Project Number:	**CELTIC / CP5-026**
Project Title:	Wireless World Initiative New Radio – WINNER+
Document Type:	PU (Public)

Document Identifier:	D1.4
Document Title:	**D1.4 Initial Report on Advanced Multiple Antenna Systems**
Source Activity:	WP1
Editors:	Petri Komulainen, Mauro Boldi
Authors:	Mats Bengtsson, Bhavani Shankar, Emil Björnson, Federico Boccardi, Mauro Boldi, Valeria D'Amico, Albrecht Fehske, Martin Fuchs, Eric Hardouin, Petri Komulainen, Bruno Melis, Magnus Olsson, Agisilaos Papadogiannis, Harri Pennanen, Peter Rost, Ahmed Saadani, Malte Schellmann, Tommy Svensson, Lars Thiele, Antti Tölli, Thorsten Wild
Status / Version:	Final / 1.0
Date Last changes:	16.01.09
File Name:	D1.4

Abstract:

This deliverable captures the first set of best innovative concepts identified in the field of Advanced Multiple Antenna Systems for potential inclusion into the WINNER+ system concept. The concepts consist of promising principles or ideas as well as detailed innovative techniques. For each concept, the associated benefits as well as the corresponding requirements on the system architecture and protocols, measurements and signalling, are considered.

The document involves two main tracks: development of new advanced antenna schemes in the context of conventional cellular networks, and a study of coordinated multipoint transmission and reception, where multiple network nodes cooperate to enhance system performance.

Keywords: Advanced multiple antenna systems, Coordinated MultiPoint systems

Disclaimer:

Table of Contents

Authors

Partner	Name	Phone / Fax / e-mail
Alcatel-Lucent Germany	Thorsten Wild	Phone: +49 711 821 35762 Fax: +49 711 821 32185 e-mail: Thorsten.wild@alcatel-lucent.de
Alcatel-Lucent UK	Federico Boccardi	Phone: +44 (0)1793776670 Fax: +44 (0)1793776725 e-mail: fb@alcatel-lucent.com
Chalmers University of Technology	Tommy Svensson	Phone: +46 31 772 1823 Fax: +46 31 772 1748 e-mail: tommy.svensson@chalmers.se
Ericsson AB	Magnus Olsson	Phone: +46 8 585 30774 Fax: +46 8 585 31480 e-mail: magnus.a.olsson@ericsson.com
France Telecom	Eric Hardouin	Phone: +33 1 45 29 44 16 Fax: +33 1 45 29 45 34 e-mail: eric.hardouin@orange-ftgroup.com
	Agisilaos Papadogiannis	Phone: +33 1 45 29 63 46 Fax: +33 1 45 29 45 34 e-mail:agisilaos.papadogiannis@orange-ftgroup.com
	Ahmed Saadani	Phone: +33 1 45 29 54 05 Fax: +33 1 45 29 45 34 e-mail: ahmed.saadani@orange-ftgroup.com
Heinrich Hertz Institut	Malte Schellmann	Phone: +49 30 31002770 Fax: +49 30 31002647 e-mail: malte.schellmann@hhi.fraunhofer.de
	Lars Thiele	Phone: +49 30 31002429 Fax: +49 30 31002647 e-mail: lars.thiele@hhi.fraunhofer.de

Kungliga Tekniska Högskolan	Emil Björnson	Phone: +46 8 790 8470 Fax: +46 8 790 7260 e-mail:emil.bjornson@ee.kth.se
	Bhavani Shankar	Phone: +46 8 790 8435 Fax: +46 8 790 7260 e-mail:bhavani.shankar@ee.kth.se
	Mats Bengtsson	Phone: +46 8 790 8463 Fax: +46 8 790 7260 e-mail:mats.bengtsson@ee.kth.se

Technical University Ilmenau	Martin Fuchs	Not with TUI anymore contact: Martin Haardt Phone: +49 3677 692613 Fax: +49 3677 691195 e-mail: Martin.Haardt@tu-ilmenau.de

Telecom Italia Lab	Mauro Boldi	Phone: +39 011 228 7771 Fax:+390112285224 e-mail: mauro.boldi@telecomitalia.it
	Valeria D'Amico	Phone: +39 011 228 7544 Fax:+390112285224 e-mail: valeria1.damico@telecomitalia.it
	Bruno Melis	Phone: +39 011 228 7121 Fax:+390112285224 e-mail: bruno1.melis@telecomitalia.it

University of Oulu	Antti Tölli	Phone: +358 8 553 2986 Fax: +358 8 553 2845 e-mail: antti.tolli@ee.oulu.fi
	Petri Komulainen	Phone: +358 8 553 2971 Fax: +358 8 553 2845 e-mail: petri.komulainen@ee.oulu.fi
	Harri Pennanen	Phone: +358 8 553 2854 Fax: +358 8 553 2845 e-mail: harri.pennanen@ee.oulu.fi

Executive summary

This deliverable captures the first set of best innovative concepts identified in the field of Advanced Multiple Antenna Systems for potential inclusion into the WINNER+ system concept. The concepts consist of promising principles or ideas as well as detailed innovative techniques. For each concept, the associated benefits as well as the corresponding requirements on the system architecture and protocols, measurements and signalling, are considered.

The document involves two main tracks: in Chapter 2 the development of new Advanced Antenna Schemes in the context of conventional cellular networks are presented, while Chapter 3 reports a study of Coordinated MultiPoint (CoMP) transmission and reception, where multiple network nodes cooperate to further enhance system performance.

Chapter 2 presents multiuser MIMO techniques in the context of cellular networks comprising base stations that employ antenna arrays and mobiles with possibly multiple antenna elements. The role of multiantenna techniques here is essentially to multiplex users and data streams in the spatial domain by taking advantage of all the degrees of freedom offered by multiantenna processing. The intelligence in the network lies in base stations that gather the channel state information (CSI) towards each active mobile and perform SDMA in a centralized manner. The proposed concepts include several detailed SDMA solutions consisting of downlink spatial user multiplexing and beamforming by means of linear transmit precoding and scheduling. The first set of proposals introduces realistic and promising improvements to the WINNER II wide-area FDD solution that employs the Grid of Beams (GoB) precoding concept. The improvement arises from interference management solutions that enable either interference rejection receiver processing in terminals, or interference avoidance scheduling in the network side. These proposals are as such readily applicable to LTE as well. On the other hand, the second set of proposals introduces more revolutionary concepts. The focus there is on the careful design of CSI feedback from mobiles to the base station, in order to facilitate beam selection and efficient transmit-receive zero-forcing. Furthermore, the third set of proposals includes a generic methodology for multiuser transmit-receiver processing under various system optimization criteria. There, nearly perfect CSIT is assumed, which implies that the method is best applicable in TDD systems with low mobility users. Finally, in order to reduce complexity and to support more general protocols, a scheduler that supports generic precoder designs and multi-cell interference avoidance is proposed.

Chapter 3 deals with Coordinated MultiPoint (CoMP) systems, which is a promising emerging concept for reducing the performance discrepancies between cell-edge and inner-cell users. An overview of CoMP and a synthesis of the foreseen impacts of CoMP on the network are provided, considering in particular the aspects related to measurements and signalling, backhauling constraints, inter-access points communication requirements, and impacts on the current radio access standard architectures. The different architectures allowing coordination to be performed in radio access networks are outlined: one refers to radio over fiber (RoF) architectures, where distributed antenna modules are connected to a central station by means of fiber links. Another implementation is through coordinated multi-cell transmission, where the distributed modules are represented by the base stations. At last, relaying is also considered as a possible coordinated multipoint system scenario. The chapter is completed by a description of the possible algorithms to be applied to CoMP systems, refering both to coordination among base stations and to coordination among base stations and relaying nodes. Preliminary results showing the improved performance that the full exploitation of CoMP systems could deliver are presented as well.

List of acronyms and abbreviations

3GPP	3rd Generation Partnership Project
ACK	Acknowledged
AF	Amplify and Forward
AP	Access Point
AS	Active Set in SHO
AWGN	Additive White Gaussian Noise
AxC	Antenna Carrier
BCH	Broadcast Channel
BCI	Best Companion Index
BD	Block Diagonalization
BLER	Block Error Rate
BS	Base Station
CAPEX	Capital Expenditure
CDD	Cyclic Delay Diversity
CDF	Cumulative Distribution Function
CDI	Channel Direction Information
CI	Channel Information
CoMP	Coordinated Multipoint transmission
CPRI	Common Public Radio Interface (http://www.cpri.info)
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
CSI	Channel State Information
CSIT	Channel State Information in Transmitter
CU	Central Unit
CWER	Codeword Error Rate
DF	Decode and Forward
DFT	Discrete Fourier Transform
DPC	Dirty-Paper Coding
DL	Downlink
FB	Feedback
FBI	Feedback Information
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FER	Frame Error Rate
FFT	Fast Fourier Transform
GoB	Grid of Beams
HARQ	Hybrid Automatic Repeat Request
ICI	Inter-Cell Interference
IEEE	Institute of Electrical and Electronics Engineers
IRC	Interference Rejection Combining
IFFT	Inverse Fast Fourier Transform
IMT-A	IMT Advanced
LA	Local Area
LMMSE	Linear MMSE
LOS	Line Of Sight
LTE	Long Term Evolution of 3GPP mobile system
MA	Metropolitan Area
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MESC	Maximum Expected SINR Combiner
MIMO	Multiple-Input Multiple-Output

MISO	Multiple-Input Single-Output
ML	Maximum Likelihood
MMSE	Minimum Mean Squared Error
MRC	Maximum Ratio Combining
MS	Mobile Station
MSE	Mean Squared Error
MU-MIMO	Multiuser MIMO
NACK	Not Acknowledged
NOK	Not OK
O&M	Operation and Maintenance
OBSAI	Open Base Station Architecture Initiative (http://www.obsai.org)
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
PHY	Physical Layer
PMI	Precoding Matrix Index
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quaternary Phase Shift Keying
RAN	Radio Access Network
REC	Relay Enhanced Cell
RoF	Radio over Fiber
RF	Radio Frequency
RN	Relay Node
RRM	Radio Resource Management
RRU	Remote Radio Unit
Rx	Receive
SDMA	Spatial Division Multiple Access
SHO	Soft Handover
SIC	Successive Interference Cancellation
SINR	Signal to Interference plus Noise Ratio
SISO	Single-Input Single-Output
SMMSE	Successive MMSE
SMUX	Spatial Multiplexing
SNR	Signal to Noise Ratio
STBC	Space Time Block Codes
STD	Standard Deviation
SU-MIMO	Single-User MIMO
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TTI	Transmission Time Interval
Tx	Transmit
UE	User Equipment
UL	Uplink
ULA	Uniform Linear Array
UT	User Terminal
WA	Wide Area
WCDMA	Wideband Code Division Multiple Access
WCI	Worst Companion Index
WiMAX	Worldwide Interoperability for Microwave Access
WINNER	Wireless World Initiative New Radio
ZF	Zero-Forcing

1. Introduction

This deliverable captures the first set of best innovative concepts identified in the field of Advanced Multiple Antenna Systems for potential inclusion into the WINNER+ system concept. The concepts consist of promising principles or ideas as well as detailed innovative techniques. For each concept, the associated benefits as well as the corresponding requirements on the system architecture and protocols, measurements and signalling, are considered. The baseline system, against which the benefits of the proposed innovations are to be evaluated, is the current LTE concept enhanced by selected features from WINNER II. From multiple antenna solutions point of view, the basic characteristics are OFDMA-based Multiple-Input Multiple-Output (MIMO) transmission, fast radio resource allocation, link adaptation and retransmissions, as well as optimisation of the transmission parameters according to the user terminal velocity.

The document involves two main tracks: in Chapter 2 the development of new Advanced Antenna Schemes in the context of conventional cellular networks are presented, while Chapter 3 reports a study of Coordinated MultiPoint (CoMP) transmission and reception, where multiple network nodes cooperate to further enhance system performance.

The principal radio techniques to be considered when developing future radio systems include multiple-input multiple-output (MIMO) communication based on multiple antennas both at the transmitters (TX) and the receivers (RX), as well as adaptive modulation and coding. The spectral efficiency of MIMO transmission can be significantly increased if some level of channel state information (CSI) is available at the transmitter, allowing the system to effectively adapt to the radio channel and take full advantage of the available spectrum. The main challenge is to make the CSI available at the transmitter (CSIT). This can be achieved by conveying CSI as feedback information over the reverse link as in frequency division duplex (FDD) systems. However, providing full CSI via feedback may cause an excessive overhead on the reverse link, and hence quantised instantaneous and/or statistical CSI are preferable in practice. A time division duplex (TDD) system uses the same carrier frequency alternately for transmission and reception, and thus the CSI can be tracked at the transmitter during receive periods, provided that fading is sufficiently slow and the radio chains are well calibrated.

Chapter 2 discusses multiuser MIMO techniques in the context of cellular networks comprising base stations that employ antenna arrays and mobiles with possibly multiple antenna elements. The role of multiantenna techniques in multiuser environments is essentially to multiplex users and data streams in the spatial domain by taking advantage of all the degrees of freedom offered by multiantenna processing. The intelligence in the network lies in base stations that gather CSIT towards each active mobile and perform SDMA in a centralized manner.

Future cellular networks will need to provide high data rate services for a large number of users, which requires a high spectral efficiency over the whole cell area, including the cell edge area. This however can not be achieved by increasing the signal power, since multi-cell systems become interference limited as each BS processes in-cell users independently, and the other users are seen as inter-cell interference.

