rather small when looking at the total system capacity. However, the gain on the number of usable D2D links is large. The paper assumes perfect MIMO channel state information.

2. Overview of interference management

This chapter gives a short overview of interference management in wireless communication systems. The purpose is to highlight the overall methods and future trends in how wireless systems deal with interference. The evolution from rigid and pre-planned interference management toward flexible, dynamic, and autonomous spectrum access is considered to be a key enabler in providing cost efficient and high data rate wireless access in the future. In this section an overview of interference management in wireless systems is given. References dealing with wireless systems in general include [90, 119, 50]. One way to classify wireless systems is based on the primary channel access method, that is, to contention based and scheduled access. An example of a contention based system is the 802.11 wireless local area network (WLAN), whereas cellular systems, such as 3GPP LTE are mostly scheduled. For an overwiev of interference management in LTE, see e.g. [8]. The focus of this thesis is on scheduled cellular wireless systems. The interference in wireless systems may be classified into self interference, multiple access interference, co- and adjacent channel interference, and coexistence interference. Each of these interference types and the corresponding main management techniques are briefly introduced in this section. The trends in interference management are also shortly discussed.

2.1 Cellular systems

The main service in 1st (e.g. Nordic Mobile Telephone, NMT) and 2nd generation (e.g. Global System for Mobile communications, GSM) cellular systems was voice for wide coverage. However, with the increase of wireless broadband internet connections and mobile internet services and usage, data is currently consuming the most of the capacity [33]. For texts on the history of mobile telephony and wireless communication the reader is referred to [37, 14].

In a circuit switched network, such as GSM, each connection (call) reserves a dedicated channel for its exclusive use. This suits voice transmission relatively well due to the static nature the connections and the delay requirements of the voice traffic. However, circuit switched networks are inefficient for data transmission since data traffic tends to be more bursty. In a packet switched network the channels are shared among different connections. The data is grouped into packets, and the channel sharing is facilitated by statistical multiplexing, where base stations (BS) coordinate the transmissions such that the data packets do not collide with each other. An essential difference between circuit switched system and a packet switched system is the time scale of this coordination: in circuit switching it is done on the connection level whereas in packet switching it is done on the packet level. This enables much more spectrally efficient systems.

While the 1st generation cellular networks were designed for voice and were exclusively circuit switched, the 2nd and, more prominently, 3rd generation systems (e.g. Universal Mobile Telecommunications System, UMTS) include a packet switched mode for data transmission, see e.g. [61]. Furthermore, 4th generation cellular systems (e.g. Long Term Evolution, LTE, and LTE Advanced, LTE-A) are exclusively packet switched with both voice and data transmitted over the Internet Protocol (IP), see e.g. [110].

2.2 Wireless local area networks

Wireless local area networks (WLAN) provide high speed data connections mainly over smaller areas such as office buildings, public spaces, and at home. The IEEE 802.11 standards define a variety technologies for WLAN, see [67]. Regarding interference management, the main difference between 802.11 and cellular systems is in the channel access method. In 802.11, each node accesses the spectrum in a distributed manner by first sensing if the channel is idle, and transmitting only when it is idle. In order to prevent multiple nodes from starting a transmission simultaneously, and consequently interfering with each other, the duration of the sensing phase of an idle channel is randomized. Thus interference is avoided provided that the nodes can sense the busy channels with sufficient reliability. This contention based channel access called carrier sense multiple access (CSMA) is efficient and has low latency when the number of contending transmitters is sufficiently low. Therefore it is suitable for local area communication where there are only a few users under the coverage area of an access point. On the other hand, the cellular systems with scheduled access can handle better a large amount of users per base station, and are more suitable for providing continuous coverage.

2.3 MIMO OFDMA

The physical layer in many current wireless systems is based on multicarrier modulation, in particular, orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA). For instance, 3GPP LTE utilizes OFDMA and 802.11n OFDM. It is also likely a key technology in the forthcoming wireless systems due to its inherent benefits, see e.g. [57, 128, 115, 13]. A single carrier receiver has to cope with inter-symbol interference in a frequency selective (i.e. time dispersive) channel using e.g. multiple tap equalizers. Multicarrier modulation converts the wideband channel to a set of parallel narrowband channels (subcarriers) experiencing flat fading. Hence, a single-tap equalizer is sufficient per subcarrier, which simplifies the receiver design. In OFDM the frequency band is divided to a large number of subcarriers which are ideally orthogonal such that there is no intercarrier interference. Hence, each subcarrier may be modulated independently which facilitates achieving rates closer to the frequency selective channel capacity. The conversion between the parallel subcarriers and the serial time-domain samples is done via the fast Fourier transform (FFT), which is a computationally efficient algorithm for performing the discrete Fourier transform (DFT). Furthermore, inter-symbol interference is eliminated by adding a cyclic prefix to each OFDM symbol. Multicarrier systems are also suitable for multiantenna transceiver techniques (multiple input multiple output, MIMO) since a flat fading channel enables straightforward implementation of MIMO schemes [48]. The spatial degrees of freedom in a MIMO system may be used for improving the capacity and/or link reliability through a trade-off among spatial multiplexing, beamforming, and diversity techniques [116, 133]. Despite the several benefits, OFDM has also drawbacks – it requires accurate frequency synchronization, is sensitive to Doppler spread, and has high peak to average power ratio (PAPR).

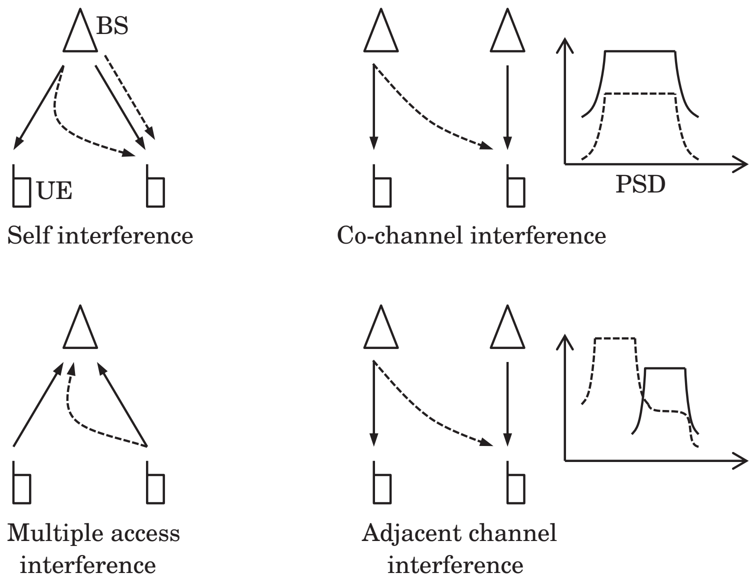


Figure 2.1. An illustration of different interference types occuring in wireless systems.

2.4 Interference in wireless systems

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

- Self interference, e.g. intersymbol interference (ISI)
- Multiple access interference (MAI)
- Co-channel interference (CCI)
- Adjacent channel interference (ACI)
- Coexistence interference (CEI)

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

2.4.1 Self interference

Self interference includes interference that occurs among signals that are transmitted from a single transmitter. The specific mechanism and amount of self interference depends on the modulation type. For instance, in OFDM there may be ICI among the subcarriers due to carrier frequency offsets caused by oscillator mismatches, and the doppler effect and fast fading caused by motion of the transceivers, see e.g. [114]. Another source of self interference is transceiver nonidealities, such as amplifier nonlinearity and IQ imbalance. ISI occurs in OFDM when the delay spread of the channel exceeds the length of the cyclic prefix or guard interval, and also when the receiver is not accurately enough time-synchronized to the transmission. Interference between the UL and DL transmissions in an FDD system may be also classified as self interference, as it occurs among signals send on the same two-way connection. This interference is mitigated by employing duplex filters. The interstream interference in a multistream MIMO transmission may be also considered as a form of self interference. In the simplest case of multistream transmission a separate codeword is transmitted from each of the transmit antennas, see e.g. [119]. The codewords then interfere with each other at the receiver, but the interference may be mitigated through multi-antenna receiver processing. The strength of the interstream interference depends on the rank and eigenvalue spread of the MIMO channel. In principle, it is required that there is a sufficient number of independent channels (significant singular values) for spatial multiplexing.

The impact of self interference is minimized by selecting the physical layer numerology such that the operating conditions and implementation technology are taken into account. These are also in part factors that are device manufacturer dependent. Self interference mitigation involves trading off between the cost and battery/power consumption of equipment, bandwidth efficiency, and robustness to extreme operating conditions. For example, short-range local area networks with limited mobility and wide area networks supporting vehicular mobility pose different demands on this respect.

2.4.2 Multiple access interference

Multiple access interference (MAI) is interference among the transmissions from multiple radios utilizing the same frequency resources to a single receiver. When multiple transmissions in cellular uplink take place simultaneously, they are interfering with each other. Even though the physical layer would allow orthogonal (in the time, frequency, code, or spatial domain) multiple access in theory, orthogonality may not be maintained in practice due to synchronization errors, RF circuitry non-idealities, and the effects of wireless propagation channel.

Cellular systems employ several mechanisms in order to maintain sufficient orthogonality in multiple access scenarios. Firstly, power control is essential. Since the terminals transmitting to the BS are distributed over the cell area, there is a large variation in the pathloss between the BS and the terminals. If all terminals would transmit with the same power the difference of the received powers can be high enough for the stronger signals to mask the weaker signals due to the limited dynamic range of the receiver. A well-known example is the UL power control in code division multiple access (CDMA) systems, which is essential to make the CDMA uplink feasible [107]. Furthermore, various transmitter non-idealties cause that perfect orthogonality cannot be maintained even if the receiver would be ideal. In case of frequency division multiple access (FDMA) and OFDMA, the power on the used sub-bands or sub-carriers leaks also on the neighboring sub-bands. The ratio of the power transmitted on the desired sub-band to the power transmitted on the adjacent sub-band is called the adjacent channel power ratio (ACPR, usually given in dB). The ACPR may easily be smaller than the range of the observed uplink pathloss values (in dB) from the terminals to the BS. This means that a FDMA UL needs to be power controlled. In CDMA systems the need for uplink power control is even more critical due to non-orthogonality of the spreading codes. For combating MAI in CDMA uplink, multiuser detection (MUD) has been studied extensively in the past, see [6] for an overview.

The uplink multiple access may have also a time domain multiple access (TDMA) component whereby there may also be MAI in between consecutive transmissions. The differences in the terminal to BS distances implies that the propagation delay of the transmissions is different among the terminals. This is compensated for by a so-called timing advance, where the propagation delay is compensated by tuning the transmission timing accordingly. The larger the cell radius is, the more timing advance is needed, while in wireless local area networks (WLAN) this effect may be largely neglected. The remaining time dispersion of the transmissions is then handled by using a guard interval between the consequtive TDMA time slots.

A more recent addition in wireless systems is spatial domain multiple access (SDMA), which is supported in e.g. LTE [110]. In SDMA uplink, several users transmit on the same time-frequency resources to the base station (or to multiple base stations, as is the case in uplink coordinated multipoint transmission, UL CoMP). When the base station is equipped with a sufficient number of antennas the signals may be separated at the

BS in spatial domain. The requirement is that the uplink channels for each simultaneously transmitted symbol are linearly independent. This technique is also called multiuser MIMO (MU-MIMO) or virtual MIMO [110]. Depending on e.g. the accuracy of channel estimates, there will be MAI among the MU-MIMO transmissions. MU-MIMO may also be used in downlink, when the BS sends data to several users on the same time-frequency resources. When the channel state is known at the transmitter, the transmission may be precoded such that interference is minimized. The downlink transmission occurs through a broadcast channel, and therefore this interference may be categorized as self interference. A tutorial on MU-MIMO techniques can be found in [47].

2.4.3 Co-channel interference

Co-channel interference (CCI) is interference between links that reuse the same frequency band (channel). In cellular systems this is also known as intercell interference. In earlier cellular systems, up to 2nd generation GSM, the impact of CCI is minimized by employing fixed frequency reuse patterns. The cellular frequency reuse may be considered as the seminal invention of the cellular wireless communication technology, which dates back to 1945 and to United States Federal Communications Commission (FCC) [37]. In a cellular network employing freqency reuse the band is divided to a set of orthogonal channels. The number of orthogonal channels is called the reuse factor of the system. Each cell is assigned a single channel such that the distance between neighboring cells using the same channel is maximized. Figure 2.2 illustrates cellular frequency reuse with reuse factor equal to 7. High reuse factor leads to low CCI on the expense of reduced bandwidth per BS. In order to enable higher peak data rates and mean spectral efficiency, there has been a shift to a reuse factor equal to 1 (that is, no fixed frequency reuse pattern) as a part of the development of 3rd and 4th generation networks [61, 110]. Such network is called a reuse-one network, and in it all cells may utilize the full system bandwidth and the system becomes interference limited in terms of its capacity.

Even though reuse-one networks provide higher average spectral efficiency and maximize the peak spectral efficiency, they have also drawbacks. The cell-edge users will experience very low SINR levels due to the high amount of CCI. For example, LTE systems display a heavy tailed SINR distribution. This is demonstrated in [16], where the 15 percent of

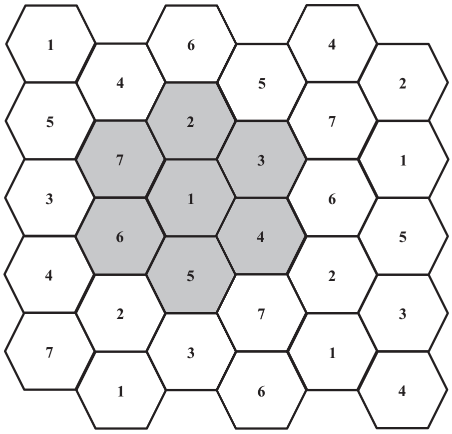


Figure 2.2. An illustration of cellular frequency reuse on a hexagonal grid of cells with reuse factor equal to 7. The number in each cell denotes the channel assigned to that cell.

measured SINR values in a deployed LTE system in urban environment fell below 0 dB (i.e., the received interference plus noise power exceeds the received signal power). Depending on the scheduling principle, the variance of the SINR distribution translates to either lower average spectrum efficiency (e.g. round robin scheduling) or reduced fairness (e.g. max C/I scheduling). It is evident that CCI is the dominant factor limiting the performance of reuse-one wireless data networks. Chapter 4 of this thesis deals with CCI in local area cellular wireless communication systems. The problem of CCI between device-to-device (D2D) and cellular communication links is addressed in Chapter 5 of this thesis.

2.4.4 Adjacent channel interference

Adjacent channel interference (ACI) is interference between links that communicate geographically close to each other using neighboring frequency bands. For instance, several network operators may deploy their own networks in the same area and operate on frequency bands that are close to each other. Hence, ACI needs to be taken into account in the system specifications so that it will not hamper the system performance. In practice, the minimum coupling loss between a transmitter and a receiver on adjacent bands may be estimated[1] and the transceivers may be

[1]That is, the maximum foreseeable channel gain between a transmitter and a receiver on adjacent bands

designed such that ACI remains at a tolerable level. In order to do so the transceivers must utilize adequate filtering on stop-bands. The needed quality of the filters may be controlled by reserving a guard band between the bands. Chapter 3 deals with ACI in more detail.

A related interference type to ACI is coexistence interference (CEI) which occurs among heterogeneous radio access technologies. CEI may arise on the same frequency band or between adjacent frequency bands. As an example, the higher frequency digital TV bands are not used because of GSM induced interference. Other examples include interference between 2nd generation and 3rd generation networks and interference between different systems operating on the unlicenced bands. A straightforward way of dealing with CEI is to take it into account in spectrum use regulations, network planning, and filtering in devices. However, in many cases these approaches lead to inefficient spectrum use, more costly devices, and/or higher operator expenditures. Flexible spectrum use and cognitive radio technology provide an alternative approach [89]. An example is wireless data networks utilizing the unused television bands (TV white spaces). In that case the CEI may be minimized by channel allocation based on the geolocation of the devices and database access to spectrum occupancy information, or periodic sensing of the spectrum [113]. Authorized shared access (ASA) is an example of such access, where the spectrum use is licensed but dynamically controlled through an ASA database/server [125]. Thorough understanding of propagation environment is important and also the possibility of asynchronity needs to be taken into account in preventing CEI.

2.5 Evolution of interference management

Due to the nature of wireless propagation there is always interference among links that operate on the same spectrum in the same geographical area. Therefore, every wireless system has to employ on interference management in order to provide efficient and reliable communication, guarantee fairness among the users, attain a good coverage, and reach a high system capacity.

As the use of wireless systems is rapidly increasing it is not sufficient to just increase point to point link capacity through wider bandwidths and physical layer technologies such as MIMO. It is also necessary to increase the base station density and, on the other hand, decrease the capital and operational expenditures of the system, see e.g. [71]. These two goals are conflicting as increasing the base station density is very expensive. Therefore, cutting the operator costs is possible only through relying less on high performance RF, tedious network planning, and expensive infrastructure and core network. This means that more autonomous and distributed interference management and network functionalities are needed.

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

In the past, interference management has been carried out off-line. It has required tedious network planning effort and has been centralized by its nature. This approach has the benefits of being a robust and reliable approach. On the other hand, it is inflexible, time-consuming, costly, and inefficient in spectrum usage. In the future interference management becomes more and more dynamic, autonomous, and decentralized. Opportunistic spectrum access enables higher and higher system spectral efficiency. The spectrum use may be organized and negotiated among the devices themselves. The goal is that future wireless systems would achieve high capacity, and at the same time, the deployment, operation, and maintenance of the networks would become cheaper, simpler, and autonomous.

3. Adjacent channel interference

Adjacent channel interference (ACI) is interference that a wireless transmitter emits on frequency bands outside the nominal band used for communication. In practice, perfect orthogonality between transmissions occurring on neighboring frequency bands can never be achieved, and some level of ACI is inevitable due to e.g. non-idealities of the front-ends and power amplifiers. Traditionally ACI is mitigated by taking it into account in assigning frequency bands to different systems, in planning the deployment of the BS, and by employing high quality RF electronics. The common feature of these methods is that they are not adaptive. Therefore, they have to be designed for the worst case scenario. This results in expensive hardware, increased costs to the operators, and lost opportunities for spectrum use. In the context of this thesis, the motivation for research on ACI comes from the fact that denser, less coordinated BS deployments are becoming necessary in order to support the wireless data traffic growth. Pico- and femtocells are an example of such trend. Also more flexibility in spectrum use is needed. This implies that traditional ACI mitigation techniques may become inefficient and too costly to maintain as careful network planning may not be possible. In this chapter adjacent channel interference (ACI) is considered in more detail. The contributions of the thesis concerning ACI management are presented as well. Publication I demonstrates how ACI manifests itself in local area TDD networks, and also characterizes the dominating interference types. The idea of managing the level of ACI at the transmitter in an online fashion is proposed in Publication II.