As described in Chapter 3, one strategy to reduce the performance-limiting interference is to reduce the Inter-Cell Interference (ICI) with the aid of Coordinated MultiPoint (CoMP) systems, sharing and reusing the degrees of freedom available to the network. With CoMP, theoretically, deploying joint processing over all the distributed transmitters, the impact of inter-cell interference can be fully eliminated. Generally, CoMP refers to a system where several geographically distributed antenna modules coordinate to improve performance of the served users in the joint coordination area. The coordinated antenna modules are connected via dedicated links (e.g. fibers, a wired backbone connection or highly directional wireless microwave links [ZTZ+05]), or connected to a central control unit.

There has been significant interest towards network infrastructure based cooperative processing between distributed BS antenna heads [ZTZ+05, ABE06, DMH06, KFV06, SZV02, SSB+06, Wyn94]. In [Wyn94], it is shown that a cellular network with a global joint-processing receiver significantly outperforms a traditional network with individual processing per BS. After the pioneering work of Shamai, Jafar et al., BS cooperation has been studied by several authors, e.g. [DMH06, KFV06, SSB+06, SSB+07, ZMM+07]. For example, Somekh et al. [SSB+06, SSB+07] provided an information theoretic analysis of distributed antenna systems under the Wyner model [Wyn94].

Coordinated multi-point systems are being considered as a promising technique for increasing capacity of new radio access systems in several standard organisations as well. In the framework of 3GPP, several contributions related to receivers/transmitters coordination in the access network have been presented in the recently opened LTE-Advanced study item (see [3GPP36814] for the current agreements about CoMP). These approaches are also considered in the WiMAX standardisation framework; see e.g. [MHM+08] for a classification of related contributions.

Different architectures can be considered under the term of CoMP; it can be both based on Radio over Fiber architectures or on an enhanced cooperation among traditional radio base stations. Under the framework of CoMP, possible synergies among relay nodes and related radio base stations are introduced as well.

2. Advanced Antenna Schemes

This chapter discusses multiuser MIMO techniques in the context of cellular networks, comprising base stations that employ antenna arrays and mobiles with possibly multiple antenna elements. The role of multiantenna techniques in multiuser environments is essentially to multiplex users and data streams in the spatial domain by taking advantage of all the degrees of freedom offered by multiantenna processing. The intelligence in the network lies in base stations that gather CSIT towards each active mobile and perform SDMA in a centralized manner. All the techniques proposed here rely on linear transmit precoding and receiver processing.

The downlink MIMO solution adopted by both WINNER II and LTE for FDD systems in wide-area cells is based on pre-defined codebooks or transmit precoder sets. In WINNER II the approach is called Grid of Beams (GoB), as the precoders essentially form geographically separable narrow beams. Beam selection is based on feedback received from each mobile. In multibeam mode several users may be served simultaneously by the same cell or sector, which results in intra-cell interference between users. Furthermore, especially for cell-edge users some of the beams from neighbouring cells may form a significant source of interference. Section 2.1 proposes advanced methods for enhancing the performance of networks employing GoB. The proposed methods include interference mitigation by receiver processing, as well as feedback design to facilitate interference avoidance by cooperative multicell scheduling.

Another approach for downlink multiuser MIMO is to allow highly adaptive generic precoder design that does not employ pre-defined precoder sets. The approach allows the base station more freedom to control or nearly null intracell interference. In Section 2.2 two methods for downlink multiuser zero-forcing by transmit-receive processing based on limited feedback are presented. The first scheme is based on feedback of CSI, where the channel quantization is based on hierarchical codebooks. The hierarchy can take advantage of slow channel fading rate, as the CSIT is refined over several feedback periods. The second scheme proposes to use a combination of long term channel statistics and instantaneous feedback from the mobile. The channel statistic can be gathered via low-rate feedback in FDD mode or alternatively by reverse link measurements in TDD mode. Again, the long-term statistics are most useful when the MIMO channel has strong and slowly changing directional components.

In networks employing TDD, nearly perfect instantaneous CSIT can be obtained in the transmitter. This allows more advanced or accurate multiuser interference balancing or zero-forcing to be performed by the base station. The benefits of TDD are best available in local and metropolitan area deployments. Section 2.3 presents a downlink joint linear transmit-receive optimisation methodology for various optimisation criteria. Additionally, zero-forcing for both downlink and its reciprocal uplink is discussed. One benefit of zero-forcing is that it decouples the beamformer power and rate allocation from the precoder design. However, careful beam and user selection is required in order to avoid extensive zero-forcing loss. Finally, a low-complexity user scheduling and beam selection method developed in WINNER II, ProSched, is described.

2.1 Enhancements for codebook based multi-antenna transmission

This section presents advanced methods to interference mitigation and avoidance for the cellular multiantenna downlink transmission systems employing codebook based precoding where the downlink transmit precoders are chosen from pre-defined sets, based on the feedback received from the terminals. In the proposed methods, both intra-cell and inter-cell interference are considered.

The adaptive FDD MIMO transmission solution developed in WINNER II [WIN2D61310] for wide-area environments is based on fixed unitary pre-coding weights derived from the DFT matrix. The concept is called Grid of Beams (GoB), since when employed with uniform linear antenna arrays, the precoders form directional beams. The contributions presented in this section are well aligned with the GoB concept. However, more general precoding and antenna array geometries can be readily supported as well. Due to the codebook-based nature, the proposals can also be easily embedded into the LTE standard.

2.1.1 Adaptive MIMO mode switching with different levels of multi-site cooperation

2.1.1.1 Multisite MIMO cooperation modes

In multicell systems employing codebook based downlink transmit precoding, different levels of cooperation between neighbouring cells can be applied. In a certain time-frequency resource, a mobile can be served in one of the following MIMO modes:

A. SU-MIMO: Multiple spatial data streams towards a single user
B. MU-MIMO: Multiple spatial data streams towards multiple users
C. Spatial interference avoidance based on beam coordination: Exchanging resource restrictions to avoid spatial collisions
D. Cooperative MIMO: Serving one or more users from two or more different sectors/sites, e.g. by a combination of beamforming and distributed space-frequency block coding

Figure 2.1 outlines the basic approaches of the different modes for an example of closely spaced linear array antennas using linear precoding codebooks for fixed beams. A coordination cluster of three different sites is shown, each having 3 sectors (coloured in yellow, blue and red). 8 beams are used within each sector, the main lobes of their antenna patterns are sketched in the figures – numbers are indicating the beam indices.

A concept for inter-cell interference mitigation by receiver processing in mode B is proposed in section 2.1.2, and a feedback concept for spatial interference avoidance (mode C) based on beam coordination is described in section 2.1.3. Cooperative MIMO (mode D) can be seen as an extended combination of macro diversity and MU-MIMO. There are coherent approaches [HKK+08], called network MIMO, and incoherent ones [SCW+07b]. For the FDD mode due to limited CSIT, the incoherent approach is the more relevant one.

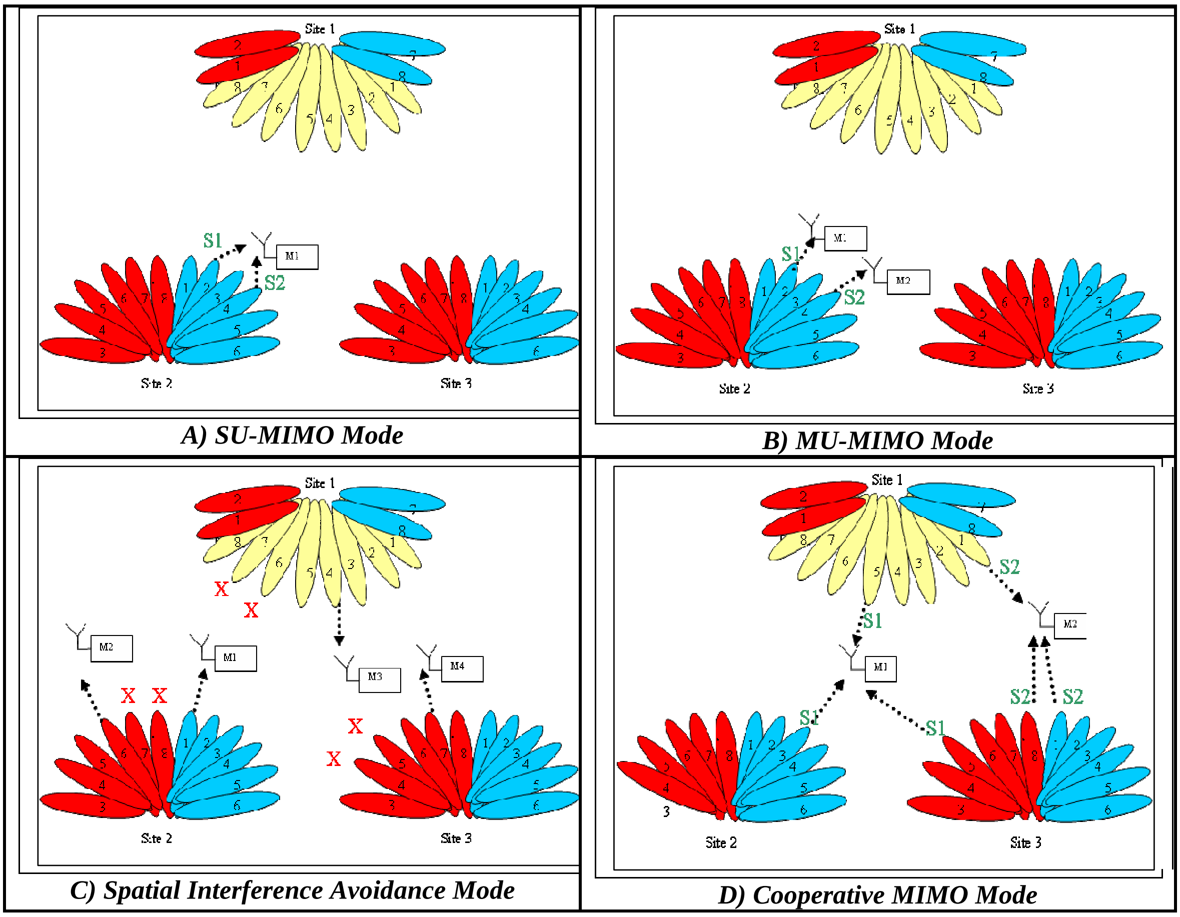


Figure 2.1: Multi-site cooperation modes

2.1.1.2 Adaptive MIMO mode switching

The demand for higher spectral efficiency and higher cell edge user rates in future mobile communication systems is increasing. Existing systems are limited by inter-cell interference. The intention of this contribution is to approach those limitations in a wide area FDD downlink scenario with multi-antenna base stations by controlling the inter-sector and inter-site cooperation.

In the proposed concept, mobile terminals are switched between different MIMO modes, depending on their SINR operating point. In order to keep the backhaul traffic in a moderate size, user data between base stations should only be exchanged when it is beneficial for a particular user to be served from different cells. On the other hand, interference avoidance by restricting the use of certain space-time-frequency resources in the neighbouring cells, should only be applied for mobiles, which are at a certain low SINR operation point.

The aim of the mode switching is:

- To find the right trade-off between cell border user throughput, summed average cell throughput and peak throughput.
- To keep the necessary backhaul traffic at a tolerable limit.
- To cope with limited feedback of channel state information.

2.1.1.3 Expected requirements on signalling and measurements

The signalling of the WINNER II wide area spatial processing concept can be reused, based on best beam index feedback and frequency selective CQI. This also fits well to LTE signalling based on PMI and CQI. On top of this, extra backhauling with low latency is necessary for the multi-site coordination case. In the LTE terminology this will happen via the X2 interface. Mode C requires only small amount of information exchange for the control plane, whereas mode D requires more information exchange as user data has to be available at multiple sites.

The mode switching uses modes C and D that require backhauling only for those users which significantly benefit from these modes to keep the required backhauling capacity as low as possible.

2.1.1.4 Expected requirements on architecture and protocols

Modes C and D will require either a central unit which serves as a joint scheduling entity for a coordination cluster or an architecture allowing to share responsibilities on a low-latency level between base stations. In order to keep the changes to the existing architectures of WINNER II and LTE low, it is suggested to use the second option where some kind of master-slave relationship can be established between base stations of a coordinated cluster.

2.1.1.5 Conclusion on the proposed concept

This concept uses small additions to the WINNER II and LTE assumptions in order to extend the capabilities and the performance of the system, without requiring large changes to the standards. It allows a mix of non-cooperating and cooperating modes.

2.1.2 Practical Performance Limitations of Adaptive MIMO transmission in Wide-Area

To enable ubiquitous broadband wireless access, MIMO transmission must be made robust against multi-cell interference. However, it is not fully evident yet how the potential capacity gains of MIMO can be realized under these conditions. In fact, early results indicate only small capacity gains of spatial multiplexing (SMUX, multi-stream transmission), compared to the classical spatial diversity (SDIV, single-stream transmission) in the interference-limited case [CDG01]. Further work has illustrated that SMUX increases peak rates for users close to the cell center, while SDIV enhances the user throughput at the cell edge [ZT03]. Hence, it might be helpful to switch between these two transmission modes, depending on the actual channel condition [HP05].

Joint ”dirty-paper” pre-coding achieves the capacity of the broadcast channel [CS03] and thus it is considered as an upper bound for the performance in multi-user environments. However, the BS would need coherent channel state information, which is difficult to obtain in frequency division duplex (FDD) systems, as a high rate feedback link may be required. Targeting a practical solution, we consider to report indices of fixed pre-coding beams together with adequate CQI information via a low-rate feedback channel. In particular, we use post-equalization signal to interference and noise ratios (SINRs) as CQI. With this limited feedback approach, bandwidth and latency requirements for the feedback can be relaxed. In [TSZ+07] we have shown that on basis of this approach, the fundamental capacity scaling law - being proportional to the minimum of the number of receive and transmit antennas - can be realized also in multi-cell environments.

2.1.2.1 Description of the concept

In WINNER phase II [WIN2D61310], an adaptive MIMO transmission was proposed based on limited feedback for the application in FDD systems deployed in the Wide-Area scenario. The concept is based on fixed unitary pre-coding weights (GoB), which are derived from the DFT matrix. The UTs are assumed to provide frequency-selective CQI feedback for both single- and multi-stream transmission (Figure 2.2). In particular, we perform an optimization with respect to the SINR conditions at the receiving side and thus consider the achievable post-equalization SINRs per chunk as CQI. At the BSs we use an extended score-based scheduler [STJ+07], which is able to switch adaptively between single- and multi-stream transmission, depending on the reported CQIs. In case of multi-stream transmission the scheduler considers SU-MIMO and MU-MIMO, i.e. the system may benefit from higher spectral efficiencies due to multi-user diversity gains and SDMA. The performance under ideal conditions has been evaluated for a full coverage multi-cellular network [TSZ+07].

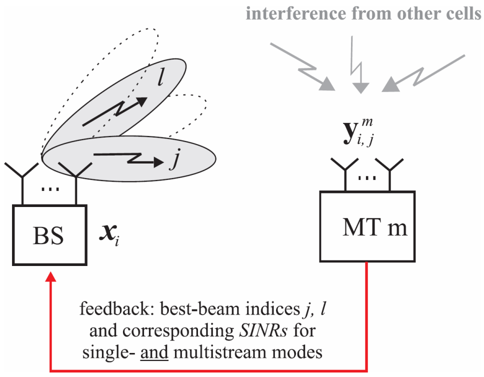


Figure 2.2: Assuming multiple antennas at the base station and terminal side, respectively, SINR feedback is provided by the terminal for possible transmission modes using a narrow band feedback channel.

2.1.2.2 Expected benefits

The performance in Figure 2.3 is evaluated in a multi-cellular simulation environment including the channels of 57 sectors in total with 4 λ spaced ULAs. 20 UTs are dropped in the center cell, which consists of three hexagonal sectors. The UTs are assumed to perform IRC. One of the elementary assumption is the ideal knowledge of all serving and interfering channels. The SINR to rate mapping is achieved by using the advanced coding and modulation (ACM) scheme from [WIN2D223] with K=1152 bits of codeword length and CWER=0.01.

We observe a capacity increase of the mean sector spectral efficiency by a factor of 1.9 for the adaptive MIMO 2x2 and by 3.5 for the adaptive 4x4 system with respect to the SISO reference case. The 5%-tile of the normalized user throughput, which may serve as a measure to represent the throughput of cell-edge users, shows similar scaling behaviour.

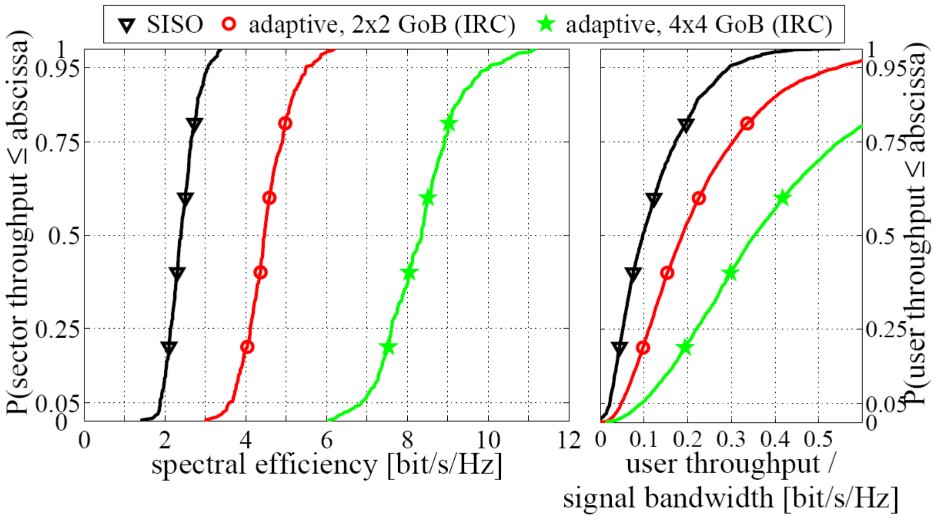


Figure 2.3: Compares the sector and user throughput for the SISO, MIMO 2x2 and MIMO 4x4 system, while meeting fairness constraints for 20 UTs assigned to the BS.

2.1.2.3 Expected requirements on signalling and measurements

The proposal for system implementation in practice is as follows:

1. Synchronize downlink transmission from all base stations with respect to carrier frequency and frame start
2. Use multi-cell channel estimation as suggested in section B.1.
3. Since the concept is based on fixed pre-coding beams, dedicated pilots are not required to obtain pre-coded channel knowledge. Thus, system concept is kept simple and cochannel interference ensured to remain predictable for the user terminals without any additional pilot overhead.
4. Employ correlation-based covariance estimation as suggested in section A.1.2.2 at the terminal side for the design of the MMSE equalization filters.

2.1.2.3.1 Channel estimation errors and their impact on IRC

The performance of the IRC approach strongly depends on the achievable precision for the required system's covariance matrix. This knowledge may be gained by utilizing the received signal or by estimating the channels of the desired and interfering signals. Both techniques give rise to estimation errors that may degrade the system performance. A brief comparison may be found in the appendix A.1 and a more detailed version in [TSW+08]. We investigate the quality of different estimates that can be achieved by different estimation techniques and quantify the performance degradation caused by channel estimation errors.

2.1.2.3.2 Feedback delay for mobile users

The feedback delay may become a critical issue if the channel is time-variant, which occurs if the user terminals are moving. Time-variance of the channel results in the fact that the SINR conditions may have changed significantly when the resource allocation that has been decided by the scheduler based on previous SINR conditions is being applied for transmission. In case the SINR conditions drop down, a collapse of the system performance is inevitable. First results for an isolated cell can be found in [STJ08].

2.1.2.4 Conclusion on the proposed concept

An adaptive MIMO transmission system based on limited feedback for the application in FDD systems deployed in the Wide-Area scenario has been proposed in WINNER phase II. It has been shown that a capacity increase of the mean sector spectral efficiency by a factor of 1.9 for the MIMO 2x2 and by 3.5 for the 4x4 system with respect to the SISO reference case can be achieved. Our investigations, which had been carried out under ideal conditions, were extended to include several impairments of the system design.

We examined the impact of impairments on the achievable system performance, which occur in a practical system setting, like channel estimation errors or the feedback delay in mobile environments. The work comprises the elaboration on adequate techniques to estimate interfering and desired channels. A further issue concerns feedback design, where adequate compression techniques should be found to match the amount of feedback data to predefined constraints. [JTW+H08] quantifies the minimum amount of feedback bits per SINR value, which are required to ensure an efficient adaptive MIMO transmission. These results are obtained from measurement data and a multi-cell simulation environment.

2.1.3 Intra-cell and inter-cell interference avoidance by partial CSIT sharing

2.1.3.1 Description of the concept

The objective of this concept is to reduce intra-cell and inter-cell interference in downlink FDD MIMO systems with codebook-based linear precoding. A novel signalling concept is introduced here, called "Best companion". The aim of the "best companion" concept is to introduce additional codebook-based channel state information in addition to existing best weight indices (called PMI in the LTE terminology) in order to reduce the interference in the overall system. Intra-cell interference will be reduced by better support of MU-MIMO pairing. Inter-cell interference will be reduced by exchanging codebook-based interference information between sites.

2.1.3.1.1 Approach for avoiding intra-cell interference in MU-MIMO (mode B)

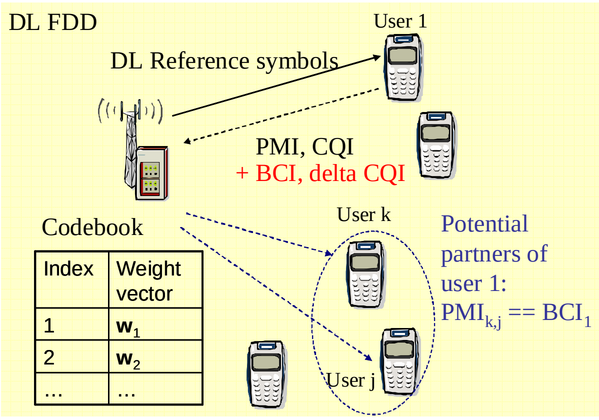


Figure 2.4: Improved reporting scheme for MU-MIMO mode

- The UEs measure the channel and report the best beam index (rank1 PMI) for their serving cell, i.e. the codebook index of the own transmit weight which maximises the SINR at the receiver output (depending on receiver algorithm supported by UE), taking into account noise and inter-cell interference.
- The UEs report so-called best-companion indexes (BCI) for the serving cell, i.e. the codebook index of a potential co-scheduled interferer which maximises the SINR at the receiver output, e.g. a linear MMSE receive matrix which is calculated based on PMI and candidate BCI.
- The UEs report the CQI for the case that the BCIs are *not* used. For the case that the best BCIs are used a delta-CQI is reported.

In order to minimize intra-cell interference, based on this additional information [Alc08], for dual stream MU-MIMO, the base station now can pair two users *n*, *m*, where the PMI of *m* is the BCI of *n* and vice versa. As a result, spectral efficiency will be increased.

2.1.3.1.2 Approach for avoiding inter-cell interference (mode C)

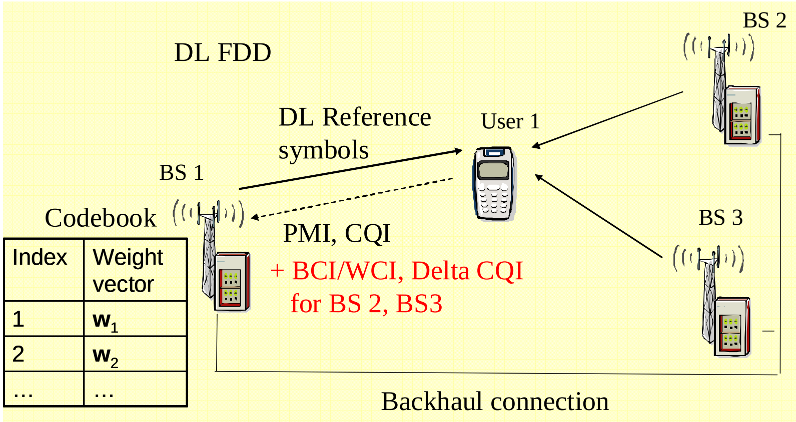


Figure 2.5: Improved reporting scheme for intercell-interference-avoidance mode

- The UEs measure the channel and report the best beam index (preferred rank 1 PMI) for their serving cell.
- The UEs further measure the channels from a set of dominant interfering cells.
- The UEs report BCIs or worst-companion PMIs (WCI) for the set of interfering cells.
- The UEs report the CQI for the case that the best-companion PMIs are *not* used and for the case that the best companion PMIs are used or the worst-companion PMIs are not used (the latter may be in the form of a delta-CQI).

In order to minimize inter-cell interference, based on this additional information ([Alc08], [Sam08]), beam coordination can now occur. E.g. for WCI-reporting, a centralized scheduler over low latency backhaul can now schedule users of different cells such that on a given time-frequency resource, no interference from reported WCIs will occur, thus reducing the overall interference of the system. As a result, especially cell edge user throughput will be increased and also spectral efficiency of the system.

2.1.3.2 Expected performance or benefits

Simulation results for mode B are described in detail in Appendix A.2. The results show a performance gain of +16% for an urban macro channel and a gain of +22% for an urban micro channel in terms of average cell throughput.

2.1.3.3 Expected requirements on signalling and measurements

The signalling of the WINNER II wide area spatial processing concept can be reused, based on best beam index feedback and frequency selective CQI. This also fits well to LTE signalling based on PMI and CQI. On top of this, extra backhauling with low latency is necessary for the multi-site coordination case. In e.g. the LTE terminology this will happen via the X2 interface.

A small addition to the existing signalling concept are the proposed BCI in mode B and WCI in mode C, as well as delta-CQI that the UEs need to report to the network. The additional signalling overhead will be small. According to the simulation settings of Appendix A.2 an additional UL feedback overhead of 0.8 kbit/s per MU-MIMO user is required in mode B to obtain the above mentioned performance gains.

2.1.3.4 Expected requirements on architecture and protocols

Mode C will require either a central unit which serves as a joint scheduling entity for a coordination cluster or an architecture allowing to share responsibilities on a low-latency level between base stations. In order to keep the changes to the existing architectures of WINNER II and LTE low, it is suggested to use the second option where some kind of master-slave relationship can be established between base stations of a coordinated cluster.

2.1.3.5 Conclusion on the proposed concept

This concept uses small additions to the LTE and WINNER II assumptions in order to extend the capabilities and the performance of these systems without requiring large changes to the standards.

2.2 Feedback methods for multiuser MIMO zero-forcing

This section introduces feedback methods for supporting downlink multiuser MIMO zero-forcing by transmit-receive processing. The methods are presented in the context of a single-cell system.