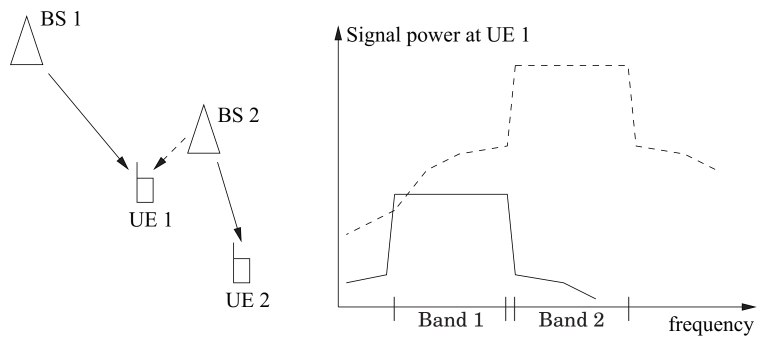


Figure 3.1. A possible interference scenario between different radio links. The receiver (UE 1) may be blocked by the close-by transmitter (BS 2) on an adjacent frequency band. On the right the PSDs of the received signals at UE 1 are sketched. Depending on the node locations the interfering signal (dashed line) can cause the SINR at UE 1 to drop to deep negative values.

3.1 The effect of ACI

There are essentially two mechanisms how ACI arises. First, any transmitter that occupies nominally a certain frequency band also leaks energy on frequencies adjacent to that band. These out of band emissions are perceived as interference by other receivers. This effect may be quantified by using the adjacent channel power ratio (ACPR), which is the ratio of the power radiated on in-band frequencies to the power radiated on an adjacent band. Specifically, for a transmitted signal y with a power spectral density (PSD) $S_y(f)$, which occupies the nominal band $[f_{\text{low}}, f_{\text{high}}]$, the ACPR for an adjacent band $[f'_{\text{low}}, f'_{\text{high}}]$ may be expressed by

$$\text{ACPR}_{\text{dB}} = 10\log_{10}\left(\frac{\int_{f_{\text{low}}}^{f_{\text{high}}} S_y(f)df}{\int_{f'_{\text{low}}}^{f'_{\text{high}}} S_y(f)df}\right). \tag{3.1}$$

Secondly, signals that are outside the nominal frequency band generate interference components on the in-band frequencies at the receiver. This occurs due to aliasing in sampling the signal and other receiver nonidealities. The ability of the receiver to cope with an out of band interferer (adjacent channel signal) is determined by the adjacent channel sensitivity (ACS) and blocking characteristics of the receiver. Properties of the receiver RF chain such as quality of channel selection filters, analogue to digital converter bitwidth, and linearity of amplifiers and mixers contribute to ACS characteristics.

The ACPR of a radio transmitter is determined by several factors. First of all, the baseband signal needs to be filtered in order to suppress the spectral leakage which occurs due to time domain truncation of the symbols, see e.g. [117]. For instance, a plain OFDM modulated signal has sinc-shape sidelobes to adjacent subcarriers after rectangular window in time domain. In the case of OFDM the effect is typically controlled by leaving a portion of subcarriers at the band edges unmodulated, and then filtering the signal to suppress the discontinuities on the OFDM symbol boundaries [117]. Also windowing the signal in the frequency domain is possible where the subcarriers at the band edges are attenuated by multiplying the signal with a window function [19]. Other techniques for mitigating the sinc-leakage include insertion of cancellation subcarriers [18], forcing continuity at the OFDM symbol boundaries by additive time domain correction terms [122], time domain OFDM symbol extensions [85], and more general (compared to windowing) subcarrier weighting [29], to name a few. In more advanced approaches, the power allocation of the subcarriers may be formulated as an optimization problem, see e.g. [10, 111, 9, 73]. This may be done, for instance, with the objective of maximizing the desired user capacity while constraining the adjacent channel leakage. In [10, 111, 9, 73] the out of band emissions are assumed to be defined by the digital pulse shaping, hence assuming an ideal RF stage and amplification. Similar optimization problem may be formulated also for the case when the dominating factor of the ACPR is the PA non-linearity, which is the approach in Publication II.

The digital baseband signal goes through several stages before the power amplification. These include digital to analog conversion, IQ-modulation, upconversion, pre-amplification, and filtering. In different transmitter architectures the upconversion, i.e. mixing to carrier frequency, may be performed in the digital or analogue domain, or by using their combination [43]. The non-idealities present in these stages contribute to the out of band emissions. However, the most significant factor is usually considered to be the non-linearity of the power amplifier [117], which is the last active component in the transmitter chain. A tutorial to power amplifier (PA) design may be found in [106]. PA linearization is one technique that may be used for suppressing the out of band emissions and also in-band distortion. One effective linearization technique is predistortion, where the signal is transformed prior to the PA with a function that approximates the inverse of the PA transfer function [106, 117]. Another factor worth mentioning in this context is the high peak to average power ratio (PAPR) of OFDM signals. In order to keep the distortion to the transmitted signal at a tolerable level, a higher back-off must be applied to the

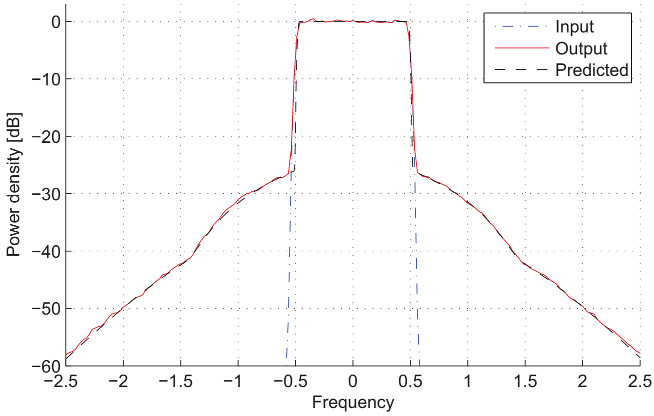


Figure 3.2. Illustration of the output power spectral density after power amplifier non-linearity. Red curve is the estimated PSD using the polynomial PA model and an OFDM modulated input. Black dashed line is the analytical output PSD assuming Gaussian input and polynomial PA model. Publication II, © 2009 IEEE.

power amplifier when the PAPR is high. Otherwise, the peaks of the signal get severely clipped which not only increases the ACI but also limits the maximum achievable spectral efficiency due to inter-carrier interference [69].

The power spectral density (PSD) of the transmitted signal may be characterized assuming a polynomial power amplifier (PA) model and Gaussian input signal [134]. Under these assumptions, the output PSD $S_y(f)$ after the PA non-linearity is a function $\mathcal{D}$ of the input PSD $S_x(f)$ as follows [134]

$$\begin{aligned} S_y(f) &= \mathcal{D}\left(S_x(f)\right) \\ &= \sum_{m=0}^{K} \alpha_{2m+1} S_x(f)^{\star(m+1)} \star S_x(-f)^{\star(m)}, \end{aligned} \tag{3.2}$$

where $S_x(f)^{\star(m)}$ denotes m-fold convolution of the function $S_x(f)$ with itself. The coefficients α_i are obtained by fitting a polynomial model to PA measurements. That is, the coefficients of the polynomial PA model and the total transmit power determine α_i. The convolution in frequency domain arises due to the polynomial model of the PA in time domain. E.g. the third order intermodulation term corresponds to the term with $m = 1$ in equation (3.2). Figure 3.2 illustrates an example of the PSDs obtained from fitting a 11th order polynomial to measured AM/AM characteristics of a GaAs power amplifier at 2 GHz.

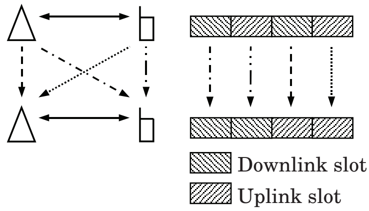


Figure 3.3. Illustration of interference among crossed slots in TDD. The solid links depict the data transmission, while the dashed lines depict interference from the link on the top to the link on the bottom. On the left the allocation of the slots in the frame to UL and DL transmission is shown and the different line style depicts the four different interference types arising.

3.2 ACI in cellular networks

The ACI may limit link throughput when the interference source is located considerably closer (or transmitting at much higher power) than the desired signal source. A typical example is two operators serving the same geographical area on adjacent frequency bands, see Figure 3.1. Depending on the relative location of the devices, the duplexing scheme, and frequency allocations, the ACI may occur among the DL transmissions, among the UL transmissions, or between the two. For instance, if the base stations transmitting on adjacent bands are not colocated, the interference among the DL and UL transmissions may be severe [59]. The interference between the UL and DL is called cross link interference, which is a problem in time domain duplexing (TDD) systems. In particular, if TDD transmission is employed and the base stations on adjacent bands are not time synchronized, cross link ACI may become severe. The time slots of a TDD frame that experience cross-link interference are called crossed slots. Even though the adjacent channel base stations would be colocated, the ACI from one BS's DL transmission to the other BS's UL reception in the crossed slots will be severe. The interference in the crossed-slots is illustrated in Figure 3.3.

ACI in crossed slots has been investigated in [59, 60, 54, 26]. Two key factors contributing to how ACI impacts the system performance are the synchronization between the operators and distances among the BSs operating on the adjacent frequency bands [60]. The ACI between two operators has been studied in [59, 60] for TDD CDMA systems. The conclusion is that in case the operators coordinate their network deployments such that the BSs are colocated, it is essential that the DL and UL transmissions are synchronized. Otherwise the ACI from DL to UL transmissions may render UL reception on crossed slots impossible. However, synchronization was found to be unnecessary in case the BSs are not colocated. The pdf of UL to UL ACI has been derived in [54] assuming perfect power control. In the derivation, a single randomly located UE in a circular cell is assumed. Unfortunately, even with these simplifying assumptions, the pdf cannot be expressed in closed form and can be only evaluated through numerical integration. There is a need to study the problem through simulations.

In a local area network with only a few users per cell, it would be beneficial to adapt the time share allocated to UL and DL transmission in the TDD frame according to the instantaneous traffic load. Such TDD systems are called flexible switching point systems. However, because the traffic loads at different cells are typically independent, flexible switching point leads to different split of time slots to UL and DL transmission in different cells. This causes ACI even among colocated and frame synchronized BSs. The traditional way of preventing such situations from happening is to enforce accurate synchronization and to disable UL/DL frame structure adaptation. This is an example case where traditional ways of ACI mitigation lead to inefficient resource use. However, if the BSs would be aware of the adjacent channel receivers in the vicinity, the presence of interference victims could be taken into account in the selection of a switching point. The co-channel interference (CCI) aspects of flexible switching point TDD systems are addressed in Chapter 4 of the thesis.

The impact of ACI in TDD FDMA cellular systems in a local area scenario is studied in Publication I through static system simulations. In contrast to a CDMA based system, in FDMA each UEs data transmission may be scheduled on non-overlapping subbands that together constitute the system band. This is the case for instance in 3GPP LTE, where OFDMA is employed in the DL and SC-FDMA (single carrier frequency domain multiple access) in the UL, see e.g. [62]. The indoor scenario used in the simulation studies consists of a grid of rooms over which the UEs are randomly distributed, see Figure 3.4.

The results of Publication I show that the most detrimental interference component is the DL to UL ACI when the BSs of the two operators are colocated. Also DL to DL ACI may be severe when the BSs are in separate rooms and the receiving UE is close to the other operator BS. This

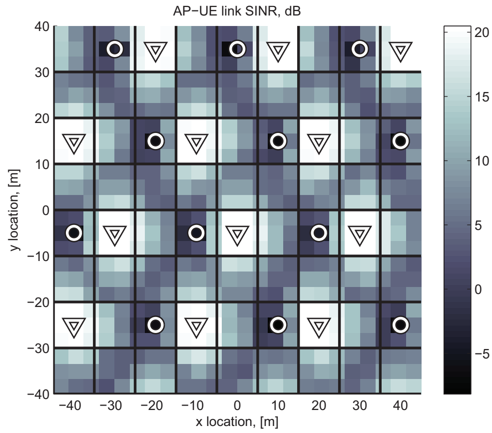


Figure 3.4. ACI system simulation scenario. The triangles and circles represent the locations of own and adjacent channel operator access points, respectively, and the black horizontal and vertical lines represent walls. The background color displays the mean DL SINR as a function of location when the two networks are synchronized. Publication I, © 2009 IEEE.

result is in agreement with the results in [60, 26] indicating that the ACI poses severe problems also in local area scenarios with frequency division multiple access. The situation is problematic in the sense that frame synchronization in needed in case BSs are colocated, whereas having the frames in opposing phases is beneficial if the BSs are well separated, see Publication I. This observation suggests that the if the interference situation is taken into account in allocating time slots to different users' UL and DL transmissions, the existence of crossed slots may be actually exploited to the advantage of the system.

3.2.1 ACI mitigation

The effect of ACI may be mitigated to some extent at the interfered cell. For instance, the receiver may be able to determine from an estimated interference PSD that there is significant interference on only at the band edge and/or in specific time instances, and then feed back such information to the BS. The information could even be obtained implicitly through the regular channel quality feedback from the UEs. The transmissions to that receiver may be then scheduled on the resources that are not suffering from interference. Moreover, with multiple spatially distributed UEs, BS may be able to schedule transmissions in such a manner that no receiver is impacted by severe ACI. This may be feasible because each receiver sees different interferers. Such interference aware allocation of the slots to the users is proposed in [26]. This reduces the ACI to some extent. Note that LTE includes some support for measuring time domain components for channel state information feedback. Two separate subframe subsets may be configured to a UE, and the UE then measures and feeds back two separate CSI messages to the BS. Such measurements could be potentially utilized for detecting ACI conditions in an LTE system.

In case it is not possible to avoid the ACI by scheduling the transmission to less interfered resources, it is still possible to at least partially suppress the interference in the spatial domain. This is feasible in receivers equipped with multiple antennas. For example, subspace approach may be employed if the covariance matrix of the received ACI component is not of full rank and the signal subspace is different from the ACI subspace. However, in practice this is possible only to a certain extent since the accuracy of covariance estimation and receiver nonlinearities limit the ACI suppression capability. Furthermore, non-linear interference cancellation at the receiver is non-trivial to implement as the interference is actually spectral leakage to the adjacent band, and therefore, a complicated function of the inband signal.

The demand for higher capacity in future networks requires to consider flexible spectrum allocation, simpler infrastructure, and reduced network planning. In such a scenario, techniques such as scheduling transmissions to non-interfered resources and interference mitigation in multi-antenna receivers may not be enough to mitigate the ACI to a tolerable level. Also transmitter side interference awareness is needed to ensure a high quality service. Additionally, seamless mobility and handover between different radio access technologies (RAT), such as LTE and WLAN, could facilitate handing the connection over to a non-interfered RAT, if available. From the radio physical layer point of view this is feasible since a typical smartphone of today supports a large number of RATs.

3.3 Spectrum shaping

Controlling of the amount of ACI by adapting the signal waveform at the transmitter in an online fashion is proposed in Publication II. Such adaptation could be facilitated by a signaling mechanism that allows the interfered receiver to inform the adjacent band transmitter of its presence. The transmitter has to then be able to predict its radiated power spectral density (PSD). A method for predicting the PSD is introduced in [134], see equation (3.2). The method is applicable to OFDM modulated signals that possess approximately a Gaussian amplitude distribution.

In Publication II a method for optimizing the transmitted signal is proposed assuming that the spectral leakage is dominated by PA nonlinearity. The method optimizes the OFDM waveform such that constraints on ACI levels are met and the capacity of inband signal is maximized. The optimization problem is formulated imposing N_C constraints on the output PSD such that the nth constraint is a maximum power constraint p_n over the frequency range $\mathcal{R}_n = [f_{n,\text{low}}, f_{n,\text{high}})$. The problem of maximizing the capacity under these N_C constraints may be written as follows:

$$\begin{aligned} \text{minimize over } S_x(f)\text{:} \quad & -\int_0^1 \log_2\left(1 + \frac{h(f)S_x(f)}{N_0}\right) df \\ \text{subject to:} \quad & \int_{\mathcal{R}_n} \mathcal{D}\{S_x(f)\}\, df < p_n,\ n = 1, \ldots, N_C, \end{aligned} \tag{3.3}$$

where $S_x(f)$ is the input PSD, $h(f)$ is the frequency dependent channel gain, N_0 is the noise floor at the receiver, and the function $\mathcal{D}$ representing the PA non-linearity is defined in equation (3.2). In this formulation the frequency range is normalized such that the own desired frequency band is within the $[0, 1]$ interval.

The cost function in (3.3) is given for any type of PSD (a non-parametric continuous function). In order to facilitate minimization using computational methods, it needs to be parametrized. A possible approach is to approximate the PSD by discrete frequency bins, i.e sub-bands. In that approach the integrals are replaced by sums over the sub-bands. The normalized signal band of $f \in [0, 1]$ is approximated by K frequency samples. The approximation corresponds to using a piecewise constant PSD $S_x(f) = S_x[k]$ when $f \in [(k-1)/K, k/K]$, i.e.

$$S_x[k] = \int_{f=(k-1)/K}^{k/K} S_x(f).$$

Consequently, the discrete version of the problem may be expressed as

$$\begin{aligned} \text{minimize over } S_x[k]\text{:} \quad & -\sum_{k=1}^{K} \log_2\left(1 + \frac{h[k]S_x[k]}{N_0}\right) \\ \text{subject to:} \quad & \sum_{k \in \mathcal{R}'_n} \mathcal{D}'\{S_x[k]\} < p_n,\ n = 1, \ldots, N_C, \end{aligned} \tag{3.4}$$

where $\mathcal{R}'_n$ are the sets of frequency bin indices that span over the continuous frequency intervals $\mathcal{R}_n$. The transformation $\mathcal{D}'$ is as in equation (3.2) where the convolution integrals are taken as convolution sums for the discretized PSD vector $S_x[k]$.

Note that neither the cost function nor the constraints are convex due to the non-convexity of the PA distortion function $\mathcal{D}$ given in equation (3.2). In order to illustrate the problem, an example spectrum shape was derived in Publication II using a numerical routine for solving convex optimization problems. A standard Matlab routine that implements sequential quadratic programming optimization algorithm, see e.g. [39, 96] was employed. Therefore, a PSD found using this approach may represent local optimum. Further analysis of the optimization problem would be needed in order to guarantee finding globally optimal solutions, e.g. through determining the duality gap of the optimization problem [17]. Such characterization was not pursued in Publication II as the purpose of the study was foremost to check the feasibility of the approach.