2.2.1 Joint transmit-receive optimisation and user scheduling for FDD downlink

MU-MIMO techniques require channel state information at the transmitter (CSIT) in order to achieve spatial multiplexing across users. If CSIT is known ideally, an effective and relatively simple linear transmission technique is known as zero-forcing (ZF) beamforming where each user is served by a user-specific beam and receives no interference from the other users' beams [YG06]. If users have multiple antennas, spatially multiplexed users could each receive spatially multiplexed data streams [SSH04,CM04,VVH03]. The assumption of ideal CSIT may not be unreasonable under time-division duplexing (TDD) where the same band is used for the uplink and downlink. In this case, CSIT for the downlink can be obtained through channel estimation on the uplink. However ideal CSIT is not an appropriate assumption under frequency-division duplexing (FDD). In this case, the base station must rely on uplink feedback from the mobiles to obtain CSIT. In cellular systems, limited uplink bandwidth allows only a few bits of feedback during each interval, resulting in limited, non-ideal CSIT. Furthermore, user mobility only makes the CSIT more unreliable.

Typically, the feedback bits are used to index a set of vectors (or codewords) in a codebook *C* which is known to the transmitter and all receivers. For example, B bits per feedback interval can be used to index a codebook with 2^B vectors. For a transmitter with M antennas, each codeword in *C* is an M-dimensional vector that characterizes the MIMO channel for that user. A well-designed codebook will contain codewords that effectively span the set of MIMO channels experienced by the users.

2.2.1.1 Description of the concept

We propose a multiuser MIMO transceiver architecture and methodology under the assumption of limited CSIT, based on linear zero-forcing beamforming and linear receiver combining. This proposal is motivated by a downlink FDD cellular network where a base station equipped with M>1 antennas serves a large number (K>M) of users, each equipped with N>1 antennas. The channel is first estimated by each user, and CSI feedback and the receiver combiner for each user are jointly computed to maximize a novel metric based on the signal-to-interference-plus-noise ratio (SINR) at the combiner output. Because the actual SINR achieved during data transmission is a function of the beamforming weights, but because users cannot know the beamforming weights in advance, the metric is based on an expectation of the SINR. We call this combining strategy the *maximum expected SINR combiner* (MESC). Once the transmitter receives the CSI feedback from all K users, it determines the set of users to serve in order to maximize the weighted sum rate. During the data transmission, serviced users can demodulate the data using the previously derived MESC or using an enhanced combiner that requires knowledge of the beamformed MIMO channel for maximizing the actual SINR. The proposed MESC is related to a previous ideal-CSIT technique [Boc07, BH07], and it is a generalization or extension of limited-CSIT techniques [Jin07, TBT07, BHT07]. In Appendix A.3, we give some details about the proposal.

2.2.1.2 Expected performance or benefits

The performance of the proposed MU-MIMO architecture will depend on how well the quantized vectors in the codebook span the realizations of the MIMO channels. The problem of finding the optimal vector quantizer for a MU-MIMO system is not solved in general. In [LH04, LHS03] the problem of maximizing the throughput of a MIMO single user system with limited feedback has been shown to be equivalent to the problem of packing one dimensional subspace known as Grassmannian line packing. This approach has been studied for MU-MIMO systems e.g. in [AG07]. Nevertheless, in our best knowledge, the optimality of Grassmannian packing has not been extended to the MU case. For spatially uncorrelated channels, random codebooks have been shown to perform well, when the number of feedback bits is not small. Alternatively, other codebook designs have been proposed for highly correlated channels [Sam06, BHA07], but their performance is very low in the case of spatially uncorrelated channels. The hierarchical structure of the latter allows reduced feedback in time-correlated channels but both perform poorly in spatially uncorrelated channels. In [TNL+98] the Lloyd algorithm is used for a point-to-point MIMO transmission in order to find the quantization region that maximizes the SNR.

In order to propose a more practical, highly adaptable technique for generating codebooks suited for *any* antenna configuration and level of spatial correlation, we will study codebook generations based on the Lloyd-Max algorithm, extending the results previously proposed in [TNL+98, BCT+07] and other papers. In practice, codebook generation would be performed offline for a large variety of channel environments, and each user would measure the MIMO channel statistics and load an appropriate codebook from memory. Different codebooks can be loaded if the mobile moves to a different spatial environment, for example, from outdoors to indoors. Our proposed codebook design creates a nested structure that lends itself to hierarchical indexing. As a result, CSI feedback can be accumulated over multiple signalling intervals in order to index a much larger codebook which results in improved performance for low mobility users. We will show an example of a simple hierarchical feedback strategy.

The proposed class of techniques will be tested and compared with other proposals (in particular with fixed beams based proposals) by means of a single-carrier system level simulator, where long-term proportional fairness is guaranteed among the users in the network. System simulation results are available in Appendix A.3.

2.2.1.3 Expected requirements on signalling and measurements

The proposed technique requires a two phase pilot signalling between base station and user terminals. Firstly, common pilots are sent to all the candidate users. Then, after the precoding matrix is generated, dedicated pilots are needed for the set of scheduled users only.

2.2.1.4 Conclusion on the proposed concept

The focus is on extensions of previous proposals [Jin07, TBT07, BHT07] to the case of multiple receive antennas, and joint design of the receive beamformer and of the vector quantizer. Quantization codebook design is also considered for different types of propagations scenarios, including successive refinement of the quantization (hierarchical quantization). Finally, the performance is assessed by analytic studies and multicell system simulations. Comparison with other approaches, like fixed beams SDMA schemes, will be carried out in the future.

2.2.2 Efficient feedback schemes combining long term and short term information

As is well-known, having access to channel state information (CSI) at the transmitter of a multiple antenna system, can boost the data rate but also requires increased signalling overhead. One possible exception that does not require increased signalling, is TDD systems with well-calibrated radio chains, where channel reciprocity can be exploited to estimate the downlink channel during the uplink transmission and vice versa.

However, even in the case of FDD or TDD with too long delays between uplink and downlink, long term CSI, i.e. the second order statistics of the CSI, can be collected at the base station using low rate feedback from mobile terminals. This would require little overhead as the statistics are assumed to vary slowly in comparison to the instantaneous channel realization. Alternatively, if the transmit and receive chains are properly calibrated at the base station, the downlink channel statistics can be estimated directly at the base station from the uplink, even for FDD systems [CHC04]. As was shown in [WIN2D341], such long term information can be combined with different forms of short term CQI. These ideas will here be developed further with extensions from MISO to full MIMO, optimized quantization strategies and more investigations of joint scheduling and precoding. Collecting long term statistics on the reverse link can not only be used to characterize channels to desired receivers but also gain some information on the unwanted (intra-cell or inter-cell) interference that a transmitter can cause on other receivers.

2.2.2.1 Description of the concept

We consider the downlink of a multi-user system with multiple antennas at each end. The transmitter has covariance information about the channels for each user. Each user, in addition to the covariance information, also estimates the instantaneous channel based on pilot transmissions. For this scenario, literature presents several transmission and reception strategies that enhance a performance metric under fairness assumptions.

In this proposal, we consider additional CQI information at the transmitter in the form of quantized feedback. This information reflects the instantaneous channel state and is of sufficiently low dimensionality so as to keep the feedback overhead at a minimum. The problem would then be to find the optimal transmission and reception scheme given the additional information and evaluate the performance gain compared to the case without quantized feedback. However, we assume that the base station employs transmit beamforming and scheduling while the receiver employs interference cancellation. Under this assumption, we formulate a framework for evolving transmission and reception schemes based on:

1. Devising a feedback strategy: This involves choosing the parameter to be fed back and the quantizer to be designed.
2. Choice of beamformers given the available information at each end.
3. Choice of the scheduling policy based on the available information.

Different schemes can be obtained by altering the metrics in any or all of the steps mentioned above. Such schemes have to be compared with prevailing techniques like Opportunistic beamforming and Beamforming quantization

Feedback supported eigenbeamforming

In this scheme [BO08], the channel covariance matrix of any user is partitioned into different eigenspaces and the transmit beamformer is chosen so as to have a large component along the dominating eigenspace. The transmit beamformer is known at the receiver by virtue of the knowledge of covariance matrix. The receiver uses the covariance information to devise a beamformer that cancels instantaneous interference with non-negligible power. The number of modes to be cancelled by the receiver beamformer is a design parameter. The problem becomes interesting with the use of a scheduler. Additional information in the form of user’s rate or Signal to Interference Noise Ratio (SINR) is needed even by the simple scheduler that performs greedy maximization of weighted sum rate. The SINR is unknown at the transmitter as it is not privy to the receiver beamformer. In the Feedback supported Eigenbeamforming scheme, a scalar variable indicating the effective channel norm is fed back using a quantizer. Assuming that the feedback link is lossless, an estimate of the user’s SINR can be obtained at the transmitter. A design parameter whose choice governs the over-estimation of SINR is also incorporated. The obtained estimate has a closed form expression involving the feedback variable and the channel statistics. With the estimates of SINR in place, a greedy low complexity scheduling is used. Further details are presented in Appendix A.4.

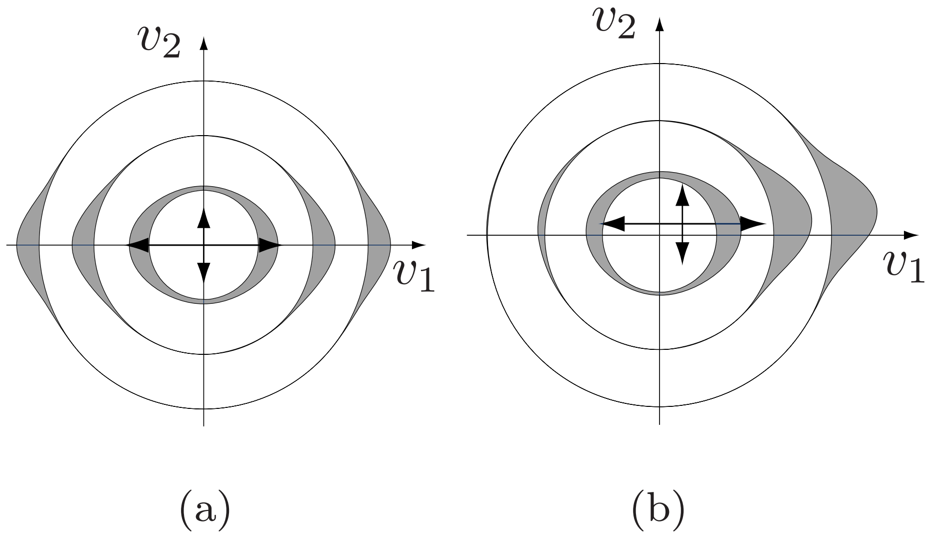


Figure 2.6: Illustration of the spatial channel information given by different norms (SNRs) in the two-dimensional real-valued channel case. Here, v_1 and v_2 are independent Gaussian random variables and the channel norm, ρ, is the distance from the center of coordinates to the realization (i.e., which circle it is on). The shaded areas show the distribution of conditional density $f(v_1, v_2| \rho)$. The inner arrows indicate the standard deviation (v_1 having larger variance than v_2) in each direction, and their crossing the mean value. The probability mass becomes more focused for higher SNRs. Thus $f(v_1, v_2| \rho)$ indicates correlation even though v_1 and v_2 are independent, thereby highlighting the spatial information provided by the channel norm.

The motivation arises from the fact that an isotropic quantity like channel norm contributes substantial directional information when combined with the statistics, while maintaining a compact representation. Moreover, the higher the channel norm, the more accurate would the directional information be. The intuition behind this is illustrated in Figure 2.6 (a) and (b) for the Rayleigh and Ricean case, respectively.

An alternative approach using quantization code books based directly on the full channel matrix has been reported in [KBS07]. These results did not exploit any long-term CSI.

2.2.2.2 Expected performance or benefits

Preliminary results for a single cell downlink multi-user MIMO system using proportional fair scheduling have been presented in [BO08] and are repeated here for completeness.

Figure 2.7 compares the throughput of opportunistic beamforming with the Feedback supported Eigenbeamforming scheme for a highly loaded cell with 32 users, each having 4 antennas. The base station has 8 antennas and the channel norm is quantized using 0, 1, 3 or 5 bits. Channels were generated according to the ‘Local Scattering Channel model’. The parameters of this model are chosen to correspond to an isotropic scattering at the receiver and an angular spread of 15^o at transmitter. It is clear that just single feedback bit is required per user to achieve 50% the gain of unquantized channel norm feedback, while 98% of the feedback gain is achieved using 5 feedback bits.