The method is tested by fitting a polynomial model to PA measurements, and then optimizing the input PSD by imposing a single constraint, and finally measuring the PSD at the PA output. The PA is driven with an OFDM input approximating the gaussian input signal with the optimized PSD. In the example a single ACI constraint is imposed where an extra 15 dB attenuation at a specific portion of the adjacent band is desired. This constraint is met by tuning the input PSD using three different methods as explained below. The capacity of the corresponding three signals is compared to that of a reference signal where there is no extra ACI constraint, i.e. the optimized spectra are compared to a signal that does not meet the required constraint on ACI emissions. In the example it is assumed that the SNR at the receiver in the reference case is 10 dB. The resulting PSDs are shown in Figure 3.5.

The first and most straightforward method for tuning the PSD is to employ back-off, i.e. adjust the output power while maintaining full band transmission with flat inband spectrum. As shown in Publication II, in this case the achieved capacity is reduced by about 50% compared to the reference case of flat PSD with full output power (i.e. with the ACI constraint not active). By allowing also bandwidth reduction in addition to the power adjustment, about 70% of the reference capacity was achieved. In the best case of freely tuning the input PSD the achieved capacity was 80% of the non-constrained reference capacity. However, it should be noted that the freely tuned PSD was obtained by a naive application of a standard iterative optimization algorithm to the non-convex problem. Therefore, it is acknowledged that there may be other PSDs that satisfy the ACI constraint equally well and at the same time yield higher signal

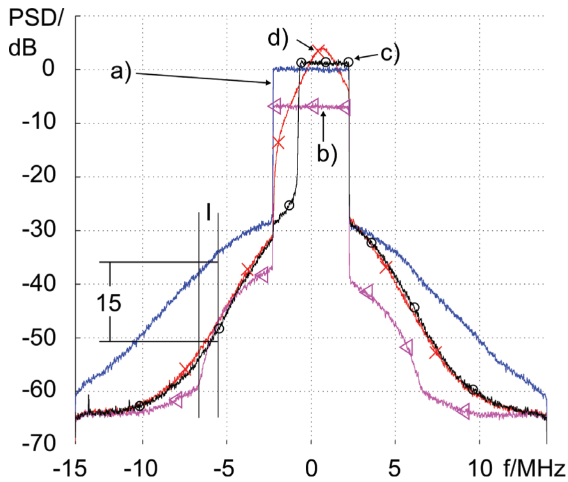


Figure 3.5. Measured power spectral densities of the test signals. Trace (a) gives the PSD without extra ACI constraint, while trace (b) meets the constraint by tuning the output power. In trace (c) the output power and bandwidth are tuned while trace (d) corresponds to the fully optimized PSD. The additional ACI constraint was 15 dB extra attenuation at the interval $[-6.75, -5.85]$ MHz (corresponding to the normalized interval $[-1.5, -1.3]$), which is fulfilled with all test signals, except the reference trace (a). Publication II, © 2009 IEEE.

capacity than the example presented here.

3.4 Discussion

In this chapter the adjacent channel interference in future wireless systems was considered. The contributions of the thesis concerning ACI in original publications Publication I and Publication II were presented. There are are several factors contributing to the way ACI manifests itself in future wireless systems. RF non-idealities continue to be an issue in future systems due to the need for low equipment cost. On the other hand, there is continuing pressure to reduce the network operating and capital expenditures, which means e.g. less planning in deploying the networks. This need is further emphasized by the shrinking cell sizes. Moreover, very conservative approach designed for worst case ACI leads to lower system spectral efficiency at the expense of robustness and reliability. Therefore, adaptive on-line interference management would be beneficial in order to guarantee a high quality of service.

Relying on autonomous ACI management in the network leads to a more complex solution. For example, it is likely that definition of new signaling mechanisms is needed. It will be more demanding to design these more complex mechanisms such that robustness and reliability is maintained. On the other hand, the deployment, infrastructure, and equipment costs can be lower, and higher system spectral efficiency may be achieved. Furthermore, less network planning is needed. As the devices have capability to employ multiple RATs, the available multi-system diversity will also increase the quality of service perceived by the end user.

Ideally the transmitters should be up to date and aware of the ACI they are generating to nearby receivers. Once this awareness is obtained, the transmitter may design its waveforms such that the ACI is sufficiently suppressed. The work presented in Publication II may be considered as a step toward that direction. Further work is needed in order to make the proposed spectrum optimization method more practical. In many cases the interference is unidirectional and the operators are competitors to each other. Therefore, it is necessary to ensure that there is strong incentive for ACI management even among operators and network device vendors. Furthermore, a feasible implementation requires defining and dimensioning the associated signaling schemes.

In the optimization problem formulation of Publication II it is assumed that the dominant cause of transmitted out of band signal energy (i.e. spectral leakage) is the PA nonlinearity. As discussed in Section 3.1, the signals have out of band energy also at base band due to discontinuities at OFDM symbol boundaries. Various authors have considered the problem of OFDM sidelobe suppression. However, the work in Publication II can be related to the works [10, 111, 9, 73], where sidelobe suppression is formulated as a constrained optimization problem. In both approaches the objective function is the inband capacity, while the assumed source of ACI is different. When the PA is the dominant source of ACI, as assumed in Publication II, the optimization problem becomes tougher to solve due to the more complex relationship between the input and output PSDs of the PA. Nevertheless, no other on-line approaches to ACI constrained waveform optimization in the case of PA dominated spectral leakage were found in the open literature. Therefore, a thorough analysis of the optimization problem is justified. The optimality of found solutions should be established, and low complexity algorithms for finding suboptimal solutions should be developed. Finally, it should be noted that it would be beneficial to consider both PA non-linearity and base band waveform induced spectral leakage simultaneously in the optimization.

4. Co-channel interference

The topic of this chapter is co-channel interference (CCI) in cellular systems. CCI occurs among close-by links that utilize the same frequency band. This starts to impact the performance whenever the received interference power is significant compared to the desired signal power. Cellular frequency reuse is a common method for CCI management. When the neighboring cells utilize different channels, CCI is mitigated but simultaneously system spectral efficiency is reduced. However, more recent wireless networks employ reuse factor 1 where all cells utilize the full bandwidth allocated to the network. This allows to maximize the system spectral efficiency but it also induces strong CCI. In this case, the SINR observed at a user equipment depends heavily on its location relative to the base stations. The varying SINR is then accommodated by adaptive modulation and coding (AMC) so that users with a higher SINR receive a higher throughput per available radio resource[1]. However, the cell edge users observe relatively low performance in comparison to the users closer to the BS. This example of channel sharing highlights the need for interference awareness in radio resource allocation and transceiver algorithms.

In general, the radio resources should be allocated to each transmission such that the current situation among transceivers within the interference range is taken into account. The interference aware scheduler (IAS) proposed in Publication III enables such functionality. Two specific example use cases for IAS were studied in Publication III, Publication IV, and Publication V. The interference among networks operating on the same band and on the same geographical area may be managed using the IAS. As a second example, IAS may also manage interference between UL and

[1]Here, radio resource refers to a spatial stream transmitted during a specific time interval on a specific frequency sub-band

DL transmissions in a TDD system with flexible UL/DL switching point is employed.

This chapter gives an overview of CCI management in cellular systems. The contributions of the thesis related to CCI management of Publication III, Publication IV, and Publication V are presented.

4.1 CCI management techniques

This section gives an overview of existing CCI management schemes. These schemes along with the ones proposed in this Thesis are summarized in Table 4.1. They are discussed in more detail in the following subsections.

4.1.1 Frequency reuse

In general, high frequency reuse factor leads to more constant data rate across the service area. In this case the throughput experienced by users at different locations of the cell is similar, and the service rate distribution of the system is said to be fair. However, this fairness comes at the expense of lower mean data rate and sum capacity. By lowering the reuse factor the system capacity (cell throughput) rises at the expense of reduced fairness. A better trade-off between system capacity and fairness may be achieved by generalizing the idea of cellular frequency reuse. Fixed frequency reuse, where the total system bandwidth is split into N equal bandwidth sub-bands, may be considered to be a special case of windowed power spectral density (PSD). More specifically, fixed frequency reuse involves defining N orthogonal and rectangular window functions in frequency and assigning these to the cells such that the minimum distance between cells employing the same window is maximized. It is then possible to consider also other types of PSD window functions. For instance, the window functions may be adaptive, and not necessarily orthogonal (i.e. partially overlapping). Such schemes are called fractional frequency reuse, soft frequency reuse, and/or enhanced frequency reuse approaches in the literature. The references [81, 16] give an overview of enhanced frequency reuse schemes. The goal of these schemes is to achieve performance that is in between fixed frequency reuse and reuse-1 systems. One may trade-off between cell-edge throughput and mean throughput [16]. Analytical comparisons of fixed and fractional frequency reuse have been carried out in e.g. [86, 98]. It is shown that reuse-1 performs better than fixed frequency reuse in terms of sum-rate under a scheduling scheme that gives equal throughput for the users [86]. However, enhanced frequency reuse may then not only improve the fairness over the reuse-1 system, but also the sum-rate. The analysis is facilitated by assuming that the BS are deployed according to a Poisson point process in [98]. Enhanced frequency reuse schemes may be also utilized in order to minimize the transmitted power, see for example [79, 80].

Another scenario where enhanced frequency reuse may be highly useful is for interference management in heterogeneous networks. As an exam-

Table 4.1. CCI management schemes and their complexity and other properties at a glance.

Scheme	Compl.	Notes / performance
Fixed frequency reuse	low	Fair, lower capacity
Enhanced frequency reuse [81, 16]	low	Trades off between fairness and capacity
CSMA, RTS/CTS signaling [75]	low	Mitigates CCI, decentralized, suboptimal resource reuse, poor performance under congestion
TX beamforming [7]	med.	Null steering requires accurate CSI
RX interference cancelation [31]	med.	Requires low interference rank, multiple RX antennas (if linear)
AMC, hybrid ARQ, rateless coding [22, 25]	med.	Adapting to CCI, no reduction of CCI
Time domain resource partitioning (LTE eICIC) [83]	med.	Does not generalize well, applicable to e.g. load balancing in heterogeneous networks
Network MIMO, CoMP [123, 45, 65, 124]	high	Expensive on infrastructure and CSI overhead, centralized
Interference alignment [20]	high	High capacity, sensitive to external interference, expensive on infrastructure and CSI overhead
Receiver beaconing with scheduled access [99, 70], Publication III	high	Mitigates CCI, decentralized, optimizes resource reuse

ple, CCI management between macro- and femtocells of LTE-A networks is proposed in [44]. Furthermore, LTE includes a time-domain resource partitioning scheme called enhanced inter-cell interference coordination (eICIC) for CCI management in heterogeneous networks [83]. eICIC is in its principle similar to frequency reuse schemes, it is only applied in the time-domain instead. More specifically, in eICIC, the LTE subframes are split into two orthogonal subsets, and separate channel quality feedback processes may be defined for the two sets. Typically, the macro cell is assigned one set, and the pico-cell layer another set. The macro cell may then not schedule data transmission on the resources that the pico-cell layer is utilizing. This way the coverage area of the pico-cell layer may be expanded beyond what would be possible under the interference from the macro-cells. This facilitates more balanced load among the macro- and pico-cells.

4.1.2 MIMO techniques for CCI management

MIMO techniques for CCI mitigation have been an active area of study, see e.g. [7, 31, 65, 16]. A variety of techniques have been proposed that make different assumptions on the degree of cooperation among the transmitters and transceiver capabilities. Transmit and receiver beamforming reduces CCI to some extent [7]. The effect is most apparent in case of single stream transmission, where the beamformers are designed such that the multiple spatial channels combine coherently at the receiver. Since the MIMO channels to the desired transmitter and interfering transmitters may be assumed independent, the signal and interference subspaces are typically not the same. This implies that the SINR improves on average when single stream beamforming is utilized. The drawback is that the degrees of freedom of the MIMO channels are not necessarily optimally used when single stream beamforming is employed. On the other hand, employing spatial multiplexing diminishes the SINR gain.

Plain beamforming does not necessarily need any information on the interference channels. If the channel toward interference victims is known at the transmitter, transmit beamforming could also be used for reducing CCI by steering nulls toward interference victims. The challenge is that null steering can be sensitive to imperfect channel state information and hence may not be applicable in general. However, if the receiver has knowledge on the spatial signature of the interference, it may be used in the receiver design. Upon estimating the interference channel coefficients (or spatial covariance matrix) it is possible to form, as an example, a linear minimum mean square error (LMMSE) receiver that maximizes the SINR when the interference is considered to be Gaussian distributed [31]. Moreover, as the interfering co-channel signals are deterministic and have a known structure, it is in some cases possible to employ more sophisticated receivers that include multiuser detection stages (MUD), and/or nonlinear interference cancellation techniques [6, 31].

More elaborate ways of dealing with CCI can be devised by considering co-operation between transmitters. Such techniques have been investigated in the literature under the name of network MIMO [123, 45, 65]. In network MIMO the interference-channel is transformed to a broadcast channel by considering the co-operating transmitters as a single transmitter. In principle the data traffic may be shared between multiple cooperating transmitters, from which it is then coherently transmitted to the intended receiver. In practice such cooperation is possible only if the transmitters are connected to each other with a reliable, high bandwidth and low latency link, such as fiber optical connection. In addition, accurate frequency and timing synchronization is needed so that coherent transmission is facilitated. Furthermore, the receivers need to measure the interference channel state and feed back the information to the transmitters. This all means that network MIMO is in practice limited to scenarios with low mobility UEs. Other drawbacks of the schemes include increased computational complexity and signaling requirements, and need for accurate synchronization. Once these practical challenges are overcome, network MIMO may obviously lead to large gains in system spectrum efficiency. Network MIMO is currently considered in the standardization of e.g. LTE-A wireless systems in 3GPP, where it is termed coordinated multipoint transmission (CoMP) [1]. CoMP schemes with reduced signaling requirements are also under consideration in 3GPP. For example, it may be assumed that only the interference channel state, and not the data, is shared between multiple transmitters. In that case the transmitters may, for example, coordinate their scheduling decisions and choose precoding vectors that minimize the impact of CCI. CoMP techniques for LTE-A systems have been investigated in e.g. [72, 108, 104].

In case the multiple transmitters can co-operate and jointly encode the messages, the channel reduces to a broadcast channel in theory. The capacity optimal transmission scheme is then called dirty paper coding [30, 124, 74], which is a non-linear method. In dirty paper coding the transmitter first picks a codeword for the first user. Then, when choosing the codeword for the second user, the interference caused to the second user from the codeword intended to the first user is perfectly known. The interference to the second user may be then pre-subtracted[2] from the transmitted signal such that it does not impact the capacity toward the second user. The drawbacks of dirty paper coding are the need for accurate channel state information at the transmitter side, and that it is computationally a highly complex method.

4.1.3 Interference alignment

CCI has been also studied in a more theoretical framework. It is known that parallel point-to-point, multiple access and broadcast channels are separable in the sense that it is sufficient to separately encode the parallel channels (e.g. subcarriers) to achieve the capacity [120, 121]. However, the same is not true for the parallel K-user interference channels. In K-user interference channels jointly encoding the messages to the parallel channels improves the capacity [21]. By the so called interference alignment technique one can utilize $K/2$ degrees of freedom in the K-user fully connected interference channel. This means that in the high SNR regime each user can achieve half the capacity that would be achievable if no interference was present [20]. The result is rather theoretical in the sense that it requires full knowledge of all channel coefficients (both desired, and interference channel) and joint encoding over the parallel channels. However, it is interesting since it essentially states that a broad class of wireless networks are, in fact, not interference limited by nature. The idea in interference alignment is that the transmitters must design their signals over the parallel channels (fading in time, frequency, and/or space) such that all interference signals are confined to a certain subspace (i.e. aligned) at each receiver. At the same time the desired signal is designed to arrive at the receivers in the complementary, interference free subspace. The downside of such techniques is that in practice imperfect channel state information limits the performance of this approach and the signaling load can be high, see e.g. [51, 118]. Moreover, the interference alignment schemes are rather sensitive to external interference and require high SNR to achieve the gains. This is a problem since the number of links over which the interference alignment is applied is in practice by

[2]This is an oversimplification, the pre-subtraction involves more elaborate processing.

necessity limited. Depending on e.g. SNR and channel state information accuracy, employing orthogonal multiple access, beamforming, and spatial multiplexing may outperform interference alignment in a practical setting [97]. Also more simple schemes such as linear interference rejection receivers are likely to provide more robust performance gains given the practical constraints.

While interference alignment provides a technique for obtaining capacity gains in multiuser interference channels, the information theoretic upper bound of the capacity of such channels has not been established so far. Even the capacity of a two user interference channel remains an open research problem, see e.g. [91].

4.1.4 Adapting to interference variation

Interference variation as a function of time is an important factor to be considered in practical wireless network design. For instance, in power controlled cellular uplink, significant interference variation is caused by the time-varying scheduling decisions made at each BS. Adaptive modulation and coding (AMC) schemes rely on feedback from the receiver about the channel quality it experiences. In a frame based system, the receiver measures the channel quality in a frame and feeds the measured information back to the transmitter. The transmitter then chooses a modulation and coding scheme (MCS) for the next frame accordingly. In essence, the MCS that maximizes the expected throughput is chosen. If the interference situation is constant, the transmitter may be more aggressive in choosing the MCS. On the other hand, if the interference is varying a lot from frame to frame, a more robust MCS should be chosen than the instantaneous channel quality estimate indicates. The variation in the interference power makes it more difficult to perform accurate link adaptation [24, 41]. The uncertainty in the channel quality may be accommodated to some extent by using e.g. hybrid ARQ technique, where the transmitter sends incremental information when the decoding at the receiver fails, see e.g. [22]. Hybrid ARQ employed in current wireless systems is a special case of rateless codes, also called Fountain codes. Rateless codes do not rely on a priori knowledge of the channel quality at the transmitter. Hence, they are inherently more robust in the face of interference variation [25].

4.2 Decentralized CCI management through receiver beaconing

A key problem in wireless systems is to determine the transmission schedule, i.e. decide which radio resources are used by which transmitters and receivers at any given time instance. Conventionally in cellular systems this is performed at the scheduler located at the BS. It is responsible for allocating the radio resources to both UL and DL transmissions of the users connected to that BS. Channel dependent scheduling is facilitated by measuring the channel quality toward each user in the cell. This way the scheduler may optimize the own cell performance under the observed interference situation. However, in order to make scheduling decisions that improve the system performance as a whole, the scheduler must not only know the channel quality to the own cell users, but also to users connected to other cells within the interference range.

Fairness is an important property in measuring the system performance. When fairness is not taken into account one may consider maximizing the sum capacity of the system over all users. This is in many cases an easier target to optimize. For instance, in order to maximize the per-cell capacity, a BS should allocate all its resources to the user that has the highest SINR in the cell. The highest SINR user may be determined by channel quality measurements and feedback. The sum capacity of a network scales asymptotically as $\log(\log(K))$ with the number of users K when the number of BSs is held fixed [46]. It is shown in [46] that such scaling is achievable using distributed schedulers and no inter-cell information exchange. However, in this case only the high SINR users close to the BS would get scheduled, which would be an extremely unfair resource allocation.