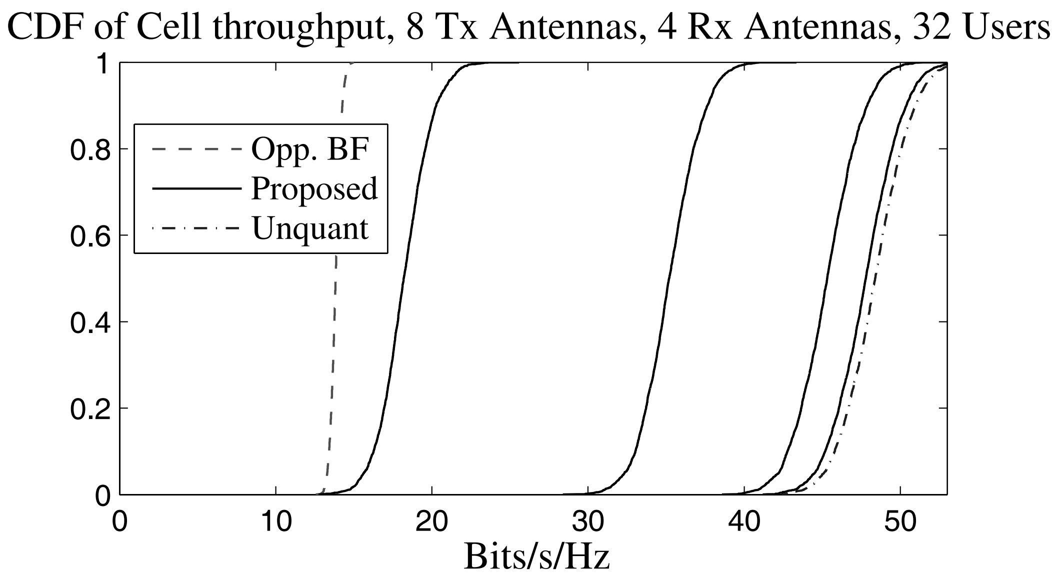


Figure 2.7: The CDF of the average cell throughput for a cell with an eight-antenna base station and 32 four-antenna users. The throughput of opportunistic beamforming and channel norm supported zero-forcing beamforming with exact feedback is compared with the latter scheme using 0, 1, 3, or 5 bits of feedback per user (increasing performance).

2.2.2.3 Expected requirements on signalling and measurements

The goal is to minimize the signalling related to CSI and CQI. The number of bits per channel realization is a design parameter and the performance is optimized for the given feedback rate. The proposed CQI based on the channel norm can be used with only common pilots, i.e. no dedicated pilots are required. The feedback is compatible with LTE ver 8 as it can utilize the CQI reporting of LTE. Also, if the scheduling rate is quicker than the channel variations, the same CQI can be used in several scheduling slots. As long as the long term information can be estimated on the reverse link, no additional measurements or signalling is needed.

2.2.2.4 Conclusion on the proposed concept

Some results and system level simulations based on these ideas were presented already in WINNERII [WIN2D341]. The intention is to extend these from MISO to full MIMO. There are also many open questions, especially related to predicting interference levels and using the available information for interference suppression. While single stream per user is considered at present, some experiments have been undertaken with multiple streams per user and further investigation of the same is underway. Combining space-time codes with beamforming also constitutes an area of interest within the proposed framework.

2.3 Resource allocation schemes for TDD systems

This section proposes advanced methods for resource allocation and multiuser MIMO precoding in cellular TDD systems, where the same carrier frequency is used alternately for transmission and reception. The typical assumptions for the operating scenario are:

- The cell sizes are relatively small and located in urban metropolitan and/or hot-spot areas.
- Use of multiple TX/RX antennas is feasible in advanced terminal equipment.
- Low TX powers are adequate due to short distances, so that very high data rates are possible also in uplink.

Furthermore, it is generally assumed that instantaneous CSI can be estimated and tracked at the transmitter side for precoding purposes, as:

- Uplink and downlink MIMO channels are reciprocal.
- The transmit and receive RF chains in all transceivers are well calibrated.
- User mobility is low, and the channel changes slowly so that the coherence time is longer than a TDD frame.
- Pilot signal is available for sounding the reverse link corresponding to the transmit subcarriers.

In order to facilitate multiuser MIMO precoding in the downlink direction, mutually orthogonal uplink pilot signals were defined in WINNER II. The number of mobile antennas to be served in the same resource block defines the amount of orthogonal pilot resources needed. Thus the number of users that can be tracked simultaneously is limited by pilot overhead. Note that the uplink pilot is needed to keep the downlink MIMO channel open even when the mobile has no data to transmit. If the traffic in uplink and downlink is relatively symmetric, the same subcarriers can easily be allocated to the same set of users in both directions. In this case the pilots embedded to data, for the purpose of coherent detection, can be re-used as a reference for transmit precoding as well, as suggested in Section 2.3.2.

Even if perfect CSIT is available in TDD systems, some form of scalar feedback is needed to support rate allocation and adaptive modulation. This is due to the fact that the interference levels are not reciprocal, and the transmitter should know the SNR seen by the receiver.

2.3.1 Downlink resource allocation for multiuser MIMO-OFDM TDD system with linear transceiver processing

A major challenge for wireless communication systems is how to allocate resources among users across the space (including different cells), frequency and time dimensions and jointly design all the transceivers with different system optimisation objectives. Advanced multi-user MIMO resource allocation and scheduling techniques can be used in both the UL and the DL to allocate resources across different dimensions. While dirty-paper coding (DPC) is known to be a capacity achieving albeit very complex non-linear precoding technique in the DL [VT03, WSS06], linear precoding/beamforming is much simpler to implement to perform multi-user transmission. Hence, the linear beamforming is an important solution in practical system design. Unlike the sum-rate capacity of the MIMO broadcast channel using the DPC, the sum rate achieved by optimal beamforming cannot be written as a convex optimisation problem [SH07]. Yet, despite its sub-optimality, beamforming combined with a proper selection of users/beams has been shown to be asymptotically sum-rate optimal [SH07, SH05, YG06]. In general, a solution for any allocation problem with linear transmission can be divided into user selection or grouping for each orthogonal dimension (frequency/sub-carrier, time), and the linear transceiver optimisation for the selected set of users per orthogonal dimension subject to a power constraint.The allocation problem remains unresolved for a large variety of optimisation criteria, especially when combined with practical modulation and coding schemes as well as user specific Quality of Service (QoS) constraints. The problem is a difficult non-convex combinatorial problem with integer constraints and finding jointly optimal solutions is most likely intractable [LZ06, SSO07]. Therefore, efficient sub-optimal solutions are required in practice.

2.3.1.1 Description of the concept

The focus in this concept is on spatial user scheduling with greedy beam/user selection combined with various linear transceiver design techniques with a near perfect transmitter CSI. The proposed greedy beam allocation allows efficient grouping of non-interfering users and/or streams/beams across different, often non-correlated frequency and time dimensions. Only restrictions for the proposed scheduling method are such that the maximum number of beams is limited by the number of BS transmit antennas while the number of beams per user can get any value between zero and the number of terminal antennas depending on the channel conditions. At the same time, the advanced precoder design (TX weight and power allocation) algorithms can be used to guarantee user/stream QoS requirements while maximising the system optimisation objectives. Differently to the methods proposed in WINNER II, the proposed transceiver design method can be optimised according to different objectives, including:

- Power minimisation subject to per stream SINR constraints
- Power minimisation subject to individual user rate constraints
- Minimum weighted SINR maximisation, i.e. SINR balancing
- Weighted sum rate maximisation
- Weighted common rate maximisation, i.e. weighted rate balancing

The transceiver optimisation method can straightforwardly handle a frequency selective OFDM system with additional QoS constraints, such as a guaranteed minimum bit rate per user. The methods allows multiple antennas both at BS's and mobile users, and any number of data streams is allowed per scheduled user. The method can accommodate a variety of supplementary constraints, e.g. upper or lower bounds for the SINR values of data streams as well as per antenna or per BS power constraints, and the feasibility of the resulting optimisation problems can be easily verified. A practical model for the rate provided by each data stream can be easily adapted. The achievable rate per stream can be modelled as $\min(\log_2(1 + \Gamma\gamma_s), r_{\max})$, where Γ describes the SNR gap to the channel capacity, γ_s is the SINR of stream s and $r_{\max}$ is the maximum rate limit, both imposed by a set of some practical modulation and coding schemes.

The optimisation problems are decomposed into a series of remarkably simpler optimisation subproblems which can be efficiently solved by using standard geometric program and/or second order cone program solvers. Even though each subproblem is optimally solved, the global optimum cannot be guaranteed in general due to the nonconvexity of most linear transceiver optimisation problems. However, the algorithms are shown to converge fast to a solution, which can be a local optimum, but remains efficient.

2.3.1.2 Expected performance or benefits

A first set of research results demonstrate the near optimality of the proposed algorithms. The results have been presented in [TCJ08a, TCJ08b, Tol08] and some of the results are reproduced in Appendix A.5 for convenience. The proposed joint transceiver optimisation algorithms are compared with corresponding generalised ZF transmission solutions, as well as with corresponding optimal non–linear transmission methods. The proposed algorithms are shown to perform significantly better than the corresponding ZF solutions providing near optimal solutions despite the fact that there is no guarantee of achieving the global optimum due to the non-convexity of the optimisation problems.

It is also shown that the performance of the generalised ZF method with greedy scheduling approaches the sum rate capacity in the high SNR region as the number of users present in the system becomes large. However, in the low SNR region the capacity loss from the noise amplification can be significant. The generalised ZF method suffers from the noise amplification in the fully loaded case. Therefore, it is often beneficial to allocate fewer beams than the spatial dimensions available allow in order to reduce the noise amplification, especially in the low SNR region and with a low number of users.

2.3.1.3 Expected requirements on signalling and measurements

The generic requirements concerning multiuser MIMO precoding in TDD systems apply here as well. The TDD frame and pilot signal structure of WINNER II supports the proposed concept with the uplink pilots dedicated to MIMO channel sounding. Scalar feedback for reporting SNR or the noise level seen by the mobile receiver is needed.

2.3.2 Uplink-downlink multiuser SDMA strategy for TDD-MIMO systems

2.3.2.1 Description of the concept

Coordinated linear transmitter-receiver processing by block diagonalization (BD) with greedy beam selection is a method to utilize all degrees of freedom available in MIMO networks. By applying instantaneous channel state information in the transmitter (CSIT), the BD criterion offers zero-forcing between the downlink data streams of different users. Any combination of the number of antennas in terminals and the base station can be supported. This contribution proposes a practical uplink MIMO scheme for time division duplex (TDD) systems to co-exist with downlink multiuser Tx-Rx zero-forcing so that the locally available CSI of the BD channel is used by the terminals in the uplink transmission [KLJ08, KTL+09]. Uplink transmit beamforming gain is significant especially when the base station employs a relatively small antenna array. The precoded pilot symbols are sufficient in both uplink and downlink to satisfy the needs of both transmission and reception.

Figure 2.8 shows an example of uplink-downlink beamforming with beam selection. The base station selects the same set of spatially compatible eigenbeams for both directions. The existence of the downlink beams accommodates reciprocal beamforming for uplink. In essence, the uplink is based on reversing the downlink signal processing chain. The power constraints and transmit data rates can be different for the base stations and terminals, even though the same space and frequency resources are reserved for both directions. If the data traffic between uplink and downlink is heavily asymmetric, the asymmetry can be dealt with by uneven allocation of resources in time domain.

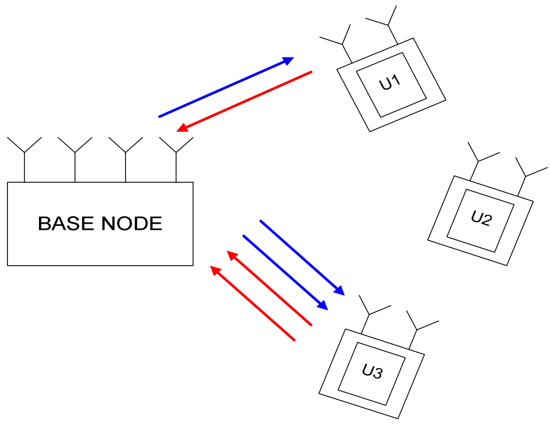


Figure 2.8: Uplink-downlink beamforming with beam selection

The concept is based on linear iterative downlink multiuser Tx-Rx zero-forcing [SS04]. The multiuser MIMO channel is effectively decoupled into a set of parallel single-user MIMO channels so that per-user precoding based on SVD can be performed. Ideally, the optimal downlink receivers become matched filters so that the terminals need not actively suppress inter-stream or multiuser interference. Thus the BS carries out all multiuser processing, whereas the terminals may act as if performing single-user MIMO. In the uplink, each mobile only sees its own zero-forced MIMO channel and thus implicitly assumes a zero-forcing receiver in the base station. However, in practice other multiuser receivers than zero-forcing can be applied to improve the robustness of the system. More details are provided in Appendix A.6.

The main innovative idea is to propose multistream beamforming for uplink, and in coupling the uplink and downlink MIMO transmission so that they support each other. Uplink can get considerable gain from transmit beamforming. At the same time, the data-stream-specific precoded downlink pilots are sufficient for creating uplink precoders. Multiuser MIMO based on CSIT was included in WINNER II already, however only for downlink and not by zero-forcing. Thus the proposed algorithm is new for both base stations and terminals.

2.3.2.2 Expected performance or benefits

The proposed concept utilizes all spatial degrees of freedom while taking advantage of CSIT. Thus both multiplexing gain and beamforming gain are obtained, which is a combination not found in the current uplink solutions. In Appendix A.6, the performance of the proposed concept is compared against two other schemes: best-user MIMO precoding and non-precoded uplink. In the simulated scenario, the capacity gain offered by the proposed concept is in the order of 35% against the best-user MIMO and 70% against the non-precoded method.

2.3.2.3 Expected requirements on signalling and measurements

The TDD frame and pilot signal structure of WINNER II support the proposed concept by precoded stream-specific pilots. In the downlink, these pilots are sufficient. However, changes to the uplink are suggested so that the pilots are appended by additional streams, resulting in each user's pilot precoder matrix becoming unitary. The unitary precoder matrix and orthogonal pilot sequences enable full multiuser MIMO channel estimation in the base station. Note that LTE Rel.8 offers only one stream-specific downlink pilot, and thus multistream precoding is not supported. In the uplink direction, transmission of multiple streams per user is not supported. This proposal affects mainly the physical layer precoding. However, it has to be ensured that scheduling and beam selection support the scheme by properly taking into account the spatial domain.