Transmitter side interference awareness that enables fair and efficient spectrum use can be obtained only if the receivers somehow signal their presence to the devices in the vicinity. Otherwise, transmitters can only sense the other transmitters and suboptimal transmission decisions will be made due to the hidden/exposed node problem, see e.g. [132]. In 802.11 networks receiver signaling can be incorporated by utilizing the RTS/CTS enhancement of the CSMA/CA MAC, [75]. The general principle is illustrated in Figure 4.1, where there are two links active in each others vicinity.

Current cellular systems do not include broadcast receiver signaling for interference awareness. The concept has, however, received attention in

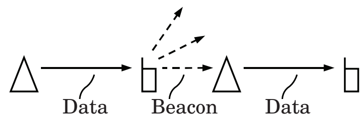


Figure 4.1. The principle of transmitter side interference awareness. In the link on the left, the BS transmits first data or control message to the UE connected to it. The data receiving UE on the left then transmits a broadcast beacon message that is received by the BS on the right. The reception of the beacon enables the BS on the right to schedule its data transmission to the UE on the right such that the interference generated to the UE on the left is controlled.

the literature. A so called busy burst has been proposed for TDD cellular systems, see [100, 55, 99, 49]. The busy burst is a short period that follows the data slots, during which the receivers sound the channel. Before attempting a transmission on a given radio resource, the transmitter measures the received power level of the associated busy burst. If the received busy burst power exceeds a predefined threshold level, transmission is not commenced. Otherwise, data is transmitted. Upon successful reception of data, a busy burst is transmitted by the data receiver. As the busy bursts enable sensing the receivers and the decision of using the associated radio resource is based on the received busy bursts, the technique solves the hidden/exposed node problem. The concept resembles the aforementioned CSMA/CA with RTS/CTS medium access protocol of 802.11 systems [67].

In the busy burst concept of [99] the receivers sound the channel after data reception. This way the medium may be reserved for a given link so that other transmissions will not interfere with that connection as long as the busy burst is transmitted. Thus, CCI is avoided although it is not guaranteed that the operation results in improved system performance in all cases. In order to make transmission decisions that increase the overall system performance one has to incorporate information in the receiver signaling. An example of such information is the so called interference price, see [70, 112, 109]. In that scheme the transmit powers of each transmitter are taken as optimization variables in the problem of maximizing the system utility. The system utility is the sum of all users utilities. It is shown in [70] that optimization of the system utility involves assigning each user an interference price. The interference prices are defined as the derivative of each user's utility with respect to the total received interference. The transmitters task is then to i) receive the interference price information from the neighboring receivers, ii) weight the prices by the channel gain of the respective channels, iii) determine its own transmit power that maximizes own utility minus the weighted sum of interference prices, and iv) broadcast an updated interference price to all neighbors for next round of transmit power updates. The conditions under which this procedure converges are established in [70]. Unfortunately, in the case of more than two risk averse users, convergence is not guaranteed. Risk aversion means here that the users' utility functions are sufficiently concave, which is the case with e.g. rate utility (sum rate system utility) and log rate utility (geometric mean system utility). The algorithm may be modified by allowing the users update their transmit powers in smaller steps. By choosing a small enough step size monotone convergence to a local optimum is guaranteed also in the case of rate and log rate utilities [112]. The drawback of having to apply a smaller step size is that the convergence of the power allocations is slower, which is likely to limit the performance gains achievable in practice under bursty traffic.

If the spectrum is shared among different systems or devices that are competing for the access to the medium, it is possible that selfish behavior arises. In this case, there is a need for strategies that ensure that devices comply with the spectrum sharing etiquette or protocol. This aspect of spectrum sharing is further discussed in e.g. [34]. For instance, in the busy burst scheme, a device vendor might choose an artifically high threshold level for busy burst detection. This would degrade the fairness of the system and therefore methods for detecting devices that are not compliant with the protocol are necessary.

4.2.1 Interference aware scheduler (IAS)

Another type of receiver signaling that enables interference awareness at the transmitters is proposed in Publication III. In this scheme the resource allocation decisions made at the schedulers may be done in a way that guarantees improved system performance. Compared to the busy burst scheme of [99], CCI is not avoided altogether, but rather a certain amount of CCI is allowed provided that the system utility is improved. The aim of the scheme is related to the interference pricing of [70]. However, the approach differs from [70] in terms of the information broadcasted. In the scheme of [70] the receivers broadcast the derivative of their utility with respect to interference power. In the proposed scheme the broadcast message is contains information that allows for the trans-

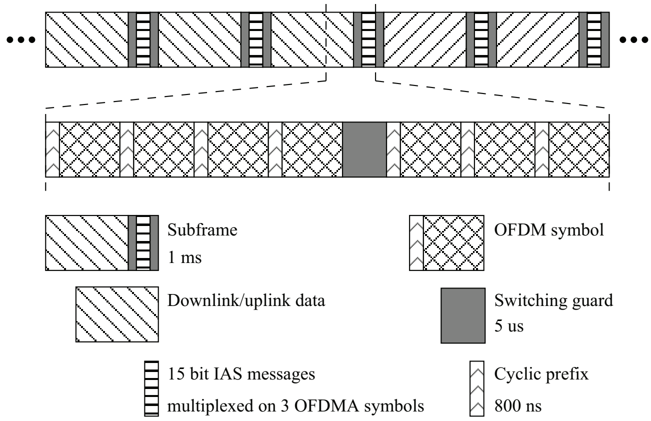


Figure 4.2. An OFDMA/TDD frame structure supporting interference aware scheduling. The overhead of the IA messages is roughly 10%.

mitters to make a system utility-wise optimal binary decision of whether it is beneficial to use a certain resource or not. This binary decision is a simple interference aware scheduling decision much like in the case of busy burst MAC. However, it is guaranteed to improve the system utility.

The IAS scheme of Publication III is comprised of two key components. First, the TDD frame structure is modified such that each data slot is accompanied with a short signaling period where the transmission direction is reversed, see Figure 4.2. In this period the data receivers broadcast short messages, called IA messages, that facilitate interference awareness. Secondly, the scheduler implements a scheduling algorithm that improves the system wide performance.

Three quantities are encoded to each IA message. Namely, the total received interference power, the received signal power, and the average throughput that the receiver is achieving. Consider now a specific transmitter that has to make a decision of whether to transmit on a specific resource or not. The conventional channel quality feedback contains a quantized SINR estimate at the receiver, which allows the transmitter to estimate what would be the throughput gained for its intended receiver on that resource. The channel gains to each IA message transmitter (i.e. data receiver) may be estimated from the received power of the IA messages exploiting the channel reciprocity and known transmit power. The IA messages together with the estimated channel gains allows the transmitter to estimate how much would the throughputs of the other receivers in the vicinity degrade. Then it is a simple matter of forming a system utility estimate based on the individual user utilities given that a transmission is made on the resource. The transmission decision is allowed only if the system utility would improve. The system utility function may be for instance the sum rate or the sum log-rate over the affected users.

The (system) utility change due to a specific scheduling decision is typically referred to as a scheduling metric. In the studies carried out in this thesis, sum log-rate has been considered as the system utility. Thus, the definition of the IAS scheduling metric $\mu_{n,k,\text{IA}}$ for n-th link being active on k-th resource is

$$\begin{aligned}\mu_{n,k,\text{IA}} = & \frac{1}{|\{m : m \notin \mathcal{L}_s\}| + 1} \left(\log(T^{+}_{n,k}) + \sum_{m \notin \mathcal{L}_s} \log(Q^{+}_{mn,k}) \right) \\ & - \frac{1}{|\{m : m \notin \mathcal{L}_s\}| + 1} \left(\log(T^{-}_{n,k}) + \sum_{m \notin \mathcal{L}_s} \log(Q^{-}_{mn,k}) \right) ,\end{aligned} \tag{4.1}$$

where $T^{+}_{n,k}$ is the resulting total throughput of link n given it is active on resource k, $T^{-}_{n,k}$ is the resulting total throughput of link n given it is not active on resource k, $Q^{+}_{mn,k}$ contains the throughput values of other cell links (indexed by m) if link n is active on resource k, and $Q^{-}_{mn,k}$ contains the throughput values of other cell links if there is no transmission on resource k by any of the links in the set $\mathcal{L}_s$ (the set of links served by scheduler s). Therefore, if the link m is active on resource k, the first term of (4.1) gives the mean log-rate for the desired and interfered links. Similarly, the second term gives the mean log-rate if the considered transmitter is not active. The scheduler evaluates the metric for all links it is scheduling and for all resources. The link and resource pair with the maximal metric is scheduled if the maximal metric is positive. If for a certain resource all links have a negative scheduling metric, there shall not be a transmission on that resource. Since in that case, the loss in interfered links' throughput would outweigh the gain in the throughput of the desired link. The detailed description of these quantities along with the explicit description of IAS scheduling algorithm can be found in Publication III.

In order for the scheme to converge to a stable transmission schedule in a distributed implementation one needs to randomize the updates of the scheduling decisions. Otherwise, two schedulers might keep on simultaneously altering their transmission schedules so that the system would oscillate between two suboptimal states. A straightforward example of such behavior is the case of two links and two resources where the interference channel gains are strong. Suppose that at time instance t_1 both of the links would be active on resource 1. The transmitters would sense the presence of other link receiver through the IA messages, and also would estimate very good throughput on the unused resource. Therefore, they would both decide to transmit on the resource 2 at time instance t_2. In the next time instance t_3 they would switch back to resource 1, and so forth, always reusing the same resource and experiencing harsh interference. The way out of such a cyclic pattern is to randomize the scheduling updates. A standard distributed scheme for this purpose is to allow scheduling updates at each transmitter independently, with a probability p less than one. Therefore, each scheduler keeps the preceding frame transmission schedule with probability $(1-p)$, and updates the schedule with probability p. As the decisions are independent, the system cannot remain in a cyclic pattern indefinitely.

It is shown in Publication III that the transmit schedules converge to a local optimum with probability one irrespective of the chosen system utility function. The local optimum is such that no scheduler can alone make a modification to its transmit schedule that would improve the system utility. In addition to the proof given in Publication III, convergence may be deduced by noting that IAS corresponds to a coordination game that has a finite improvement path property [93]. Specifically, each scheduler may be represented as a player, whose action space is formed by the possible transmission schedules to the users that the scheduler is serving. Therefore, the action spaces are finite. Furthermore, the IA messages enable the schedulers to observe the system utility. Thus, the utility function of each player is identical, and maps the actions of all schedulers to the system utility. Such a game may be represented as an absorbing Markov chain, and is therefore always convergent, see [93]. It should be noted that there may be multiple absorbing states, each corresponding to a different system utility. In other words, the distributed IAS may not converge to a global optimum.

Practical implementation aspects of IAS

Developing a practical implementation of IAS requires trading off between various design criteria. A crucial part is to design reliable enough IA message transmission with minimal overhead. All interference victims that are affected by the scheduling decisions at a certain transmitter should be sensed reliably. Otherwise, the scheduling decisions will not be optimal and fair spectrum access is not guaranteed. Moreover, the convergence of IAS can not be guaranteed under unreliable IA messaging.

However, several non-idealities of a practical implementation are considered in the system simulations of Publication III, including quantization and decoding of the messages and non-orthogonality of the multiple access employed in the IA message transmission.

In practice the estimation of the impact of a scheduling decision to the throughput of desired and interfered links can be only approximate. For instance, the ability of a receiver to measure absolute signal and interference power may be somewhat limited. Moreover, if the nodes employ multiple antennas, the impact of transmit precoding and receiver processing to the signal and interference power measurements needs to be taken into account. Taking this into account in the transmitter (scheduler) side is subject to speculation. These factors may make the practical IAS performance worse.

A key design parameter that impacts the IA message overhead is the granularity of the radio resource allocations. In principle, having a finer granularity in the frequency domain allows to achieve closer to the maximum capacity of a frequency selective channel. Moreover, in a multiuser network frequency selectivity may be exploited by allocating each user the frequency resources where the channel quality is high. On the other hand, having a short allocation in time domain enables low latency of the physical layer and also faster convergence of IAS. In TDD systems the granularity in time domain also determines how well the UL and DL access time may be adjusted to the traffic load of the cell. Additionally, the number of independent radio resources in a frame determines how many users may be multiplexed to a frame, which also justifies fine granularity. However, fine granularity resource allocation (small allocation unit) has the drawback that the relative control signaling and IA message overhead increases. Therefore a good trade-off among these goals needs to be found for best system performance. That is, one has to minimize the signaling overhead and at the same time provide low latency, high spectral efficiency, and accommodate enough users per frame.

It is beneficial to schedule transmissions such that the interference does not vary too much in consecutive frames. The randomized transmission schedule updates that enable convergence of distributed implementation of IAS naturally reduce the variance of interference somewhat. This is because the resource allocations is only allowed to change with a probability less than one. However, if there are more users to be served than can be accommodated to a single frame, the scheduler must serve different users in consecutive frames for fairness. This induces high variance of interference, which slows down the convergence of IAS. A straightforward way of dealing with the problem would be to use a finer resource granularity, at the cost of a larger overhead. A more sophisticated solution is to form clusters of links that share a common IA message. In case of downlink communication, this means that the UEs need to be informed about the common IA message, and then transmit it coherently.

4.3 CCI management for efficient radio resource sharing

In this section two cases are presented where CCI management using interference aware scheduling enables efficient radio resource sharing. In the first one described in Section 4.3.1, there are two networks operating on the same geographical area, and the networks either employ orthogonal frequency bands or share the same wide frequency band. In the second one in Section 4.3.2, a single TDD network is considered. There, either fixed or adaptive switching point between the DL and UL frame portions is employed in order to enhance effective user data rates under varying UL/DL traffic load.

Let us assume that the radio links (transmitter-receiver pairs) operating on a certain geographical region are divided into groups based on e.g. the network operator or link direction (uplink or downlink). For instance, a group of links could be formed from those links that correspond to DL transmission from a specific BS to the UEs that it serves. The links of each group are allowed to transmit on a set of radio resources (in time-, frequency-, and/or code-domain). Traditionally, the systems utilize fixed and mutually orthogonal sets of radio resources for different groups of links. Each operator utilizes its own frequency bands and the DL and UL transmissions take place on separate resources. Furthermore, if the neighboring cells are assigned separate frequency bands through a cellular frequency reuse scheme, the signal to co-channel interference ratio at each receiver is guaranteed to be high.

Wireless systems are rarely fully loaded in practice. If observed at any one time instance each group has a random amount of queued traffic. Also, depending on the locations of the transmitters and the receivers it may or may not be beneficial to allocate common resources to certain links. The degree of interference coupling between the links dictates whether higher throughputs are achieved by utilizing common or orthogonal resources. In case there are only a few active links in each group at any time instance, allowing all groups to use all resources would not result in excessive interference. This kind of resource sharing (also called trunking) increases the system capacity as well as the data rates perceived by the users when the system is not fully loaded. The system is considered not fully loaded when the arrival rate of data to the queues is smaller than the maximum service rate offered by the system.

Obviously, the gain from resource sharing is higher when the variance of traffic load in each group of links is high. The variance increases when the traffic gets more bursty and when there are fewer links per group, as in for example pico-cells. As an example, a wide area cellular system serving voice traffic would not benefit much from resource sharing among the operators. This is mainly because each cell serves a large number of users. A large user base implies that the traffic load per cell tends to be similar across neighboring cells and operators. If the users are uniformly distributed over a continuous coverage area with homogeneous scattering environment, the interference coupling between the different cells is similar. However, local area networks exhibit a different scenario. Few users per cell and bursty, dynamic, and non-stationary traffic means that there is more opportunity to share radio resources.

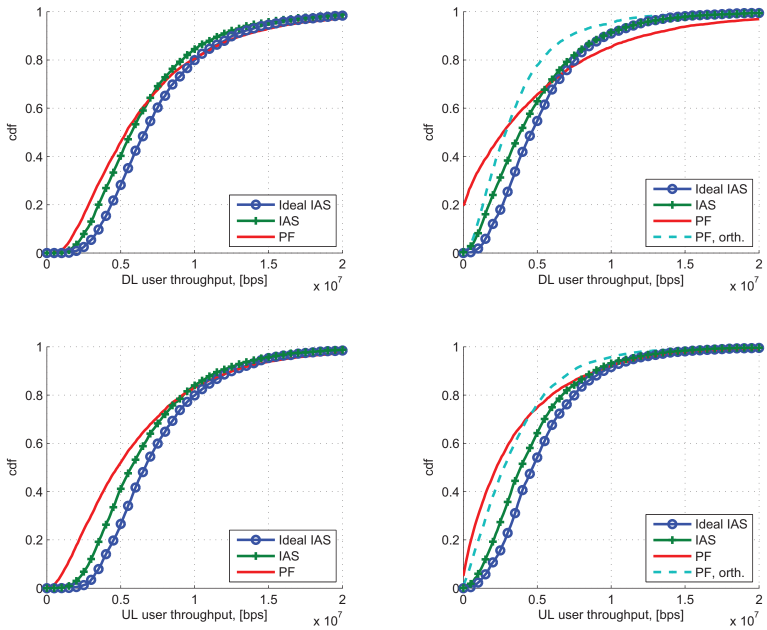
4.3.1 Spectrum sharing among local area networks

The performance of spectrum sharing approach between two operators that serve users on the same area is evaluated in system simulations in Publication III. An indoor communication scenario is assumed where the BSs are deployed on corridors. The UE throughput in three radio resource sharing cases is investigated. In the first case the operators employ distinct, orthogonal frequency bands. In the second case the operators share the frequency bands. A third case of BS sharing between the operators was also simulated as a benchmark. That is, in the third case each UE is allowed to connect to the closest BSs regardless of the operator, while in the first two cases the closest BS may be from different operator and therefore not available.

The results of the system simulations are presented in Figure 4.3. On the right, Figure 4.3a, the DL and UL user throughput cdfs are presented under the assumption of BS sharing. BS sharing means here that an open subscriber group (OSG) is employed where the operators share hardware and allow also other operators UEs access their base stations. Both a non-interference aware PF scheduler and IAS were simulated. In the OSG case no severe CCI is arising because each UE is served by the closest BS. The performance with the PF scheduler is typical for a reuse-1 system where cell edge UEs (low percentiles of the cdf) experience rather low throughput compared to the cell center UEs (high percentiles of the cdf). In this case fairness is not very good but the outage probability is very small. By employing IAS the performance of the cell edge UEs is improved considerably. Two curves for the IAS are shown, where the better performance represents ideal IAS. For the ideal IAS we assume no overhead, perfect IA message transmission and no quantization of the IA message content. The second curve represents the performance when several non-idealities of a practical IAS implementation have been taken into account. In particular, the overhead of 10%, quantized 15 bit IA messages, and 0 dB SINR threshold for IA message detection were assumed. The user throughput gain from non-ideal IAS in the 5th percentile of the DL cdf is roughly 1.5 fold, and in the UL roughly 2.5 fold compared to the PF scheduler. Also the median of the throughput cdf is increased by the IAS, while the highest percentile throughputs are reduced. These results indicate that IAS provides both higher median throughput and better fairness.