2.3.3 Low complexity resource allocation for multi-user SDMA

2.3.3.1 Description of the concept

When multiple antennas are available at base stations transmitting on the downlink, the spatial signatures of the users’ channels can be separated and multiple users can be served simultaneously (SDMA) in any resource element of the underlying transmission system. To fully exploit the benefits of SDMA and to reach the targeted throughput values in Local Area and Metropolitain Area scenarios, channel adaptive transmit precoding is required, either based on long-term or short-term channel knowledge.

An algorithm is needed to decide which users should be served simultaneously by the SDMA scheme at each transmitting base station in each resource element. Terminals with spatially correlated channels should not be served simultaneously, because correlation impairs the spatial separability of the channel subspaces and leads to less efficient precoding weights. In channel adaptive precoding, for each possible subset of users the precoding weights need to be re-computed, thus creating an intractable computational complexity when brute force searches are employed. Low complexity approaches such as ProSched are key to fully exploiting the benefit of the SDMA scheme in practice.

Inter-cell or inter-site interference can be mitigated as well, including that generated by relay nodes, depending on the amount of coordination available between the transmitters. This leads to additional gains especially in interference limited scenarios such as LA and MA.

The multi-user spatial scheduling concept for SDMA (including distributed antennas systems) was already developed in WINNER I/II [WIN2D341]. The concept is based on the low complexity scheduling algorithm ProSched [FDH05b] and its extension to interference avoidance scheduling for multiple base stations with cooperation and/or coordination [FDH06]. The extension of the concept to relay enhanced systems with coordination has also been presented in a basic form. For a brief discussion of the concept in relay mode see Section 3.4.3. More details of the whole scheduling concept as well as simulation results on interference avoidance in relay enhanced cells are provided in Appendix B.10.

2.3.3.2 Expected requirements on signalling and measurements

A scheduler for SDMA systems with linear precoding can make use of the same channel measurements (CSI at transmitter) which are required for performing channel adaptive precoding. In a TDD system, this channel knowledge can be obtained with the help of pilots on the reverse link. In the multi-cell coordination mode, the genie performing coordination needs to know the channel matrices between all combinations of nodes in the system to be able to estimate interference.

3. Coordinated MultiPoint (CoMP) Systems

In Chapter 2 a set of innovative concepts for advanced antenna schemes were presented. The proposed concepts include several detailed SDMA signal processing solutions for improving the capacity of cellular networks employing multiple antenna base stations and terminals. The main framework of the presented schemes consists of downlink spatial user multiplexing and beamforming by means of linear transmit precoding and scheduling in a single-cell environment. In Section 2.1 inter-cell interference and methods for multi-cell cooperation were addressed as well.

Most of the SDMA principles presented in Chapter 2 can be extended to more general network layouts, paving the way to Coordinated MultiPoint (CoMP) systems. In this chapter, an overview of CoMP is first provided in section 3.1, which addresses in particular the impacts that CoMP may have on the system concept. The possible architectures allowing CoMP to be implemented, including relay nodes, are described in section 3.2.

All CoMP architectures, fully exploiting benefits of coordination among scattered transmitters, have the capability to enhance signal quality and increase system capacity. In addition, CoMP can be combined with new and more flexible radio resource management techniques and algorithms and thus outperform conventional wireless communication systems. Section 3.3 firstly illustrates the possible approaches to fully exploit CoMP and then examines some preliminary simulation results performed to assess CoMP possible performances with respect to conventional radio systems.

The final section (3.4) of this chapter is fully dedicated to relay systems intended as possible CoMP implementations, with preliminary performance estimations of the proposed concepts.

3.1 Overview of CoMP and main impacts on the network

3.1.1 Overview of CoMP

The Coordinated MultiPoint (CoMP) framework encompasses all the system designs allowing tight coordination between multiple radio access points for transmission and/or reception. Three types of coordinated entities can be considered, as depicted in Figure 3.1:

- Remote radio units (RRU);
- Cells, which involve intra-BS or inter-BS coordination;
- Relay nodes (RNs).

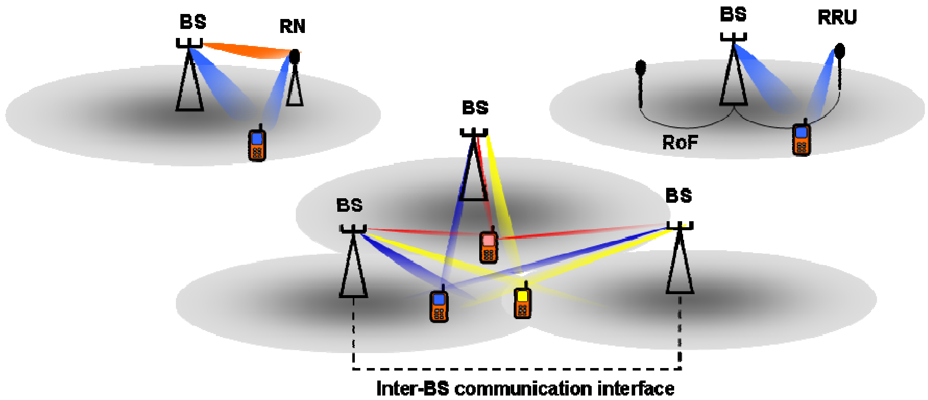


Figure 3.1: Different instances of systems able to implement CoMP

Each type of entity puts specific constraints on the system architecture in order to realise the actual coordination. Indeed, the coordination requires control and possibly user data to be exchanged between the collaborating nodes through dedicated communication links. The availability of these links, together with their latency and capacity determines the feasible type of coordination.

- Remote radio units are connected by means of radio over fiber (RoF) links to a control unit, through a (generally) proprietary interface, allowing a tight coordination (on the order of the millisecond). Several architectures are possible in order to connect the RRUs to the central unit, as will be detailed in Section 3.2.2.

- Inter-cell coordination through intra-BS coordination is the easiest inter-cell coordination mode since the same processing unit generally controls different cells. Therefore, the latency of information exchange (both control and/or data) is in effect zero.

- Inter-cell coordination through inter-BS coordination heavily relies on the capacity and latency of the links between the coordinated BSs. Base stations are inter-connected under the flat architecture through standardised interfaces (e.g. the X2 interface for LTE), the latency available in todays specified systems being on the order of ten milliseconds (maximum delay on the order of 20 ms in LTE Release 8 for control-plane messages, and typical average delay on the order of 10 ms). Note that this latency can be lower depending on the actual link.

- Finally, relay nodes are connected to a base station via over-the-air in-band links (e.g. specific control channels or in-band backhaul, depending on the relay type), enabling a tight coordination but at the price of a possible delay between the coordinated nodes.

Combinations of the various types of entities are conceptually possible, i.e. a network deployment may use multi-cell coordination with coordinated RRUs, and RNs within each cell, although it is likely that the actual coordination would require a much higher complexity. Different architectures for a CoMP system are described in Section 3.2, taking into account the specificities of each scenario.

CoMP involves several possible coordinated processing schemes between access points, among which joint transmission of the user data, for instance using distributed (multi-user) linear precoding, and coordinated scheduling/beamforming. Section 3.3.1 describes in details the different possible CoMP approaches. In addition, Section 3.3.2 presents achievable performance and benefits of CoMP schemes as well as innovative proposals for CoMP. Note that CoMP is a generic concept that can basically be applied from various types of access points, including RRUs, BSs and RNs.

Coordinated relaying schemes are a particular way to implement CoMP, which has to account for the specificities of relays regarding the coordinated processing: the delay inherent to the 2-hops transmission between a base station and a user terminal (UT), and/or the potential errors affecting the first hop. Coordinated relaying schemes are introduced in Section 3.4.

The impacts of CoMP on the system design are summarized in the next section.

3.1.2 Impacts of CoMP on the network

This section reports some impacts that CoMP introduces on the network compared to non-coordinated systems. These impacts are common to all the modes of coordination (i.e. whatever the involved entities).

3.1.2.1 Measurements and radio signaling aspects

As a function of the mode of transmission retained for CoMP, e.g. joint precoding from several access points, or coordinated beamforming, knowledge of different parameters need to be acquired, including

- channel state information (CSI) between the UT antennas and those of the coordinated points, which can be either short-term CSI (i.e. the channel coefficients) or long-term CSI (channel covariance matrix)
- preferred precoding matrices indexes from each coordinated point
- received power from each coordinated point
- long-term fading from each coordinated point

In FDD, this information needs to be estimated at the UT, quantized and fed back to the transmitter(s). In TDD, the coordinated points can acquire some of these parameters using the channel reciprocity property. This section discusses the impact of CoMP on the operations associated with channel estimation, compared to a non-coordinated network deployment.

Channel estimation in TDD systems

Under the TDD assumption channel estimation can be obtained at the AP side by channel reciprocity. The main problem is to understand how the coherence time of the channel and the estimation accuracy affects the different techniques. When the cooperation occurs between non-collocated entities (e.g. in the case of BSs cooperation or relay-aided systems), another problem is the quantization and feedback of the channel estimations through a wired or wireless backhaul. For example for closed-loop TDD relay-based transmissions, the main issue is that the feedback should be gathered for each hop of the transmission. For this reason, partially distributed approaches seem to be more appealing for realistic applications.

Channel estimation in FDD systems and feedback issues

Under the FDD assumption channel estimation is obtained at the UT side and then fed back to the AP side. The main problem in this case is how to design the feedback channel. The impact of feedback design in FDD systems has been extensively studied for single-user and multi-user MIMO transmissions (see [LHL+08] for an overview about limited feedback for wireless communication systems). Nevertheless, some of the results seem to directly apply to CoMP systems. For example some CoMP techniques can be seen as multiuser MIMO transmissions with antennas belonging to different sites. In this case, the problem of sending the feedback from a user to a given base station is very similar to the one already considered in the multiuser MIMO literature.

3.1.2.2 System design parameters

Pilot design

In practice, it is difficult to obtain the precise downlink channel state information required for CoMP amongst desired BSs. This imposes requirements on the pilots design to enable such estimation with sufficient quality, or additional signal processing to be able to separate the pilots from different cells; in addition the UT needs to be able to decode the BCH channel of the neighbouring cells.

In the uplink, in order to attain the full CSI between all users and BS antennas in the cellular network, the user channels should be jointly estimated at each antenna head. However, the received signal levels of UL transmissions from different users can vary significantly between different network nodes. Therefore, the joint channel estimation across different users may be difficult if not impossible to implement in practice.

Appendix B.1 introduces a multi-cell channel estimation based on pre-defined, partially correlated time-domain scrambling sequences, which can be applied to standard common reference signals. This concept defines virtual pilot sequences and arranges them to the cells taking the pathloss into account; it assumes a fully synchronized cellular radio system, i.e. with respect to the carrier frequency and frame start of OFDM symbols. Note that the defined cyclic prefix ensures inter-symbol interference free transmission as long as the delay spread of the channel is small enough.

The concept described in Appendix B.1 enables mobile terminals to distinguish more strong interference channels with an increasing length of the correlation window utilized for the estimation process. It does not require higher pilot overhead than in current systems but results in a trade-off between the mobility of the user and the ability to track interfering channels.

Cyclic prefix /OFDM parameter choice

Typically, the parameters of the OFDM transmission, e.g. frame length and cyclic prefix length, are designed based on the characteristics of the radio environment, such as average or worst case delay and Doppler spreads. Cooperative BS processing may potentially induce increased delay spreads due to the fact that the coordinated antennas can be placed far apart. The impact of the CoMP on the design of OFDM parameters must be evaluated.

3.1.2.3 Backhaul and inter-access point information exchanges aspects

Backhauling is required to connect the cell sites to the backbone network. For the backhauling including the “last mile”, several technology options exist: copper (e.g. using xDSL: 100 Mbit/s is a typical limit), microwave (Gigabit microwave links will soon become commercially available), fiber.

The technologies and mediums available for backhauling will have a strong impact on the available data rates and latency for inter-access point information exchange. The cost in terms of CAPEX/OPEX of those technologies will be an important aspect as well. In case of multi-cell cooperation, regarding backhauling, it is important to distinguish between cooperation between sectors of the same site, requiring no backhauling bandwidth, or cooperation between base stations / access points at different sites; for the amount of data to be transmitted over backhaul it is important to distinguish whether the cooperation is on control plane only (e.g. in case of coordinated scheduling for interference avoidance) or control plane and user plane (for joint transmission from different sites).

Multi-user multi-cell precoding techniques for CoMP are very challenging from the practical implementation point of view. If performed in a fully centralized manner, they require (in both FDD and TDD mode) a large amount of data to be exchanged on high-speed links between the collaborating entities: the CQI and CSI from the APs to the central entity, and the scheduling decision together with the computed precoding weights from the central entity to the coordinated APs. The number of cells involved in the coordination scheme increases the amount of backhaul traffic, depending on the network topology. As an example, when full coherent coordination is used [KFV06], assuming a star network topology, the increment of data traffic in the backhaul is proportional to the number of base stations coordinated. Different approaches have been considered that limit the coordination to only a subset of the cells in the system, in order to limit the amount of data backhaul signaling, see e.g. [PBG+08].

In a relay-aided wireless network there is not a clear distinction between *backhaul phase*, where the base station "feeds" the relays, and *access phase*, where one or more relays serve on or more users. The main challenge is how to find the optimal switching point between backhaul and access phase in order to maximize the end-to-end throughput (see for example [BKK+08]).

3.1.2.4 Impact on the architecture and protocols

Different impacts on the architecture can be foreseen depending on the selected scenarios (coordination among base stations, possibly using RoF, or coordinated relaying), affecting both data plane and control plane.

RoF-like approaches have a small impact on the current network architecture since interface between base station control unit and related remote heads is a proprietary one (CPRI and/or OBSAI based) and ring or bus scenarios are already in the evolution of these interfaces. Nevertheless it is necessary to further study how to circulate data and, especially, control information on top of RoF interfaces. In case of resource pooling (i.e. when several base stations controlling different remote antenna heads are collocated) in the central unit of a RoF-like architecture, further impacts on this architecture can be foreseen, increasing the impact on the overall architecture of this approach as well. The architecture for RoF deployments is addressed in details in Section 3.2.2.

Cooperation among distributed base stations has a higher impact on the network. First of all, a central control unit may be necessary depending on the coordination scheme adopted, where will be run part or most of the coordination algorithm. That central unit plays a role similar, but not equal, to that of a central unit in a RoF scheme. Secondly, the interface between every radio base stations should be modified depending on the information they must exchange to one another; this information can be control information only or user data in more complex schemes. The architecture for inter-BS coordination is addressed in more details in Section 3.2.1. In addition, this section introduces a decentralized approach for inter-BS coordination with reduced impact on the architecture, but higher sensitivity to feedback errors.

Relaying impact is similar to that of the above mentioned scenarios.

3.1.2.5 Impact on other system aspects

Other important aspects to be considered when introducing CoMP in the network are:

- control information related to the management of UTs connected to a multiplicity of transmitters/receivers;
- coherence in the transmission from a multiplicity of transmitters/receivers and related synchronization data exchange among them;

Most contributions addressing multiple-antennas schemes consider a power constraint on the sum of power transmitted by the different antennas. This assumption does not hold in the following cases:

- each antenna in a multi-antenna base station is powered by its own amplifier and is limited by the linearity of that amplifier;
- the system is using distributed antennas, belonging to the same base station or to different base stations coordinated together, each one subject to a power limit due to national/international regulations.

We refer to [YL07] as an important reference about implications of per-antenna-power-constraints.

3.1.2.6 Impact on 3GPP LTE specifications

The following areas of the LTE physical layer specifications have been identified as being potentially impacted by the introduction of CoMP in the downlink [3GPP36814]:

- Feedback and measurement mechanisms from the UE: to report dynamic channel conditions between the multiple transmission points and the UE, and to report relevant information in order to facilitate the decision on the set of transmission points participating in the coordination;
- Downlink control signalling: to support the preprocessing schemes, e.g. joint processing prior to transmission of the signal over the multiple transmission points;
- Reference signal design: specification of additional reference signals may be required depending on the transmission scheme.

In addition, it is worth to note that there is no difference between intra-BS (called eNodeB in the 3GPP terminology) and inter-BS coordination from the radio interface perspective, even though the necessary information signalling between BSs may need appropriate specification support at layers above the physical one.

In the uplink, coordinated multi-point reception is expected to have very limited impact on the RAN1 specifications, in particular because UE-specific reference signals allow BSs to distinguish between UEs belonging to different cells. In addition, transmitting UEs may not need to know which BSs will collaborate to receive and process their signal. In case scheduling decisions are coordinated among cells to control interference, the physical layer specifications may be impacted.

3.2 The CoMP architectures

Under the term of CoMP we assume to consider all the possible coordination approaches for radio access network, comprising

- coordination among a set of multiple radio stations exchanging information to perform the coordination
- coordinated relaying schemes, involving coordination among relay nodes and/or coordination among realy nodes and radio stations

The first set of system proposals comprise the coordination among base stations and the coordination among remote units of a pool of collocated base stations as well, exploiting in the latter case the Radio over Fiber (RoF) technology.

3.2.1 Coordination among radio base stations

Coordination between neighbouring base stations is a very promising way to reduce inter-cell interference in the network, either in the uplink (coordinated reception) or in the downlink (coordinated transmission). Although different time scales are possible for the coordination, the most efficient schemes require the information needed for scheduling to be available at each coordinated BS, which calls for very low-latency (on the order of the millisecond) information exchanges between coordinated nodes, or between the UT and all the coordinate nodes. Two extreme approaches can be distinguished regarding how to make this information timely available at distant BSs: centralised and decentralised coordination. These approaches are described in the following in the most general case where joint processing is performed across various BSs. Nevertheless, these approaches also apply in the simpler case of coordinated scheduling.

3.2.1.1 Centralised coordination

Centralised coordination is the approach that has been mostly considered so far for inter-BS coordination. On the downlink of FDD systems its differences with respect to a non-coordinated system are as follows:

- UTs need to estimate the channel state information (CSI - coherent approach) related to all cooperating BSs or another channel quality metric, e.g. a precoding matrix indicator (PMI - non-coherent approach) and feed their estimate back to the network. In the following, we use the term channel information (CI) to refer to either CSI or PMI.
- A central entity (CE) is needed in order to gather CI and CQI from all UTs in the area covered by the cooperating BSs and perform user scheduling and signal processing operations (e.g. pre-coding design).
- User data need to be available at all collaborating BSs. This may necessitate a capacity upgrade of the existing backhaul links.
- Collaborating BSs need to be tightly time-synchronised.

In TDD systems, downlink CI may be obtained by uplink training at the BSs using the principle of channel reciprocity and therefore UTs may not need to estimate and feed back CI. However all the involved BSs need to transmit their CI estimate to the central entity.

One of the main architecture impacts of tight inter-BS coordination is the central entity and the associated communication links. This central entity is a logical entity that can be accommodated at one of the collaborating BSs, by establishing a non equal-to-equal relation between BSs. In addition, the information related to the UTs to be served in a coordinated manner (CQI, CI) has to be made available at the central entity. One possibility to achieve this is that each UT feeds back its CQI and CI to a specific BS, defined as the anchor BS hereafter. This is can be the serving BS for each UT in case there is no multi-cell coordination (e.g. the BS that provides the best channel quality). The phases that coordinated multi-cell transmission follows are then (in the FDD case):

- UTs estimate the CI related to all cooperating BSs, as well as CQI.
- UTs feed back their CI and CQI estimates to their anchor BS. Therefore each BS gathers local fed back information (FBI), i.e. the FBI related to the MSs assigned to it in case there is no multi-cell coordination.
- The BSs forward their local FBI to the central entity which performs scheduling, designs the transmission parameters and communicates them to the corresponding BSs.

The need of a central entity entails the following changes upon the conventional architecture of cellular systems: collaborating BSs need to be interconnected via the central entity with low latency links in order to exchange local FBI. Furthermore this information exchange needs to be coordinated with the use of additional communication protocols.

3.2.1.2 Decentralised approach

An alternative to alleviate the constraints of having centralised processing is to perform decentralised coordination (see Figure 3.2). A possible solution to achieve decentralised coordination is described hereafter [PHG08]. The two main ideas behind this proposal are as follows

- identical independent schedulers receiving the same input parameters (CQI, CI, buffer states, etc.) will take the same decisions.
- the FBI information can be made available to all the cooperating nodes using radio feedback.

Considered together, the two principles above suppress the need for inter-BS communication, while providing the same network behaviour as if a centralised entity would control the coordination.

It is worth to note that the radio feedback to several nodes can be achieved without additional overhead provided the same feedback resources are allocated to one UT by the cooperating BS, especially when the UT is located at equal distance from them. The only possible increase of the feedback overhead compared to non-coordinated operation is when one uplink link is worse than the uplink link towards the anchor BS, since the feedback MCS has to be adapted to the worst link.

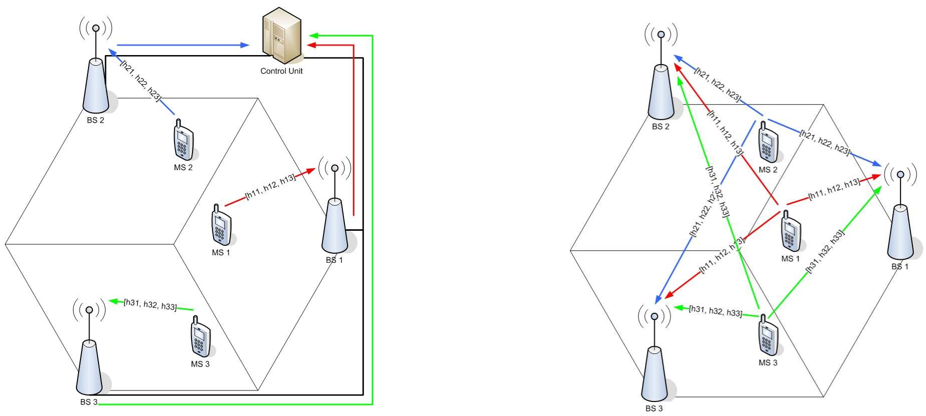


Figure 3.2: Centralized (on the left) and de-centralized framework for coordination among BSs

Therefore the phases to be followed for a decentralised coordinated multi-cell transmission on the downlink are (in the FDD case) [PHG08]:

- UTs estimate the CI related to all cooperating BSs and CQI.
- They feed back their estimate to all collaborating BS. Therefore each BS gathers local together with non-local FBI (it possesses global FBI).

- The BSs schedule UTs independently. Employing the same scheduling algorithm and having the same input parameters, they end up selecting exactly the same UTs. The design of the transmission parameters is also performed in a distributed manner according to the chosen transmission algorithm by the cluster BSs.

Under this decentralised framework, infrastructure cost and signalling protocol complexity for CI exchange can be minimised, since neither a central entity nor low latency links connecting it with the cooperating BSs are required. Hence, the structure of the conventional systems can undergo minimal changes in order for the coordinated multi-cell transmission to be incorporated. Furthermore, with the decentralised framework, radio feedback overhead may remain similar comparing to the conventional framework for coordinated multi-cell transmission, as explained above.

The main obstacle associated with the decentralised collaborative framework is the handling of errors on the different feedback links. This affects both CI feedback and HARQ ACK/NACK reports. Under the decentralised framework, error patterns can be different on each feedback link, since CI and ACK/NACK are fed back to all collaborating BSs (the number of feedback links used is equal to the number of collaborating BSs). Under the inter-BS FBI exchange approach only one radio link is utilised per UT for feedback transmission and therefore there is only one error pattern affecting feedback information per UT. In Appendix B.2, the impact of feedback errors on the system performance with respect to CI feedback and ACK/NACK reports is discussed, and solutions for enhancing the robustness of decentralised multi-cell coordination are proposed. Two types of solutions are introduced: some for reducing malfunctions probability, and others for recovering from potential malfunctions, providing leads to design a practical decentralised multi-cell coordination scheme.

3.2.1.3 Other approaches

Other alternatives lying between these two extreme approaches are possible, where some pieces of information are transmitted to a central entity, while others are derived in a decentralised way. For instance, [SCW+07a] describes a scheme with a centralised scheduling but where the precoding weights are locally designed at each BS. Therefore, the amout of information to be exchanged between the collaborating nodes is reduced compared to the fully centralised approach.

3.2.2 Base station with distributed antennas connected by RoF links

The growing demand of bandwidth in mobile access networks led to a fast and extensive adoption of fiber as the most suitable carrier for backhauling data. In its turn, fiber has become more and more convenient from an economic standpoint as well, with cheaper solutions made available in last years.

Radio over Fiber (RoF) solutions gained new attention as an alternative in backhauling architectures, allowing to shift complexity of the standard and traditional radio base stations towards the antennas and to pool resources in a centrally located unit, responsible of the base band resources management. RoF makes it possible to centralise the signal processing functions in one shared location (Central Base Station), and then to use optical fiber to distribute the signals to the remote antenna units. Besides point-to-point simple RoF configurations, more complex architectures (such as ring or bus ones, exploiting daisy-chaining in RoF links) are being introduced.

In general, Radio over Fiber technology can be implemented using Digital or Analogue approach. Currently RoF applications are focusing on digital approaches, since the digital data exchanged between the Central Station and the scattered Remote Units paves the way to the reconfigurability and dynamic management of resources along RoF distributed architectures, which can be also organized in ring or bus configurations.

Furthermore, digital RoF has been partly specified by some international consortia, such as CPRI and OBSAI ([OBS20] introduces OBSAI base station architecture, as a possible example), particularly as far as data transport over the fiber is concerned. A wise exploitation of the digital data transport in CPRI/OBSAI or newly introduced formats is considered, so as to enable the reconfiguration of the distributed system of transmitters.

The architecture that could enable an efficient digital RoF based architecture is the one in Figure 3.3, where M Remote Units (RU) are connected via digital/optical fiber in daisy chain to the Base-Band modules of the Base Station (Central Unit, CU), the Central Unit is able to transmit/receive N AxCs[1] (OBSAI/CPRI standards terminology) and each RU has Km (m=1…M) antenna elements forming an antenna array.