The more interesting case of spectrum sharing among operators without BS sharing is presented in Figure 4.3b. When the hardware is not shared between the operators so called closed subscriber groups (CSG) are formed by the UEs each operator serves. In this case, the performance achieved by the traditional approach of non-interference aware schedulers on orthogonal bands may be compared to the shared band operation with IAS. It can be seen that interference aware shared band operation gives roughly 40% better median user throughput than orthogonal band deployment with PF scheduling. Note especially that the gain in median throughputs is not achieved at the expense of cell edge throughput. On the contrary, the 5th percentile of the user throughput cdf is also improved by a factor of 1.2 in the DL and by a factor of 2.6 fold in the UL.

The results indicate the high potential of more efficient spectrum sharing between wireless networks with overlapping coverage area, even under high traffic loads. Interference awareness at the MAC level is essential to achieve the gain. If there is no interference awareness, the shared band operation leads to severe outage and poor fairness, as can be seen from the user throughput cdfs for the PF scheduler in Figure 4.3b. Note that when the traffic load is low, the spectrum sharing essentially



(a) OSG **(b)** 2 CSGs

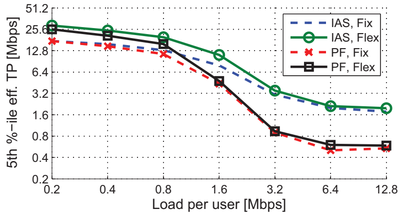
Figure 4.3. User throughput distributions in the scenario with 96 UEs and 32 BSs. The figures on the left represent OSG network and the figures on the right represent 2 CSGs network. The largest gains from IAS are evident in the lower percentiles of user throughput, while there is also gain in the median throughput. The coverage of PF scheduler with two CSGs on shared band is very poor with 20% DL outage. IAS is able to remedy the situation remarkably. The 'PF, orth.' curve represents the case of PF scheduler with the 2 CSGs on orthogonal bands, where it can be seen that just orthogonalizing the band between the 2 CSGs and running a PF scheduler is a suboptimal solution. Publication III.

doubles the perceived throughputs since the UEs are able to utilize the full spectrum under low interference. In essence, interference awareness enables spectrum sharing, which provides significantly higher peak data rates under low load and also significantly higher median and cell edge user throughput under high load.

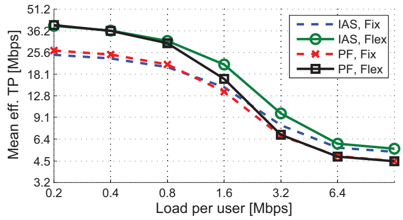
4.3.2 Flexible UL/DL switching points

Consider now an example of radio resource sharing between UL and DL of a TDD system in more detail. Flexible allocation of the radio resources between the UL and DL communication is an advantage of TDD systems over FDD [26]. However, if the switching point is adapted according to the traffic load, a new type of interference arises that occurs among BSs and also among UEs, see Figure 3.3. Such interference may be severe if the interferer is close to the victim receiver. Moreover, in wide area networks the interference between BSs may be strong due to the high BS transmit power and a high probability of a line of sight (LoS) connection between the BSs [60]. This interference may reduce the gains from flexible switching points. In order to avoid severe intercell and interoperator interference, it is usually recommended that the switching point between DL and UL transmissions are synchronized across all cells and neighboring frequency bands, see e.g. [60]. However, the switching point adaptation may also be exploited when there is a more static asymmetry between the UL and DL traffic loads. In such case, the network may be kept synchronized while still adapting to long term traffic asymmetry [8, 78]. On the other hand, in a local area data network the instantaneous traffic load may vary significantly in the UL and DL directions due to the lower number of users per cell. CCI management is then needed to enable more dynamic switching point adaptation [99, 126, 92, 68]. Interference among highly sectorized BSs may be managed by pairing the UL transmissions of a cell with suitable DL transmissions in neighboring cells [68]. This is possible by coordinating the pattern by which the neighboring BSs activate the sectors. However, such a scheme requires more static configuration, which naturally limits its applicability. Angular domain interference management is addressed in [27, 126]. It can be argued that the feasibility of interference suppression through precise null steering between BSs depends heavily on the antenna configuration, propagation environment, and presence of scatterers. A method for controlling user activity in crossed slots based on pathloss thresholds toward the serving and neighboring cell base stations is proposed in [92]. In another type of UL-DL interference management the BSs allocate transmissions to either crossed slots or non-crossed slots based on the observed interference state [53]. Such operation is further enhanced by busy burst beacon signals transmitted from data receivers in [99].

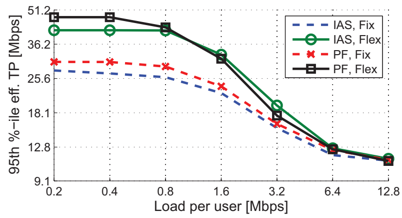
The throughput gain from flexible switching point can be studied analytically by using the framework of balanced fair resource allocation of [15] for simple scenarios. When the system is not fully loaded, a relevant performance statistic is the effective user throughput. It is defined as the mean user throughput over the time that the user has data in the queue. It is shown in Publication IV and Publication V that the effective user throughput can be theoretically doubled in a single cell and single user system by enabling flexible UL/DL switching point. The effective throughput doubles under very light load. However, when the load in-



(a) 5$^{\text{th}}$ %-ile effective throughput



(b) Mean effective throughput



(c) 95$^{\text{th}}$ %-ile effective throughput

Figure 4.4. Effective throughput versus link load in system simulation of the flexible switching point TDD network. Compared to fixed switching point, the gain from flexible switching point in low load is directly proportional to the amount UL and DL subframes. In high load the gain vanishes. Interference-aware scheduler supports higher loads and also provides gain from flexible switching at higher load than PF scheduler. Publication IV, © 2011 IEEE.

creases, the gain from flexible switching point decreases. Also a two cell system with a single user in each cell is analyzed in Publication IV. In this second scenario the effective user throughput performance is studied under low, moderate, and high interference coupling. In the low interference case, it is beneficial for the two links to share the radio resources, while in the high interference case using orthogonal time resources gives better capacity. In the moderate interference case sharing the radio resources between the UL and DL of the two links may be beneficial. This occurs when the UL-DL coupling between the links is weaker than the UL-UL and DL-DL coupling. The results demonstrate that if the interference can be taken into account in the scheduling, the same system performance gain can be expected as in the single link case. Furthermore, in the moderate interference scenario, the load level at which the system saturates can be even higher when flexible switching point is enabled. This is because the transmissions can be organized such that the UL and DL of the two links utilize common instead of separate resources.

A simple theoretical performance analysis in Publication IV involves abstracting various functionalities of the wireless network and a very small scale scenario. In order to verify the gains in a more practical scenario, system level simulations are needed. The effective user throughput ver-

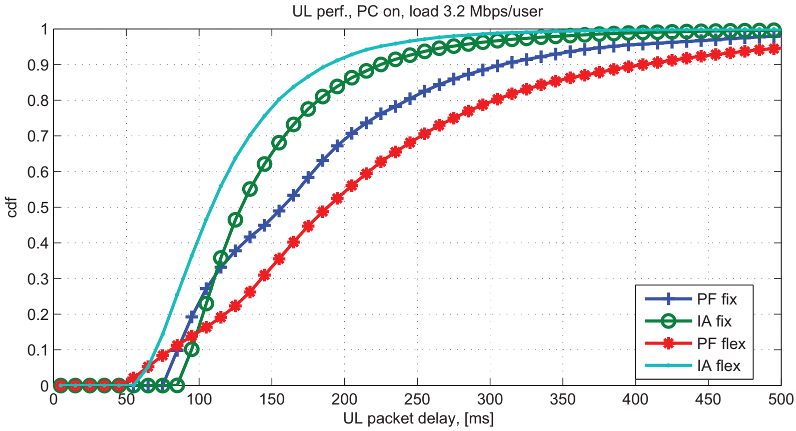


Figure 4.5. UL packet delay CDF's when UL is power controlled and the link load is 3.2 Mbps. Publication V, © 2012 Springer.

sus system load level is investigated in Publication IV and Publication V through system simulation. In this study, a non-interference aware proportional fair (PF) scheduler is compared to the interference aware scheduler (IAS). The results are shown in Figure 4.4. As expected, the effective throughput gain is proportional to the maximum UL/DL asymmetry of the frame structure. In the simulated frame structure the first slot out of 6 was always DL and the last slot UL while the rest can be freely assigned to either direction. Interestingly, no loss in the system performance due to flexible switching point and crossed slot interference in the high system load regime is observed. When comparing the two schedulers to each other, it can be seen that the IAS gives much better fairness than the PF scheduler. This is evident in the 5-th percentile of the effective user throughputs which reflects the cell edge performance. The mean throughput is higher when the IAS is employed, except on very low system loads. This means that the system is able to support higher loads when the scheduler has interference awareness. This gain comes irrespective of whether flexible switching points are employed or not. Moreover, the region where there is a gain from flexible switching is extended by the IAS.

In many scenarios it is possible that either the UL or DL starts to suffer from crossed slot interference when the system load gets higher. A prominent example is when the DL transmit power is higher than the UL transmit power and there exists a strong LOS link between the BS. This is demonstrated in simulations where the same fractional power control scheme was applied in both link directions and the links among the BSs were all non line of sight (NLoS). Also, the link direction is not distinguished in Figure 4.4. By mixing the link directions in the effective user throughput distribution, the difference in overall system performance may be evaluated. In Publication V the effect of different DL and UL power control strategies on the DL and UL packet delays is further investigated. Here the DL transmits at a constant power, while UL employs full pathloss compensation via power control, i.e. the received SNR at BS is constant for all links. The resulting UL packet delay distributions shown in Figure 4.5. When the PF scheduler is employed, the UL packet delay is increased when flexible switching point is enabled. This is due to the high interference from DL transmissions in crossed slots, which effectively prioritizes DL transmissions over the UL transmissions. However, by using interference awareness in the scheduler, the UL packet delay improves with flexible switching. It is notable that in the packet delay domain, the gain from interference awareness is very high in the fourth quartile, while the PF scheduler provides slightly lower delays in the very lowest percentiles. The latter effect is due to the IA message overhead.

4.4 Discussion

In this chapter an overview of CCI management techniques was given. The concept of receiver beaconing for transmit side interference awareness was considered in detail. The novel IAS scheduler of Publication III was presented, which constitutes a key contribution of the thesis.

Transmitter side interference awareness can be used in controlling the CCI in wireless networks. This enables low level CCI management which is beneficial in radio resource sharing scenarios in the face of severe CCI. The proposed scheme was applied in two exemplary cases of resource sharing in Publication III, Publication IV, and Publication V. The examples demonstrate the achievable gains from resource sharing and interference awareness in the related CCI management. Alternative solutions to interference awareness in the literature include the busy burst scheme of [99] and the broadcast interference price scheme of [70]. The advantage of IAS over the busy burst scheme is that it allows making optimal decisions on resource allocation in the sense of improving the system-wide utility. Compared to the interference pricing, the IAS is more suitable for practical implementation, especially in case of bursty traffic, since it does not require slow adaptation of transmit powers. On the other hand, the signaling schemes employed by IAS are more demanding to implement than in case of the busy burst scheme. Therefore, the IAS scheme developed in this thesis provides a relevant trade-off between the schemes of [99] and [70]. Network MIMO and CoMP schemes may be also considered as competing solutions to the IAS. The key difference between such schemes and IAS is that IAS provides decentralized CCI management, while CoMP targets centralized inter-cell interference management. Consequently, the scheme proposed in this thesis is more readily applicable in a wider range of resource sharing scenarios. As an example, IAS could find applications in interference management among cellular and D2D transmissions. At the same time, a distributed scheme has its drawbacks in that it requires time for convergence to suitable resource allocations. Centralized CCI management can in principle adapt to changes in e.g. the traffic load immediately.

All the above mentioned schemes provide link level CCI management where individual receivers are taken into account in resource allocation decisions. The enhanced frequency reuse schemes [81] can be interpreted to be cell level CCI management methods. The cell level approach can be more readily incorporated in current systems as it requires only minor modifications to the standards. It may be also implemented with less signaling overhead, and is therefore inherently more robust. However, link level CCI management enables better performance than schemes that operate on larger groups of links, as shown in Publication III, Publication IV, and Publication V. It can also find a wider range of use cases.

There are still a number of open research problems in IAS implementation. To name a few, an extension of IAS to MIMO transceivers should be developed. The same holds for a mechanism for forwarding IA messages received by the UEs to the BS. Also the multiple access mechanism employed in IA message transmission should be investigated taking various transceiver impairments into account. A careful analysis on the trade-off between the impact of quantization error and signaling overhead remains to be carried out. Nevertheless, the work in this thesis shows the potential of link level CCI management in providing efficient spectrum use and dynamic radio resource sharing in a wide variety of scenarios relevant to future wireless systems.

5. Device-to-device underlay in cellular systems

Local data traffic is an emerging traffic type that should be considered in future wireless systems. An example is multimedia content distribution among devices that are located close to each other, see e.g. [12]. Direct device-to-device (D2D) transmissions provide an efficient way of serving local traffic [64]. As an example, ad hoc wireless networks with contention based access protocols on license exempt bands lend themselves naturally to D2D transmissions. However, it may also be beneficial to support D2D traffic in cellular networks. Interference management techniques that enable sharing of radio resources among D2D and cellular transmissions is the topic of this chapter. For a recent overview on D2D communication in cellular systems see [103, chapter 9]. Aspects related to enabling D2D communication specifically in LTE systems are investigated in [40]. It is worth noting that recently a study item has been initiated in LTE to consider standardization of D2D communication both for commercial and public safety use [3].

The chapter deals with interference management for D2D connections underlaying a cellular network. In particular, the case when the cellular network allows the terminals to form direct D2D links that reuse the cellular spectrum is investigated. This work is motivated by the fact that enabling direct D2D links has potential to increase the system spectral efficiency tremendously if local traffic is to be supported in the cellular system. The operation on cellular TDD bands is especially attractive since it may not require additional RF transceiver chains to the devices. However, the interference between the D2D underlay and the cellular links has to be controlled so that the quality of service for the cellular links is not compromised. Publication VI, Publication VII, and Publication VIII deal with this problem. This chapter gives a brief overview of D2D communication along with a literature review on interference management schemes for D2D. The contributions of the thesis related to interference management between D2D and cellular links are then presented, which be briefly summarized as follows:

- For the UL sharing case, a power control scheme that controls the interference from D2D transmitting UE to the UL receiving BS is proposed in Publication VI. In that scheme the cellular UL power control mechanism is utilized for controlling the interference.

- For both UL and DL resource sharing cases, an interference aware radio resource allocation scheme is proposed in Publication VII. In that scheme the multiuser diversity that arises when there are multiple cellular UEs and multiple D2D links in the cell is utilized. Specifically, each cellular link is paired with a D2D link such that interference between the links that share the same radio resources is minimized.

- For the DL sharing case, an interference avoiding DL MIMO transmit scheme is proposed in Publication VIII. In that scheme the BS employs a beamformer that maximizes the DL capacity while steering a null toward the D2D receiver.

5.1 D2D in wireless systems

License exempt bands provide a natural medium for D2D communication. The operators owning the licensed bands do not have immediate incentive for providing their spectrum for D2D use. The widely used interference management methods on cellular networks are not readily applicable for D2D connections. On the other hand, the predominant distributed and contention based MAC architecture used on license exempt bands supports D2D communication well. For instance, the 802.11s standard for mesh networking naturally supports D2D connections, see e.g. [36, 23]. Also other 802.11 standards [67] have specified ad-hoc modes whereby the devices may establish a D2D connection without the presence of a WLAN AP. Bluetooth is another technology for local D2D transmissions that operates on the license exempt band [88]. A direct D2D transmission mode is also defined in Terrestrial Trunked Radio (TETRA), which is a standard for wireless networks targeted mainly for governmental and

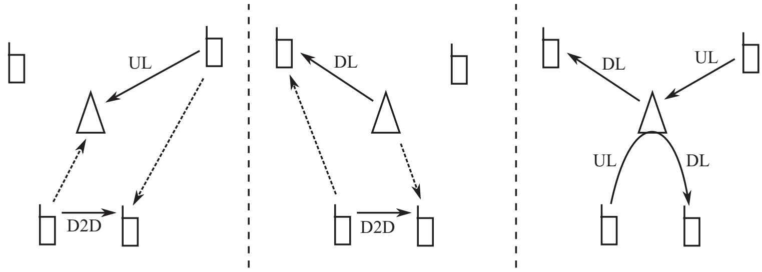


Figure 5.1. Illustration of resource sharing between cellular and D2D links and the virtual D2D link formed via the BS. Virtual D2D means that the cellular UL and DL channels are used for D2D traffic and the data packets may be redirected at the BS to the receiver in the same cell. Interference between cellular and D2D links is indicated by dashed arrows.

emergency use [35].

The cellular systems support transmissions between the terminals (user equipment, UE) and the base stations (BS). Therefore, D2D traffic gets routed through the BS and the backbone network if the network does not provide support for D2D transmission. A virtual D2D connection may be established by routing the traffic only through the BS. However, when compared to direct D2D transmission, such operation leads in many cases to higher delays and inefficient use of radio resources due to the fact that it enforces relaying. Figure 5.1 illustrates the difference between a direct and a virtual D2D transmission. There is no fundamental reason why the direct D2D transmissions could not be supported within the cellular network. The advantages of a D2D underlay in a cellular network when compared to e.g. 802.11 and Bluetooth have been discussed in e.g. Publication VI. For instance, using the licensed frequency bands of the cellular network for the D2D communication provides a controlled interference environment and hence in principle better reliability may be provided. Automated service discovery is possible by using the cellular connection for advertising the local services. Encryption may be easily organized by distributing the keys over the cellular network. In principle, licensed bands allow also a higher transmit power than license exempt bands, which could be translated to longer D2D communication range. For instance, public safety networks would benefit from the reliability of the licensed spectrum and higher transmit power [40]. In addition, an obvious advantage of supporting the D2D transmission in a cellular system is that it can complement other available radio access technologies supporting D2D communication through interworking. Ideally, the D2D communication should be possible to be assigned flexibly to the best available spectrum opportunity. For instance, while underutilized, the cellular UL resources provide good opportunity for D2D operation. Otherwise, when the cellular network is experiencing high load, the majority of data could be transmitted using another radio access technology, e.g. via 802.11 WLAN. Even in this case many of the D2D communication management tasks could be performed with the aid of the cellular infrastructure. In addition to capacity improvement, another advantage of using local transmissions for local traffic is that the transmission power may be reduced which leads to better energy efficiency [4, 5]. For instance, D2D transmit power may be minimized under a sum-rate constraint [42]. In that approach the goal is to find the minimum transmit powers for the cellular and D2D link such that the sum rate over the two links reaches a predetermined level. Network architecture related aspects of D2D communication have been inspected in e.g. [38, 28].

In a broader sense, secondary communication has been studied in the research field of cognitive radio. A cognitive radio utilizes frequency bands that are allocated to licensed users and services. Secondary use may be allowed in order to exploit underutilized spectrum in time, frequency, or location [89, 58, 132]. In the cognitive radio context D2D communication can be viewed as a secondary radio that opportunistically utilizes the radio resources of the primary cellular links. According to [132], in a cognitive spectrum underlay the secondary signal is spread over a wide bandwidth so that the primary users see it as a slight increase in the background noise and interference power. A cognitive overlay (also called interweave) means that the secondary users detect vacant sub-bands and time slots and use them in an opportunistic manner. The coexistence of D2D transmissions on a cellular band is here termed an underlay mode, which does not relate to the cognitive radio taxonomy of underlay and overlay communication. In the work done in this thesis the assumption is that the D2D devices are connected to the cellular network. The system is centralized such that a cellular BS controls the transmissions and collects information on spectrum utilization and interference within a cell. Therefore, D2D communication as an underlay to the cellular system is different from typical cognitive radio operation, where the devices themselves have to ensure that they do not cause interference to the primary users.

5.1.1 Improving the cellular service by D2D relaying

D2D communication may be employed even if there is no local traffic present. It is possible to improve the cellular service by D2D relaying of the cellular transmissions [82, 84, 63, 94, 38, 28, 101, 105]. For example, higher system capacity may be achieved when UEs with good channel conditions are used for relaying each others traffic to and from the BS, see e.g. [82, 63]. Terminal assisted relaying has been considered also for the case where the D2D and cellular links are using a different RAT, see e.g. [84]. In general, the use of D2D and cellular links should be coordinated by the BS in order to achieve performance gains [63]. Otherwise, the inefficiencies related to distributed coordination of D2D links leads to lower throughput as compared to pure single hop system with BS coordination.

Coverage extension of the cellular service is another possible application for D2D transmissions in the absence of local traffic. For example, an ad-hoc GSM system is proposed in [94]. The goal is to increase the coverage by using UEs with good link conditions for relaying traffic to and from coverage holes. If the majority of traffic is in the downlink direction, an FDD system may end up being congested in DL while the UL band is under utilized. In this case a gain may be achieved from relaying DL data to the cell edge UEs via UEs with better connection to the BS. A mode where D2D pairs located on the cell edge communicate using an contention based TDD MAC is proposed in [101]. The D2D transmission takes place on otherwise underutilized FDD UL band. A D2D relaying underlay utilizing the cellular FDD UL band may also facilitate more efficient content distribution in the cellular DL [105].

5.2 Interference management for the D2D underlay

D2D transmissions cause severe interference if they are allowed in the proximity of cellular mode devices (either mobile terminals or base stations) and on the same time-frequency resources. Unless this interference is carefully managed it will result in unacceptable degradation both in cellular and D2D link qualities. The interference between the D2D and cellular links is illustrated in Figure 5.1. When the D2D link is active on a radio resource that is in use by a cellular UL transmission, interference is induced from the UL transmitting UE to the D2D receiving UE. Interference is also induced from the D2D transmitting UE to the cellular BS. Similarly, when the D2D transmission shares radio resources with the cellular DL transmission, interference is induced from the cellular BS to the D2D receiving UE. Also, interference is induced from the D2D transmitting UE to the DL receiving UE. In both cases the BS may allocate orthogonal resources to the D2D and UL transmissions so that interference does not occur. This is straightforward, if the cellular UL or DL band is not fully utilized. However, in this thesis the focus is on the opportunities for D2D underlay communications in a fully loaded cellular system.

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

5.2.1 Admission control and mode selection

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

In a more general sense, the RRM functionality at the BS needs to choose a proper mode for the D2D transmission. The available options are relaying through the BS, D2D link on dedicated resources, or D2D link on shared resources together with a cellular UL or DL transmission. The optimal mode for D2D communication is strongly dependent on the node locations and D2D link distance, as is shown in Publication VI. On the other hand, the results of [56] indicate that a simple mode selection scheme is sufficient if the D2D link distance is short. Specifically, when the D2D link distance is in the order of one hundredth of a cell radius, it suffices to simply categorically enforce D2D mode transmission for the D2D links. Otherwise, interference awareness in mode selection is crucial. The work in [56] assumes a WCDMA system. A similar study is carried out in [77], where D2D communication within small device clusters is considered. In [130] the SINR distributions for D2D resource sharing with cellular UL and DL have been derived as a function of the location of the D2D terminals in an isolated cell. The propagation environment and the relative locations of the cellular and D2D devices affect the SINR distributions. In some cases it is more favorable to employ UL sharing while other cases favor DL sharing. This indicates that there is potential for performance gains from interference awareness in selecting between DL and UL sharing. Several studies show that interference aware mode selection is able to provide reliable D2D and cellular link quality while maintaining a large proportion of direct D2D transmissions and thus large system capacity [32, 11, 40, 52].

5.2.2 Power control

Another simple interference management principle is to allow only very low power D2D transmissions. This limits the range of the D2D links but guarantees that the interference toward cellular links will remain at a tolerable level. The advantage of this approach is that it requires minimal signaling. The low power D2D transmission mode could be naturally implemented using wide-band transmission, e.g. through spread spectrum modulation. The BS may, for instance, merely periodically broadcast the current allowed D2D power level, and let the D2D communication take place in an ad-hoc manner. An example of low power D2D underlay is given in [105]. However, interference aware power control is needed in case longer D2D transmission range is to be supported. The effectiveness of ideal interference aware power control is demonstrated in [131].

In case the D2D transmission shares the radio resources with cellular DL transmission the BS or the D2D transmitter should estimate the channel gain to the terminals receiving a DL transmission. This can be problematic due to the fact that there are several terminals that may be interfered, depending on the scheduling decisions made at the BS. Also neighboring cell terminals are impacted by the interference so that inter-BS coordination would be needed. Furthermore, the signaling requirements also increase. This is because the power control scheme needs to take into account also the different received signal power at each DL receiver. Therefore, accurate interference aware power control for D2D transmissions sharing cellular DL radio resources becomes complicated.

The situation is different when D2D transmissions share cellular UL resources. In this case, the interference is experienced at the BS no matter which cellular terminal is scheduled for UL transmission. Hence, power control is easier to arrange. Also, the received signal power at the BS has much narrower dynamic range when UL power control is employed for the cellular transmissions. The BS may employ a mechanism similar to the conventional UL power control in setting the D2D transmit power, as proposed in Publication VI. The D2D transmit power may be controlled by the same mechanism as the UL transmit power, but with a lower target received power level. It is also possible to increase the UL transmit power to counter the extra interference from the D2D transmission. However, such UL power boosting in both the UL and the D2D transmit powers results in extra inter-cell interference. The added benefit from power boosting is that the D2D transmission range may be extended.

The impact of D2D transmit power setting and the interference aware power control was evaluated in static system simulations in Publication VI. The simulation scenario was chosen to represent a local area indoor network with 9 BSs, see Figure 5.2, and all radio resources are assumed to be shared by one cellular transmission and one intracell D2D transmission. The results show that the proportion of D2D links that have SINR greater than 0 dB can be more than doubled with interference aware power control, while the degradation to the cellular links is held fixed.

It is noted that a similar power control mechanism for D2D transmissions that share the resources with cellular UL transmission was proposed in [76] independently from the work presented in this thesis. The two power control schemes are formulated differently but define essentially identical operation. Regarding the implementation, [76] suggest that the D2D terminals determine the appropriate transmit power autonomously by assuming that the power control parametrization is known and the interference channel gain is estimated from the known BS transmit power and received signal power measurements. In that case the devices need to interrupt the D2D communication in order to perform the measurements. In Publication VI the power control of both the D2D transmitters and cellular UL transmitters is suggested to be performed by the BS. This would give more control and freedom to the BS to manage the interference but on the other hand it requires more signaling.

5.2.3 Multiuser scheduling

A more elaborate way of managing the interference between D2D and cellular links is to let the BS manage the radio resource usage by schedul-

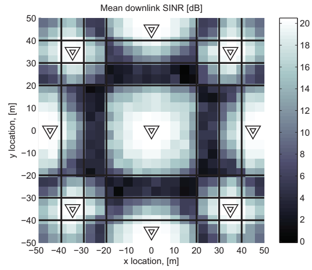


Figure 5.2. The communication scenario used in the D2D simulations. The triangles represent base stations, an the black horizontal and vertical lines represent walls with 5 dB attenuation each. The shade of the background color corresponds to DL SINR in case no D2D transmissions are present. Publications VI–VIII, © 2009 IEEE.

ing decisions such that the impact of interference is minimized. The extent to which such schemes may be applied depends on the nature of the channel state information (CSI) available at the BS. The CSI may be collected through explicit channel sounding and measurements. Alternatively the link qualities could be monitored under varying scheduling decisions thereby implicitly learning the interference conditions. Also channel reciprocity may be exploited. In any case, interference aware RRM is more readily feasible in local area scenarios with only a few users per cell. In such a scenario the dimensionality of the problem is manageable and excessive signaling may be avoided. In addition, it has been shown that information on large scale propagation conditions including pathloss and shadowing may be sufficient for achieving most of the gains [129]. The implementation becomes more feasible by ignoring fast fading and frequency selectivity since there is significantly less large scale channel data. On the other hand, in local area scenarios low mobility and short delay spread are typically assumed, which reduces the CSI overhead. If accurate channel state information is available, the frequency selectivity of the channels may be considered as frequency diversity, which actually improves the system capacity [32]. A more straightforward interference management scheme is to allocate dedicated time-slots for D2D communication [12]. The BS may then act as a support node to the D2D links by managing the radio resource use of the D2D links. The aim of the D2D RRM in [12] is to maximize the D2D capacity through clustering the D2D links close to each other, and then optimizing the frequency reuse among the clusters.

A practical method for acquiring the CSI for interference aware multiuser scheduling is proposed in Publication VII. In that approach it is proposed that the D2D terminals perform interference measurements during the cellular UL transmissions. Specifically, the D2D terminals may listen to the BS control channels in order to identify the cellular UL transmitters and the radio resources on which they transmit. The D2D terminals measure the received power of the corresponding UL transmissions, and further signal the measurement to the BS. A slight drawback is that the devices need to interrupt data communication for the duration of such measurements. Note that when the cellular UL is power controlled, the power measurement by the D2D terminals does not directly reflect the channel gain between the cellular terminal and the D2D terminal. However, it is shown in Publication VII that such measurement is actually highly useful. In case of resource sharing among cellular UL and D2D, the measurement enables minimizing the maximum intracell interference to the D2D receiver. Similarly, in the DL case, the measurement enables maximizing the minimum cellular DL SINR, assuming channel reciprocity and that intracell D2D transmissions are the dominant interference source. The performance gain in system simulation from the scheme of Publication VII is illustrated in Figure 5.3. Enabling direct D2D transmission instead of relaying the transmission through the BS increases the median cell capacity roughly 2.3-fold when using random resource allocation. In case of interference aware resource allocation the gain rises to 2.5-fold. In this evaluation the signaling overhead of acquiring the interference awareness has not been taken into account (i.e. it is assumed that it is due to low mobility). The large capacity gain may be explained by two factors. First, when the traffic is relayed through the BS, the same data is transmitted twice, while in direct D2D communication a single transmission is enough. Second, by allowing the D2D underlay to reuse the cellular resources, the same resources may be used twice. Therefore, it is apparent that the majority of the capacity increase from direct D2D communication comes from enabling direct transmission itself. Interference management can be seen as a further improvement to the concept. However, the interference awareness may prove more useful in improving the reliability of the communication.

5.2.4 Spatial domain techniques

When the BSs and terminals are equipped with multiantenna transceivers, part of the interference may be mitigated in the spatial domain. Such operation has been proposed for interference mitigation for cognitive ra-

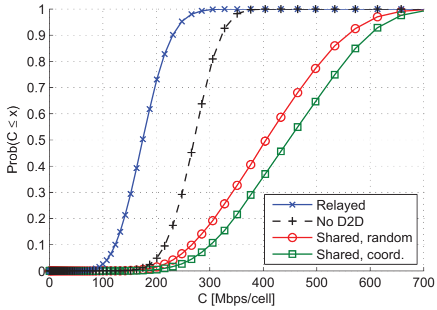


Figure 5.3. Comparison of cell capacity CDFs when D2D traffic is relayed through the BS and when direct D2D transmissions are enabled. The cell capacity CDF under pure cellular traffic is included for reference while for the other curves half of the traffic is assumed to be local. The gain from enabling D2D transmission is large as compared to the additional gain from interference aware resource allocation. Publication VII, © 2009 IEEE.

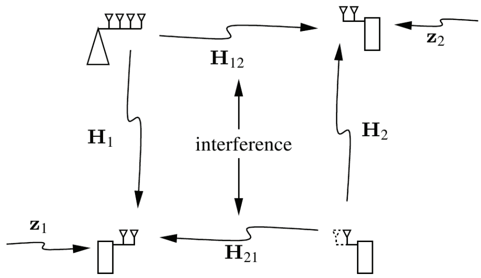


Figure 5.4. The interfering transmissions in the DL of a given cell. Publication VIII, © 2009 IEEE.

dios in [95], where a secondary communication system employs null steering toward primary system transceivers. The spatial domain interference suppression is possible both at the receiver and at the transmitter. Figure 5.4 illustrates the problem for the case where D2D communication shares the cellular DL resources, as considered in Publication VIII.

Implementing the spatial processing at the receiver is more straightforward than at the transmitter[1]. The receiver may simply estimate the interference covariance matrix and an LMMSE receiver may be designed. Such a receiver suppresses interference effectively when the interference covariance matrix does not have full rank. As an example, adding a second antenna to the D2D receiver may double proportion of D2D links with SINR greater than zero [102]. The result is obtained assuming resource sharing among cellular DL and D2D, and further assuming rank one transmissions. Successive interference cancellation (SIC) may be also

[1]Here, receiver and transmitter may correspond to either terminals or base stations

considered by modeling the interference as a deterministic signal. SIC is actually not a spatial domain method in itself, but may be applied in conjunction with LMMSE spatial receiver (although in principle, SIC is possible even in the case of SISO channels). The use of SIC may theoretically almost double the capacity of the system [66] when radio resources are shared among cellular UL and D2D transmissions. The result is derived in [66] by means of stochastic geometry. In [66] a simplified model for SIC receivers is assumed where each interferer whose received power exceeds the desired signal power by 2 dB may be canceled. However, the SIC receiver requires in practice a lot of support in terms of e.g. signaling of the modulation and coding scheme of the interfering transmission. The LMMSE receiver does not require such support and is computationally less complex as well.

Interference may be also avoided at the transmitter by interference aware MIMO precoding. If accurate interference channel state information is available at the transmitter, beamforming algorithms may be employed to steer a null toward the interfered receiver and also maximize the gain toward the intended receiver. Accurate estimates of the channel matrices toward the D2D receiver and the intended DL receiver are needed for such schemes. This can be facilitated through accurate receiver feedback. Channel reciprocity may be utilized as well, if the D2D receiver is active in the UL. A transmit precoder can be designed such that the DL capacity is maximized under the constraint that a null is steered toward the D2D receiver as proposed in Publication VIII. According to the system simulations of Publication VIII, the median system capacity (sum of D2D and DL capacities) may be improved roughly 15 %. The study assumes a four antenna array at the BS, dual receive antenna terminals, and perfect channel state information. This gain is similar in magnitude as the gain from interference aware multiuser scheduling. However, when looking at the D2D capacity improvement separately, it is roughly doubled resulting in a much more balanced D2D and DL capacities. The selection of a cellular UE and a D2D pair that are sharing the same subband was done randomly in the evaluations. In case there are multiple DL receivers and D2D pairs in the cell it is possible to use channel state information in the selection of the DL receivers and D2D pairs. This is because choosing a precoder that transmits to the null space of the D2D receiver does not in general match fully with the signal space of the DL receiver. However, the pairing of a D2D receiver and a DL receiver may be done such that the null space of the D2D receiver and the signal space of the DL receiver are more separated to begin with. This would enhance the gains as the null steering would then imply less penalty to the DL transmission.

5.3 Discussion

The concept of direct D2D communication underlay to cellular communication systems was treated in this chapter. The emphasis was on interference management schemes for the case when the D2D communication reuses the cellular radio resources. The problem of co-channel interference between the D2D underlay and cellular communication was addressed with an assumption that the cellular communication has priority over the D2D communication. The opportunities for D2D underlay operation without compromising the cellular communication in a fully loaded cellular system were investigated. The contributions of the thesis related to D2D communication include interference aware D2D transmit power control for resource sharing with cellular UL, interference aware resource allocation, and interference aware MIMO precoding for the cellular DL. The performance gains from proposed methods were evaluated in a variety of simulations.

It can be inferred from Publication VI that the usable transmission range for the D2D underlay will remain very small in case no dynamic interference management is employed. This is because a very conservative approach has to be taken where the D2D transmission power has to be set to a very low and fixed level so that the cellular transmissions are not disturbed. The situation may be improved by adjusting the D2D power according to the location of the D2D transmitter with respect to the cellular interference victims. Such an interference management scheme is straightforward to implement for resource sharing with the cellular UL communication, as is shown in Publication VI. In Publication VII a higher degree of interference awareness is considered where the channel gains between cellular UEs and D2D terminals are taken into account in resource allocation. In that case the multiuser diversity can be exploited leading to further improvement in the D2D link quality. As discussed in Publication VII, acquiring the needed interference channel state information can be feasible also in practice. Interference suppression or avoidance in spatial domain provides yet another means of improving the link quality. The specific case of interference avoiding precoding at the BS proposed in Publication VIII has potential to significantly improve the D2D link quality on common resources with the cellular DL. However, further work is required to find out how much of the gain can be obtained in a practical implementation. Additional work is needed to quantify the impact of quantization error and latency of the channel state information feedback related to the interference channel. This is justified by the fact that steering a null toward a certain receiver is more sensitive to imperfect channel state information than steering the maximum power. Robust algorithms for null steering should be considered, e.g. angular domain methods. In this respect, the antenna array geometry and the spatial channel properties (namely, the angular spread) are factors that impact the efficiency and gains from null steering.

All of the proposed interference management schemes address intracell interference. However, the intercell interference among a D2D pair in one cell and the cellular transmission in another cell may also be significant. Also the case when the terminals engaging in D2D communication are not in the same cell poses a slightly different scenario. Assuming that the use of radio resources is controlled by the base stations, interference management for the intercell case would need to utilize cooperation between the base stations. In another approach, a distributed interference management scheme could be utilized. However, the UL based power control scheme of Publication VI is applicable to the inter-cell interference case also since it may be assumed that the D2D transmitter is associated to the base station with the strongest link.

The proposed interference management methods may be compared to other methods in the literature in terms of the role of the cellular network in the D2D radio resource usage. In an extreme case, the network may merely indicate a low transmission power to the D2D communication. If the interference from D2D communication is further randomized, the two communication tiers may coexist but the resulting D2D transmission range is limited [56]. Next in the order of increasing network coordination, one may consider allocating radio resources for clusters of D2D devices [12], or a pair of devices. The specific mode selection schemes of e.g. [129] assume even tighter network coordination. The interference aware resource allocation scheme proposed in Publication VII takes the control yet further, where each the interference is controlled among individual cellular and D2D terminals by taking the interference into account in the multi-band scheduling decisions. The spatial domain interference suppression scheme of Publication VIII may be seen as the other extreme of the considered interference management techniques. In this classification the different methods offer different trade-offs between the amount of needed signaling / complexity and the resulting system level spectral efficiency. The challenge of designing a practical D2D enabled cellular system lies in obtaining the best trade-off between these aspects. It is clear that several interference management techniques are needed in the end to guarantee reliable operation of both communication modes. For instance, the three interference management schemes proposed in this thesis are complementary to each other, and could be therefore applied jointly.

6. Summary

Demand for high speed wireless access continues to grow due to increasing usage of smart phones, mobile internet, and new wireless services. In principle, the capacity of the wireless networks may be enhanced by utilizing wider frequency bands, improving the spectral efficiency, and increasing base station density. For example, flexible spectrum access, multiantenna-, and multicarrier techniques provide solutions that tackle the first two of these strategies. Increasing base station density in a cost effective manner is facilitated by relying on lighter infrastructure and automation of network deployment, planning, optimization, and maintenance. As the cell sizes shrink, network deployments become less coordinated, and data traffic becomes burstier and more local, it is necessary to rely on automated and dynamic interference management techniques in order to maintain high spectral efficiency and reliability. The techniques and analysis contributed in this thesis provide solutions toward these goals.

Adjacent channel interference (ACI) management is one enabler that facilitates flexible spectrum use and reliability in face of uncoordinated network deployments. In this thesis, the severity of ACI in local area TDD cellular systems was investigated through system simulations. ACI management is needed in order to ensure fairness in the spectrum use. A method was proposed where the transmitters optimize their transmitted spectral shape on-line, such that constraints on ACI induced by power amplifier non-linearity are met. The proposed technique enables more flexible spectrum use among operators and more relaxed RF requirements at transceiver front-end, without compromising fairness and reliability.

An optimization problem was formulated for the case when PA non-linearity is the dominant source of ACI. In a further study, also other sources of ACI could be incorporated in the model. No detailed analysis of the optimization problem was carried out, which is a topic for further research. In order to make on-line ACI management practical one would also need to develop the associated signaling mechanisms. Detailed system simulations could verify the effectiveness of the proposed ACI management in practice.

Co-channel interference (CCI) caused by increased spectrum reuse is the most important factor limiting the performance of future wireless networks. As the future systems need to extract as much capacity from the limited spectrum, the distance between transceivers that potentially use the same time/frequency resources is reducing. Maintaining reliability and fairness among the users in a cost-effective manner is a non-trivial task in the scenario. As a potential solution to the problem, a novel interference-aware scheduling (IAS) technique was proposed and analyzed in this thesis. The technique relies on so called reverse beacons, which are messages broadcasted from the data receivers. The messages contain information on the received power levels and throughput, which enables managing co-channel interference (CCI) in an autonomous and decentralized fashion. It was demonstrated that IAS enables spectrum sharing between operators, independent adaptation of UL/DL switching points in TDD networks, and provides overall more fair and spectrally efficient wireless access. It was further shown that shared band operation among local area networks is much more efficient than orthogonal band operation once interference awareness is incorporated to the MAC. The gains from independent adaptation of UL/DL switching points were demonstrated both analytically and in simulations.

Further research is needed on the IAS method and its performance. Especially the trade-off between the achieved gains and the signaling overhead should be carefully evaluated, taking realistic transceiver impairments into account. This involves e.g. verifying the reliability of the beacon messages in practice. The impact of quantization error and rate prediction at the transmitter side should be studied in detail as well. Furthermore, an efficient extension of IAS to MIMO transceivers should be developed. In case MIMO transceivers are utilized, especially the transmitter side rate prediction for the desired receiver and the interference victims is likely to be an interesting and challenging problem.

New services are emerging that generate local traffic among the users, and also among users and machines. Such Device-to-Device (D2D) traffic is effectively served by direct transmissions among the devices. Although unlicensed band provides a natural medium for the D2D communication, the thesis demonstrates the potential in allowing such direct D2D transmissions on a shared band together with the cellular communication. The licensed band operation could provide a more controlled interference environment and a higher transmit power in comparison to unlicensed band operation. However, the potentially strong interference between the D2D and cellular links necessitates elaborate interference management techniques in order to facilitate reliable and efficient shared band operation. For this purpose, three methods are proposed that provide interference aware power control, interference aware multiuser and multiband resource allocation, and interference avoiding MIMO precoding. The proposed interference management techniques were shown to increase the opportunities for direct D2D communication and improve the system capacity.

The proposed techniques facilitate mitigating the interference among the D2D and cellular links. However, in order to exploit the spectral opportunities to the full, one needs to utilize them in conjunction with other interference management techniques proposed in the literature, such as intelligent selection of the communication mode. The proposed techniques rely on coordination from the cellular base stations. Moreover, only intracell interference is managed. For example, extending the techniques to a scenario where multiple cells are coordinating their transmissions (CoMP) would provide means to tackle inter-cell interference. Finally, it should be noted that even though the gains in system capacity are potentially very high, it is inevitable that the resulting system is very complex. Trade-off analysis taking into account the cost of related signaling overhead would be beneficial to find out when the shared band operation is practically feasible.

An interesting future research topic would be to investigate whether the proposed concepts could be unified. This would enable completely decentralized interference management among cellular communication links of different operators and D2D links, taking both co-channel and adjacent channel interference into account. The importance of such research is emphasized by the interest in co-channel heterogeneous networks, where base stations of different power classes operate on a common frequency band. Note that the D2D and cellular communication scenario assumed in this thesis corresponds to a heterogeneous network. In particular, the applicability of IAS to heterogeneous networks should be assessed.

Bibliography

[1] 3GPP TR 36.814, "Evolved universal terrestrial radio access (E-UTRA); further advancements for E-UTRA physical layer aspects," Mar. 2010. [Online]. Available: http://www.3gpp.org/

[2] 3GPP TS 36.300, "Evolved universal terrestrial radio access (E-UTRA) and evolved universal terrestrial radio access network (E-UTRAN); overall description; stage 2 (release 11)," Mar. 2013. [Online]. Available: http://www.3gpp.org/

[3] 3GPP TSG RAN Meeting 58, RP-122009, "Study on lte device to device proximity services," Dec. 2012. [Online]. Available: http://www.3gpp.org/

[4] T. Adachi and M. Nakagawa, "Battery consumption and handoff examination of a cellular ad-hoc united communication system for operational mobile robots," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 1998*, Boston, MA, USA, Sep. 1998, pp. 1193–1197.

[5] T. Adachi and M. Nakagawa, "Capacity analysis for a hybrid indoor mobile communication system using cellular and ad-hoc modes," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2000*, 2000, pp. 767–771 vol.2.

[6] J. Andrews, "Interference cancellation for cellular systems: a contemporary overview," *IEEE Wireless Communications Magazine*, vol. 12, no. 2, pp. 19–29, Apr. 2005.

[7] J. Andrews, W. Choi, and R. Heath, "Overcoming interference in spatial multiplexing MIMO cellular networks," *IEEE Wireless Communications Magazine*, vol. 14, no. 6, pp. 95–104, Dec. 2007.

[8] D. Astely, E. Dahlman, A. Furuskar, Y. Jading, M. Lindstrom, and S. Parkvall, "LTE: the evolution of mobile broadband," *IEEE Communications Magazine*, vol. 47, no. 4, pp. 44–51, Apr. 2009.

[9] G. Bansal, Z. Hasan, M. Hossain, and V. Bhargava, "Subcarrier and power adaptation for multiuser OFDM-based cognitive radio systems," in *National Conference on Communications, NCC 2010*, Jan. 2010, pp. 1–5.

[10] G. Bansal, M. Hossain, and V. Bhargava, "Optimal and suboptimal power allocation schemes for OFDM-based cognitive radio systems," *IEEE Transactions on Wireless Communications*, vol. 7, no. 11, pp. 4710–4718, Nov. 2008.

[11] M. Belleschi, G. Fodor, and A. Abrardo, "Performance analysis of a distributed resource allocation scheme for D2D communications," in *IEEE GLOBECOM Workshops, 2011*, Dec. 2011, pp. 358 – 362.

[12] M. Bennis, G. Middleton, and J. Lilleberg, "Efficient resource allocation and paving the way towards highly efficient IMT-Advanced systems," *Wireless Personal Communications*, vol. 45, no. 4, pp. 465–478, 2008.

[13] G. Berardinelli, L. Ruiz de Temino, S. Frattasi, M. Rahman, and P. Mogensen, "OFDMA vs. SC-FDMA: performance comparison in local area IMT-A scenarios," *IEEE Wireless Communications Magazine*, vol. 15, no. 5, pp. 64–72, Oct. 2008.

[14] Q. Bi, G. Zysman, and H. Menkes, "Wireless mobile communications at the start of the 21st century," *IEEE Communications Magazine*, vol. 39, no. 1, pp. 110–116, Jan. 2001.

[15] T. Bonald, L. Massoulié, A. Proutiere, and J. Virtamo, "A queueing analysis of max-min fairness, proportional fairness and balanced fairness," *Queueing systems*, vol. 53, no. 1, pp. 65–84, 2006.

[16] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. Vrzic, "Interference coordination and cancellation for 4G networks," *IEEE Communications Magazine*, vol. 47, no. 4, pp. 74–81, Apr. 2009.

[17] S. Boyd and L. Vandenberghe, *Convex optimization*. Cambridge University Press, 2004, 727 pages.

[18] S. Brandes, I. Cosovic, and M. Schnell, "Reduction of out-of-band radiation in OFDM systems by insertion of cancellation carriers," *IEEE Communications Letters*, vol. 10, no. 6, pp. 420–422, Jun. 2006.

[19] D. Cabric and R. Brodersen, "Physical layer design issues unique to cognitive radio systems," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2005.*, vol. 2, Sep. 2005, pp. 759–763.

[20] V. Cadambe and S. Jafar, "Interference alignment and degrees of freedom of the K-user interference channel," *IEEE Transactions on Information Theory*, vol. 54, no. 8, pp. 3425–3441, Aug. 2008.

[21] V. Cadambe and S. Jafar, "Multiple access outerbounds and the inseparability of parallel interference channels," in *IEEE Global Telecommunications Conference, GLOBECOM 2008*, Dec. 2008, pp. 1–5.

[22] G. Caire and D. Tuninetti, "The throughput of hybrid-ARQ protocols for the Gaussian collision channel," *IEEE Transactions on Information Theory*, vol. 47, no. 5, pp. 1971–1988, Jul. 2001.

[23] J. Camp and E. Knightly, "The IEEE 802.11s extended service set mesh networking standard," *IEEE Communications Magazine*, vol. 46, no. 8, pp. 120–126, Aug. 2008.

[24] M. Castaneda, M. Ivrlac, J. Nossek, I. Viering, and A. Klein, "Outdated uplink adaptation due to changes in the scheduling decisions in interfering cells," in *IEEE International Conference on Communications, ICC 2008*, May 2008, pp. 4948–4952.

[25] J. Castura and Y. Mao, “Rateless coding over fading channels,” *IEEE Communications Letters*, vol. 10, no. 1, pp. 46 – 48, Jan. 2006.

[26] P. Chan, E. Lo, R. Wang, E. Au, V. Lau, R. Cheng, W. Mow, R. Murch, and K. Letaief, “The evolution path of 4g networks: FDD or TDD?” *IEEE Communications Magazine*, vol. 44, no. 12, pp. 42–50, Dec. 2006.

[27] C.-J. Chen and L.-C. Wang, “Suppressing opposite-direction interference in TDD/CDMA systems with asymmetric traffic by antenna beamforming,” *IEEE Transactions on Vehicular Technology*, vol. 53, no. 4, pp. 956–967, Jul. 2004.

[28] T. Chen and M. Katz, “Cooperative architecture for cellular-short-range combined mesh networks,” in *International ICST Mobile Multimedia Communications Conference, Mobimedia 2009*, 2009, pp. 1–6.

[29] I. Cosovic, S. Brandes, and M. Schnell, “Subcarrier weighting: a method for sidelobe suppression in OFDM systems,” *IEEE Communications Letters*, vol. 10, no. 6, pp. 444–446, Jun. 2006.

[30] M. Costa, “Writing on dirty paper,” *IEEE Transactions on Information Theory*, vol. 29, no. 3, pp. 439 – 441, May 1983.

[31] H. Dai, A. Molisch, and H. Poor, “Downlink capacity of interference-limited MIMO systems with joint detection,” *IEEE Transactions on Wireless Communications*, vol. 3, no. 2, pp. 442–453, Mar. 2004.

[32] K. Doppler, C. Yu, C. Ribeiro, and P. Jänis, “Mode selection for device-to-device communication underlaying an LTE-advanced network,” in *IEEE Wireless Communications and Networking Conference, WCNC 2010*, Sydney, Australia, Apr. 2010, pp. 1–6.

[33] Ericsson, “Mobile data traffic surpasses voice,” Mar. 2010, press release. [Online]. Available: http://www.ericsson.com/thecompany/press/releases/2010/03/1396928

[34] R. Etkin, A. Parekh, and D. Tse, “Spectrum sharing for unlicensed bands,” *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 3, pp. 517–528, Apr. 2007.

[35] ETSI, “Terrestrial trunked radio (TETRA); voice plus data (V+D); designers’ guide; part 3: Direct mode operation (DMO),” TR 102 300-3, v1.2.1, 2002.

[36] S. Faccin, C. Wijting, J. Kneckt, and A. Damle, “Mesh WLAN networks: concept and system design,” *IEEE Wireless Communications Magazine*, vol. 13, no. 2, pp. 10–17, Apr. 2006.

[37] T. Farley, “Mobile telephone history,” *Telektronikk*, vol. 2005, no. 3/4, pp. 22–34, 2005.

[38] F. Fitzek, M. Katz, and Q. Zhang, “Cellular controlled short-range communication for cooperative P2P networking,” *Wireless Personal Communications*, vol. 48, no. 1, pp. 141–155, 2009.

[39] R. Fletcher, *Practical methods of optimization*, 1st ed. John Wiley & Sons, 1987, 450 pages.

[40] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Miklos and, and Z. Turanyi, "Design aspects of network assisted device-to-device communications," *IEEE Communications Magazine*, vol. 50, no. 3, pp. 170–177, Mar. 2012.

[41] G. Fodor, A. Furuskar, P. Skillermark, and J. Yang, "On the impact of uplink scheduling on intercell interference variation in MIMO OFDM systems," in *IEEE Wireless Communications and Networking Conference, WCNC 2009*, Apr. 2009, pp. 1–6.

[42] G. Fodor and N. Reider, "A distributed power control scheme for cellular network assisted D2D communications," in *IEEE Global Telecommunications Conference, GLOBECOM 2011*, Dec. 2011, pp. 1–6.

[43] A. Frappe, A. Flament, B. Stefanelli, A. Cathelin, and A. Kaiser, "All-digital RF signal generation for software defined radio," in *European Conference on Circuits and Systems for Communications, 2008. ECCSC 2008.*, Jul. 2008, pp. 236 – 239.

[44] L. Garcia, K. Pedersen, and P. Mogensen, "Autonomous component carrier selection: interference management in local area environments for LTE-advanced," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 110–116, Sep. 2009.

[45] D. Gesbert, S. Hanly, H. Huang, S. Shamai Shitz, O. Simeone, and W. Yu, "Multi-cell MIMO cooperative networks: A new look at interference," *IEEE Journal on Selected Areas in Communications*, vol. 28, no. 9, pp. 1380–1408, Dec. 2010.

[46] D. Gesbert and M. Kountouris, "Resource allocation in multicell wireless networks: Some capacity scaling laws," in *International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks and Workshops, WiOpt 2007*, Apr. 2007, pp. 1–7.

[47] D. Gesbert, M. Kountouris, R. Heath, C.-B. Chae, and T. Salzer, "Shifting the MIMO paradigm," *IEEE Signal Processing Magazine*, vol. 24, no. 5, pp. 36–46, Sep. 2007.

[48] D. Gesbert, M. Shafi, D. shan Shiu, P. Smith, and A. Naguib, "From theory to practice: an overview of MIMO space-time coded wireless systems," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 3, pp. 281–302, Apr. 2003.

[49] B. Ghimire, G. Auer, and H. Hass, "Busy bursts for trading off throughput and fairness in cellular OFDMA-TDD," *EURASIP Journal on Wireless Communications and Networking*, vol. 2009, no. 1, pp. 1386–1393, 2009.

[50] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005, 672 pages.

[51] K. Gomadam, V. Cadambe, and S. Jafar, "Approaching the capacity of wireless networks through distributed interference alignment," in *IEEE Global Telecommunications Conference, GLOBECOM 2008*, Dec. 2008, pp. 1–6.

[52] J. Gu, S. J. Bae, B.-G. Choi, and M. Y. Chung, "Mode selection scheme considering transmission power for improving performance of device-to-device

communication in cellular networks," in *Proceedings of the 6th International Conference on Ubiquitous Information Management and Communication, ICUIMC '12*, 2012, pp. 1–6.

[53] H. Haas and S. McLaughlin, "A dynamic channel assignment algorithm for a hybrid TDMA/CDMA-TDD interface using the novel TS-opposing technique," *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 10, pp. 1831–1846, Oct. 2001.

[54] H. Haas and S. McLaughlin, "A derivation of the PDF of adjacent channel interference in a cellular system," *IEEE Communications Letters*, vol. 8, no. 2, pp. 102–104, Feb. 2004.

[55] H. Haas, V. Nguyen, P. Omiyi, N. Nedev, and G. Auer, "Interference aware medium access in cellular OFDMA/TDD networks," in *IEEE International Conference on Communications, ICC 2006*, vol. 4, Jun. 2006, pp. 1778–1783.

[56] S. Hakola, T. Chen, J. Lehtomäki, and T. Koskela, "Device-to-device (D2D) communication in cellular network - performance analysis of optimum and practical communication mode selection," in *IEEE Wireless Communications and Networking Conference, WCNC 2010*, 2010, pp. 1–6.

[57] L. Hanzo, M. Münster, B. J. Choi, and T. Keller, *OFDM and MC-CDMA for Broadband Multi-User Communications, WLANs and Broadcasting*, 1st ed. Wiley-IEEE Press, 2003, 1014 pages.

[58] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[59] S. Heikkinen, H. Haas, and G. Povey, "Investigation of adjacent channel interference in UTRA-TDD system," in *IEE Colloquium on UMTS Terminals and Software Radio (Ref. No. 1999/055)*, 1999, pp. 13/1–13/6.

[60] H. Holma, S. Heikkinen, O.-A. Lehtinen, and A. Toskala, "Interference considerations for the time division duplex mode of the UMTS terrestrial radio access," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 8, pp. 1386–1393, Aug. 2000.

[61] H. Holma and A. Toskala, *HSDPA/HSUPA for UMTS*. Wiley, 2007, 268 pages.

[62] H. Holma and A. Toskala, *LTE for UMTS - OFMDA and SC-FDMA Based Radio Access*. John Wiley & Sons, 2009, 450 pages.

[63] H.-Y. Hsieh and R. Sivakumar, "On using peer-to-peer communication in cellular wireless data networks," *IEEE Transactions on Mobile Computing*, vol. 3, no. 1, pp. 57–72, Feb. 2004.

[64] R. Hsieh and J. Iinatti, "Persistent bidirectional peer traffic in fix-network augmented broadband wireless access," in *International Workshop on Wireless Ad-hoc Networks, IWWAN 2005*, 2005, pp. 1–4.

[65] H. Huang, M. Trivellato, A. Hottinen, M. Shafi, P. Smith, and R. Valenzuela, "Increasing downlink cellular throughput with limited network MIMO coordination," *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 2983–2989, Jun. 2009.

[66] K. Huang, V. Lau, and Y. Chen, "Spectrum sharing between cellular and mobile ad hoc networks: transmission-capacity trade-off," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 7, pp. 1256–1267, Sep. 2009.

[67] IEEE 802.11, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," IEEE-SA, Tech. Rep., Jun. 2007. [Online]. Available: http://standards.ieee.org/getieee802/download/802.11-2007.pdf

[68] W. Jeong and M. Kavehrad, "Cochannel interference reduction in dynamic-TDD fixed wireless applications, using time slot allocation algorithms," *IEEE Transactions on Communications*, vol. 50, no. 10, pp. 1627–1636, Oct. 2002.

[69] T. Jiang and Y. Wu, "An overview: Peak-to-average power ratio reduction techniques for OFDM signals," *IEEE Transactions on Broadcasting*, vol. 54, no. 2, pp. 257–268, 2008.

[70] H. Jianwei, R. Berry, and M. Honig, "Distributed interference compensation for wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 5, pp. 1074–1084, May 2006.

[71] K. Johansson, A. Furuskar, P. Karlsson, and J. Zander, "Relation between base station characteristics and cost structure in cellular systems," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2004*, vol. 4, Sep. 2004, pp. 2627–2631.

[72] V. Jungnickel, L. Thiele, T. Wirth, T. Haustein, S. Schiffermuller, A. Forck, S. Wahls, S. Jaeckel, S. Schubert, H. Gabler, C. Juchems, F. Luhn, R. Zavrtak, H. Droste, G. Kadel, W. Kreher, J. Mueller, W. Stoermer, and G. Wannemacher, "Coordinated multipoint trials in the downlink," in *IEEE GLOBECOM Workshops*, Dec. 2009, pp. 1–7.

[73] X. Kang, H. Garg, Y.-C. Liang, and R. Zhang, "Optimal power allocation for OFDM-based cognitive radio with new primary transmission protection criteria," *IEEE Transactions on Wireless Communications*, vol. 9, no. 6, pp. 2066–2075, Jun. 2010.

[74] M. Karakayali, G. Foschini, and R. Valenzuela, "Network coordination for spectrally efficient communications in cellular systems," *IEEE Wireless Communications*, vol. 13, no. 4, pp. 56–61, Aug. 2006.

[75] P. Karn, "MACA – a new channel access method for packet radio," in *ARRL/CRRL Amateur Radio Computer Networking Conference*, 1990, pp. 134–140.

[76] B. Kaufman and B. Aazhang, "Cellular networks with an overlaid device to device network," in *Asilomar Conference on Signals, Systems and Computers, ACSSC 2008*, Pacific Grove, CA, USA, Oct. 2008.

[77] T. Koskela, S. Hakola, C. Tao, and J. Lehtomäki, "Clustering concept using device-to-device communication in cellular system," in *IEEE Wireless Communications and Networking Conference, WCNC 2010*, 2010, pp. 1–6.

[78] T. Kriengchaiyapruk and I. Forkel, "Adaptive switching point allocation in TD/CDMA systems," in *IEEE Vehicular Technology Conference, VTC Fall 2002*, vol. 3, 2002, pp. 1456–1460.

[79] N. Ksairi, P. Bianchi, P. Ciblat, and W. Hachem, “Resource allocation for downlink cellular OFDMA systems Part I: Optimal allocation,” *IEEE Transactions on Signal Processing*, vol. 58, no. 2, pp. 720–734, Feb. 2010.

[80] N. Ksairi, P. Bianchi, P. Ciblat, and W. Hachem, “Resource allocation for downlink cellular OFDMA systems Part II: Practical algorithms and optimal reuse factor,” *IEEE Transactions on Signal Processing*, vol. 58, no. 2, pp. 735–749, Feb. 2010.

[81] R. Kwan and C. Leung, “A survey of scheduling and interference mitigation in LTE,” *Journal of Electrical and Computer Engineering*, vol. 2010, pp. 1–10, 2010, article ID 273486.

[82] Y.-D. Lin and Y.-C. Hsu, “Multihop cellular: A new architecture for wireless communications,” in *Joint Conference of the IEEE Computer and Communications Societies, INFOCOM 2000.*, vol. 3, Mar. 2000, pp. 1273–1282.

[83] L. Lindbom, R. Love, S. Krishnamurthy, C. Yao, N. Miki, and V. Chandrasekhar, “Enhanced inter-cell interference coordination for heterogeneous networks in LTE-Advanced: A survey,” *ArXiv e-prints*, pp. 1–18, Dec. 2011.

[84] H. Luo, R. Ramjee, P. Sinha, L. E. Li, and S. Lu, “UCAN: a unified cellular and ad-hoc network architecture,” in *International Conference on Mobile Computing and Networking, MobiCom ’03*. New York, NY, USA: ACM, 2003, pp. 353–367.

[85] H. Mahmoud and H. Arslan, “Sidelobe suppression in OFDM-based spectrum sharing systems using adaptive symbol transition,” *IEEE Communications Letters*, vol. 12, no. 2, pp. 133–135, Feb. 2008.

[86] M. Maqbool, P. Godlewski, M. Coupechoux, and J.-M. Kélif, “Analytical performance evaluation of various frequency reuse and scheduling schemes in cellular {OFDMA} networks,” *Performance Evaluation*, vol. 67, no. 4, pp. 318 – 337, 2010.

[87] M. McHenry, P. Tenhula, D. McCloskey, D. Roberson, and C. Hood, “Chicago spectrum occupancy measurements & analysis and a long-term studies proposal,” in *International Workshop on Technology and Policy for Accessing Spectrum, TAPAS 2006*, 2006, pp. 1–12.

[88] B. Miller and C. Bisdikian, *Bluetooth revealed: The insider’s guide to an open specification for global wireless communication*. Prentice Hall, 2001, 320 pages.

[89] J. I. Mitola and G. Q. J. Maguire, “Cognitive radio: Making software radios more personal,” *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, Aug. 1999.

[90] A. Molisch, *Wireless Communications*. Wiley, 2010, 884 pages.

[91] A. Motahari and A. Khandani, “Capacity bounds for the gaussian interference channel,” *IEEE Transactions on Information Theory*, vol. 55, no. 2, pp. 620–643, Feb. 2009.

[92] J. Nasreddine and X. Lagrange, "Time slot allocation based on a path gain division scheme for TD-CDMA TDD systems," in *IEEE Vehicular Technology Conference, VTC Spring 2003*, vol. 2, Apr. 2003, pp. 1410–1414.

[93] J. Neel, R. Menon, A. MacKenzie, J. Reed, and R. Gilles, "Interference reducing networks," in *International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CrownCom 2007*, Aug. 2007, pp. 96–104.

[94] G. Neonakis Aggelou and R. Tafazolli, "On the relaying capability of next-generation GSM cellular networks," *IEEE Personal Communications*, vol. 8, no. 1, pp. 40–47, Feb. 2001.

[95] K. Nishimori, H. Yomo, P. Poposvski, Y. Takatori, R. Prasad, and S. Kubota, "Interference cancellation and avoidance for secondary users co-existing with TDD-based primary systems," *Wireless Personal Communications*, vol. 45, pp. 403–421, 2008.

[96] J. Nocedal and S. Wright, *Numerical optimization*, ser. Springer series in operations research. Springer, 2006, 664 pages.

[97] B. Nosrat-Makouei, J. Andrews, and R. Heath, "Mimo interference alignment over correlated channels with imperfect CSI," *IEEE Transactions on Signal Processing*, vol. 59, no. 6, pp. 2783 – 2794, Jun. 2011.

[98] T. Novlan, R. Ganti, A. Ghosh, and J. Andrews, "Analytical evaluation of fractional frequency reuse for OFDMA cellular networks," *IEEE Transactions on Wireless Communications*, vol. 10, no. 12, pp. 4294–4305, Dec. 2011.

[99] P. Omiyi, H. Haas, and G. Auer, "Analysis of TDD cellular interference mitigation using busy-bursts," *IEEE Transactions on Wireless Communications*, vol. 6, no. 7, pp. 2721–2731, Jul. 2007.

[100] P. Omiyi and H. Haas, "Improving time-slot allocation in 4th generation OFDM/TDMA TDD radio access networks with innovative channel-sensing," in *IEEE International Conference on Communications, ICC 2004*, vol. 6, Jun. 2004, pp. 3133–3137.

[101] P. Omiyi and H. Haas, "Maximising spectral efficiency in 3G with hybrid ad-hoc UTRA TDD/UTRA FDD cellular mobile communications," in *IEEE International Symposium on Spread Spectrum Techniques and Applications, ISSSTA 2004*, 2004, pp. 613–617.

[102] A. Osseiran, K. Doppler, C. Ribeiro, M. Xiao, M. Skoglund, and J. Manssour, "Advances in device-to-device communications and network coding for IMT-Advanced," in *ICT Mobile and Wireless Communications Summit, ICT-MobileSummit 2009*, Santander, Spain, Apr. 2009.

[103] A. Osseiran, J. Monserrat, and W. Mohr, Eds., *Mobile and Wireless Communications for IMT-Advanced and Beyond*. John Wiley & Sons, 2011, 328 pages.

[104] S. Parkvall and D. Astely, "The evolution of LTE towards IMT-Advanced," *Journal of Communications*, vol. 4, no. 3, 2009.

[105] L. Popova, T. Herpel, and W. Koch, “Enhanced downlink capacity in UMTS supported by direct mobile-to-mobile data transfer,” in *International IFIP-TC6 Conference on Ad Hoc and Sensor Networks, Wireless Networks, Next Generation Internet, NETWORKING 2007*, 2007, pp. 522–534.

[106] F. Raab, P. Asbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary, J. Sevic, and N. Sokal, “Power amplifiers and transmitters for RF and microwave,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 3, pp. 814–826, Mar. 2002.

[107] A. Sampath, P. Sarath Kumar, and J. Holtzman, “Power control and resource management for a multimedia CDMA wireless system,” in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 1995*, vol. 1, Sep. 1995, pp. 21 – 25.

[108] M. Sawahashi, Y. Kishiyama, A. Morimoto, D. Nishikawa, and M. Tanno, “Coordinated multipoint transmission/reception techniques for LTE-advanced,” *IEEE Wireless Communications*, vol. 17, no. 3, pp. 26–34, Jun. 2010.

[109] D. Schmidt, C. Shi, R. Berry, M. Honig, and W. Utschick, “Distributed resource allocation schemes,” *IEEE Signal Processing Magazine*, vol. 26, no. 5, pp. 53–63, Sep. 2009.

[110] S. Sesia, I. Toufik, and M. Baker, *LTE - The UMTS Long Term Evolution*. Wiley, 2011, 680 pages.

[111] M. Shaat and F. Bader, “Low complexity power loading scheme in cognitive radio networks: FBMC capability,” in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2009*, Sep. 2009, pp. 2597–2602.

[112] C. Shi, R. Berry, and M. Honig, “Distributed interference pricing for OFDM wireless networks with non-separable utilities,” in *Conference on Information Sciences and Systems, CISS 2008*, Mar. 2008, pp. 755–760.

[113] K. Shin, H. Kim, A. Min, and A. Kumar, “Cognitive radios for dynamic spectrum access: from concept to reality,” *IEEE Wireless Communications Magazine*, vol. 17, no. 6, pp. 64–74, Dec. 2010.

[114] A. Stamoulis, S. Diggavi, and N. Al-Dhahir, “Intercarrier interference in MIMO OFDM,” *IEEE Transactions on Signal Processing*, vol. 50, no. 10, pp. 2451–2464, Oct. 2002.

[115] M. Sternad, T. Svensson, T. Ottosson, A. Ahlen, A. Svensson, and A. Brunstrom, “Towards systems beyond 3g based on adaptive OFDMA transmission,” *Proceedings of the IEEE*, vol. 95, no. 12, pp. 2432–2455, Dec. 2007.

[116] G. Stuber, J. Barry, S. McLaughlin, Y. Li, M. Ingram, and T. Pratt, “Broadband MIMO-OFDM wireless communications,” *Proceedings of the IEEE*, vol. 92, no. 2, pp. 271–294, Feb. 2004.

[117] H. Tang, “Some physical layer issues of wide-band cognitive radio systems,” in *IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN 2005*, Nov. 2005, pp. 151–159.

[118] R. Tresch and M. Guillaud, “Cellular interference alignment with imperfect channel knowledge,” in *IEEE International Conference on Communications Workshops, ICC Workshops 2009*, Jun. 2009, pp. 1–5.

[119] D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*. Cambridge University Press, 2005, 564 pages.

[120] D. Tse, “Optimal power allocation over parallel gaussian broadcast channels,” in *IEEE International Symposium on Information Theory, ISIT 1997*, Jul. 1997, pp. 1–27.

[121] D. Tse and S. Hanly, “Multiaccess fading channels. I. Polymatroid structure, optimal resource allocation and throughput capacities,” *IEEE Transactions on Information Theory*, vol. 44, no. 7, pp. 2796–2815, Nov. 1998.

[122] J. van de Beek and F. Berggren, “N-continuous OFDM,” *IEEE Communications Letters*, vol. 13, no. 1, pp. 1–3, Jan. 2009.

[123] S. Venkatesan, A. Lozano, and R. Valenzuela, “Network MIMO: Overcoming intercell interference in indoor wireless systems,” in *Asilomar Conference on Signals, Systems and Computers, ACSSC 2007*, Nov. 2007, pp. 83–87.

[124] S. Vishwanath, N. Jindal, and A. Goldsmith, “Duality, achievable rates, and sum-rate capacity of gaussian MIMO broadcast channels,” *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2658–2668, Oct. 2003.

[125] VTT Technical Research Centre of Finland, “Up to 18% more bandwidth for mobile broadband users with spectrum sharing,” Apr. 2013, press release. [Online]. Available: http://www.vtt.fi/news/2013/25042013_ASA.jsp?lang=en

[126] L.-C. Wang, S.-Y. Huang, and Y.-C. Tseng, “Interference analysis and resource allocation for TDD-CDMA systems to support asymmetric services by using directional antennas,” *IEEE Transactions on Vehicular Technology*, vol. 54, no. 3, pp. 1056–1069, May 2005.

[127] M. Wellens, J. Wu, and P. Mähönen, “Evaluation of spectrum occupancy in indoor and outdoor scenario in the context of cognitive radio,” in *International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CrownCom 2007*, Aug. 2007, pp. 420–427.

[128] H. Yin and S. Alamouti, “OFDMA: A broadband wireless access technology,” in *IEEE Sarnoff Symposium 2006*, Mar. 2006, pp. 1–4.

[129] C.-H. Yu, K. Doppler, C. Ribeiro, and O. Tirkkonen, “Performance impact of fading interference to device-to-device communication underlaying cellular networks,” in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2009*, Sep. 2009, pp. 858–862.

[130] C.-H. Yu, O. Tirkkonen, K. Doppler, and C. Ribeiro, “On the performance of device-to-device underlay communication with simple power control,” in *IEEE Vehicular Technology Conference, VTC Spring 2009*, Apr. 2009, pp. 1–5.

[131] C.-H. Yu, O. Tirkkonen, K. Doppler, and C. Ribeiro, “Power optimization of device-to-device communication underlaying cellular communication,” in *IEEE International Conference on Communications, ICC 2009*, Jun. 2009, pp. 1–5.

[132] Q. Zhao and B. Sadler, “A survey of dynamic spectrum access,” *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 79–89, May 2007.

[133] L. Zheng and D. Tse, “Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels,” *IEEE Transactions on Information Theory*, vol. 49, no. 5, pp. 1073–1096, 2003.

[134] G. Zhou and R. Raich, “Spectral analysis of polynomial nonlinearity with applications to RF power amplifiers,” *EURASIP Journal on Applied Signal Processing*, vol. 2004, no. 12, pp. 1831–1840, 2004.

Errata

Publication II

The second paragraph in Section III of the publication contains an error. The effect of in-band distortion (EVM) cannot be captured in the proposed method. The numerical examples in presented in the publication are not affected by the error as the noise floor N_o was selected such that it dominates over the in-band distortion. The level of the in-band distortion was rougly -25 dBc, while the noise floor was at minimum set to -21 dBc. The paragraph should read as follows:

> Let us assume the objective is to maximize the in-band capacity assuming a certain SNR at the receiver, g is chosen as
>
> $$g(S_x(f)) = -\int_0^1 \log_2\left(1 + \frac{h(f)S_x(f)}{N_o}\right)\, df, \qquad (7)$$
>
> where $h(f)$ is the channel gain at frequency f and N_0 is the receiver noise floor. Here we have assumed, without loss of generality, that the wanted signal is at the frequency band $f \in [0, 1]$.

In addition, the frequency range of $[-3.375, -2.935]$ MHz in the caption of Figure 4 is given wrong, and should read $[-6.75, -5.85]$ MHz.

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