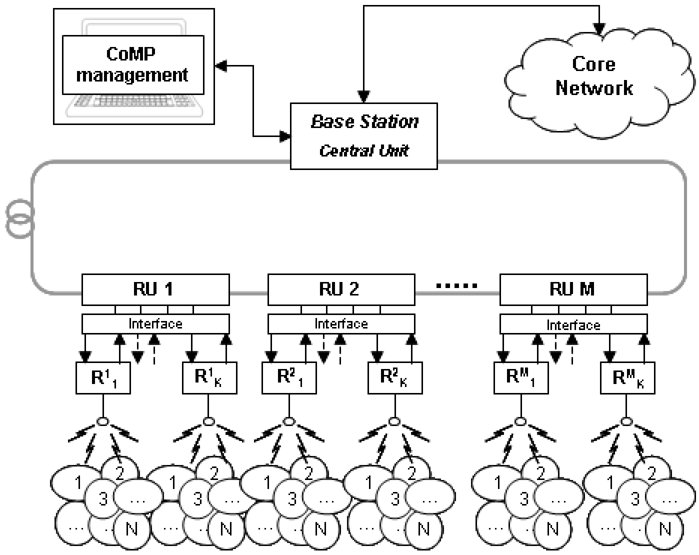


Figure 3.3: RoF based CoMP architecture

Depending on the values of M (number of RUs), Km (number of antennas of the m-th RU) and N (number of antenna carriers) different CoMP architectures are introduced.

The case with M=1 means no CoMP with a single point to point link between CU and RU; if N=1, K=1 the architecture is a traditional point-to-point RoF. If N>1 AxC multiplexing over fiber link is introduced, while with K>1 antenna arrays instead of single antenna, possibly enabling reconfigurable and/or adaptive multiple antenna concepts (MIMO, beamforming, etc.), are considered.

More efficient CoMP architectures are with M>1, generally with K and N $\geq$ 1 for each one of the M RUs. Transmission of data along the fiber is managed following one of the specifications introduced (CPRI, OBSAI or similar). Remote units architecture is quite simple: the remote units only have to convert digital to analogue signals, amplify and transmit them to the antenna(s) in the downlink chain (for the uplink the received signals are amplified, converted to digital and sent via the fiber connection to the central unit). Of course, in case of beamforming, a signal processing performed over the digital AxCs could be introduced.

The network layout is reported in Figure 3.4, focusing on the downlink path (the uplink is straightforward).

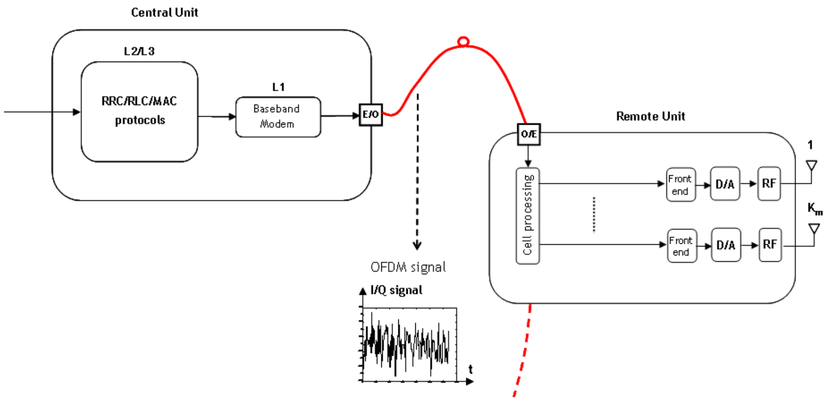


Figure 3.4: Downlink network layout in RoF architecture CoMP

[1] Antenna Carrier (AxC) definition used in CPRI for W-CDMA: one antenna-carrier is the amount of digital baseband (IQ) U-plane data necessary for either reception or transmission of one UTRA-FDD carrier at one independent antenna element

Remote units receive data and perform data processing (in order to execute the reconfiguration of the remote unit, as explained in the following) before transmitting data to each of the K antennas they are equipped with. If fiber link capacity is sufficiently high, more than a single AxC can be managed by the remote unit, enabling signal multiplexing; the number of AxCs that can be transmitted over the fiber link depends on the radio system bandwidth and, additionally, on the overall capacity supported by the connection.

As stated above, consortia such as CPRI and OBSAI specify format and allocation of data over the fiber connection. Specifications take care also of the frequency synchronization of the remote transmitters, with dedicated extensions to every radio system (from 2G/3G onwards).

Besides cell data, control data shall be transmitted over the fiber as well, in order to perform the cell processing in the remote units. These data can be multiplexed in the currently existent data formats (CPRI, OBSAI or others) exploiting overhead data allocation.

A feasible architecture based on digital RoF distributed antenna systems can include newly-introduced so-called reconfigurable antennas in the remote antenna units. A system capable of making digital beam forming so as to optimize the beam for the cell can be called reconfigurable antenna. Reconfigurable antennas can be effectively used in cellular network planning. In fact by means of an optimization procedure, it is possible to define a set of beam patterns that the reconfigurable antennas can radiate in order to maximize several output parameters like coverage, signal to interference ratio, capacity, etc. When working conditions change, a new optimization procedure has to be run in order to keep the value of the output parameters to the desired level.

These concepts can be easily transformed into an automatic process:

- the information coming from the network (quality of service, number of lost calls, traffic counter, etc.) are provided to a CoMP Management entity (see Figure 3.3);
- this entity drives the optimization procedure and determines new beamforming weights;
- this entity sends new weights to the reconfigurable antenna that discards the old configuration and sets the new one.

If the remote unit is equipped by a reconfigurable antenna array the amount of control data (or reconfiguration data) that are to be exchanged between the central unit and the remote units via the fiber link is very low. A detailed description of the reconfiguration management is given in Appendix B.3, together with an estimation of the fiber bandwidth occupation.

The “reconfiguration” in the CoMP assumes a double meaning: reconfiguration of the cell resources assigned to the remote units, and reconfiguration of the radiating diagrams of their antennas (particularly, reconfigurable antennas). Network planning procedures can exploit the two reconfiguration options given, enhancing quality and capacity in the area of the CoMP. While reconfiguration of the radiation diagram is a straightforward and an already-known approach, reconfiguration of the radio resources paves the way to coordinated transmission schemes (see chapter 3.3.1 for details).

3.2.3 Coordinated relaying systems

When relay nodes (RN) are present in the network, the coordination of APs can be limited to the joint coverage area of the BS and/or its associated RNs.

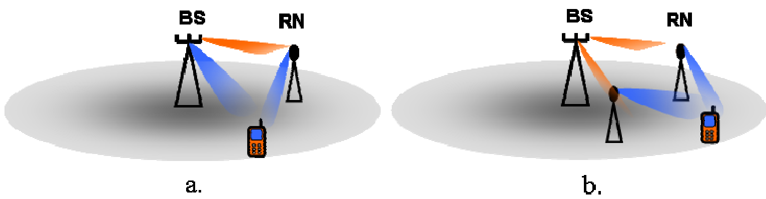


Figure 3.5: Example of coordinated transmission involving RNs. The orange and blue colors represent the transmission at time slots n and n+Δ, respectively, where Δ is a delay.

Two coordination configurations involving RNs are possible: in the first one, depicted on the left-hand side of Figure 3.5, the BS and one of its associated RNs transmit in a coordinated way. In the second configuration, depicted in the right-hand side of Figure 3.5, two RNs are coordinated. Compared to the BS cooperation schemes, the impact on the infrastructure in case of centralised coordination is reduced by such schemes since the BS may act as the central entity, by imposing constraints to the RN(s) scheduler (e.g. serve a UT in a given time slot), while the BS-RN links may act as the low-latency/high capacity communication links, as well as backhaul links. Nevertheless, the overhead on the backhaul yielded by coordinated operation translates in the case of coordinated relays into a radio capacity loss due to the in-band backhauling.

Note that in the case of joint transmission, the capacity benefit of the BS-RN coordination scheme would be questionable compared to transmission from the BS only, since the user data would need to be first transmitted from the BS to the RN, before being jointly transmitted from the BS and the RN to the UT. Nevertheless, link throughput gains can still be expected due to the diversity and joint transmission gains.

3.3 Coordinated multipoint approaches and algorithms

In this section we will outline the different possible coordinated multipoint (CoMP) approaches that can be envisioned in uplink and downlink, and also get a hint of the achievable performance of some CoMP approaches. This section does not consider relaying CoMP approaches, since they are described in section 3.4.

3.3.1 Overview of CoMP approaches

Once the network infrastructure for CoMP is in place, whether it is a centralised or a decentralised architecture, different approaches with different level of coordination and/or cooperation can be envisioned. They typically have different requirements in terms of measurements, signalling, and backhaul, where as usual the most advanced approaches achieving the best performance also have the highest requirements. Hence, it is important to consider all approaches in order to find the trade-off between performance and system complexity.

3.3.1.1 Downlink

3.3.1.1.1 Dynamic network reconfiguration and coordinated scheduling

A very simple form of CoMP would be dynamic network reconfiguration and management. The easiest reconfiguration scheme envisaged is that of turning on/off the remote units in the CoMP system, according to network planning or traffic constraints. When needed, the planner could easily turn on/off a remote unit in order to upgrade/downgrade the overall coverage and/or capacity in the area.

A further advancement could be to adapt the network characteristics to the traffic requirements. In fact, there are various application scenarios in which the traffic may present very significant variations in time. An exemplary case is that of stadiums or other sports and show venues and facilities. For example, a considerable mass of people may crowd a stadium for a short period of time (e.g. for a few hours or little longer) for an event. In such a case the capacity of the network can be locally increased by providing a larger number of carriers to the remote units that serve the considered venue for the corresponding period of time. A more complex form of reconfiguration can be based on an effective transmit power management. In this way it is very easy to implement transmit power schemes to mitigate interference between transmission points or also to improve the coverage for users that experience bad channel conditions (e.g. cell edge users, indoor users, etc). This brings us to another form of CoMP; dynamic coordinated scheduling. In this case, the transmission points coordinate their schedulers in order to avoid interference. The coordination takes place on fast time scale, which means that the fast fading can be followed. A particular application is coordinated beamforming (also discussed in sections 2.1.1.1 and 2.1.3.1.2), where the beams activation at different transmission points is coordinated in order to minimise the probability of beam collision or minimise the inter-beam interference. Hence, the term coordinated beamforming should in this context be seen as coordinated scheduling in the spatial domain.

The main advantages of these schemes compared to schemes involving joint transmission from several transmission points (see Section 3.3.1.1.2 below) are that the requirements on the coordination links and on the backhaul are much reduced, since typically

- only information on the activated beams (in case of practical implementations, for the ideal case full CSI is required, see appendix B.5) and/or scheduling decisions need to be coordinated, and
- the user data do not need to be made available at the coordinated transmission points, since there is only one serving transmission point for one particular user.

3.3.1.1.2 Cooperative transmission

The next form of coordinated transmission is cooperative transmission, where two or more transmission points cooperate in serving a particular user, which is illustrated in Figure 3.6 below. Several different schemes can be envisioned in this case. The simplest form of cooperative transmission is simulcast from several transmission points, similar to what normally is referred to as macro diversity. This improves the total transmitted power and is typically applicable to cell edge users. Another form of cooperative transmission is joint signal processing, where both non-coherent and coherent approaches can be envisioned. In the follwing subsections we will discuss the different approaches of cooperative transmission in somewhat more detail. Note also that cooperative transmission is briefly touched upon in section 2.1.1.1.

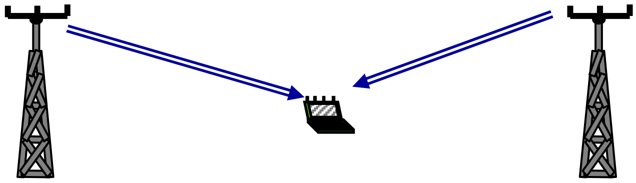


Figure 3.6: Illustration of cooperative transmission

3.3.1.1.2.1 Macro diversity approaches

The simplest form of cooperative transmission is simulcast from several transmission points, which typically is referred to as macro diversity. This technique is suitable for users located at the cell edge in order to improve the robustness of the radio link. On top of this, one can put space-time or space-frequency coding, e.g. the Cellular Alamouti technique [PR07] which increases the cell-edge performance even further through enhanced diversity. However, the benefits of such techniques compared to single-cell transmission is unclear from the network capacity perspective, since the time-frequency resources allocated to one user have to be reserved also at the cooperating cells, leading to a reduced amount of available resources for the overall system.

3.3.1.1.2.2 Non-coherent joint signal processing

One example of a non-coherent approach would be coordinated multi-site multi-user beamforming based on channel statistics, which is a reduced complexity approach compared to the coherent approaches described below. Two approaches can be distinguished; in the first one the linear pre-coding is performed jointly and transmitted from a selected set of transmission points in the coverage area. In this case we consider a joint beamforming concept [VAL+06] and joint scheduling for all transmission points in the cooperation area.

In the second approach, see e.g. [SCW+07a], each transmission point performs individually the multi-user linear precoding of the scheduled UTs, which reduces the need to exchange CSI and joint precoding weights between the collaborating transmission points and the central entity, at the price of residual inter-cell interference. A similar proposal is given in [YSL+08], involving codebook-based single-cell beamforming (or Grid of Beams), where the UT receives one beam from each collaborative transmission point. This scheme requires the UT to feedback to the network only the index of the best beam received from each transmission point. Common for this second type of approaches is that the transmission points jointly serve the users in the cooperation area by providing the standard pre-coding beams, i.e. by transmitting from each site separately. The scheduling process in done jointly, but the beamforming is done separately for all sites belonging to a specified cooperation area. Since the residual interference is suppressed at the user terminals, the total number of beams/streams transmitted to one or more users at a given time/frequency chunk is limited by the number of antennas at the user terminals.

3.3.1.1.2.3 Coherent joint signal processing

The most advanced forms of CoMP involves coherent joint signal processing relying on instantaneous channel state information (CSI). This facilitates multi-cell multi-user precoding techniques like linear beamforming which allow at most N users to be served simultaneously, where N is the total number of antennas of the collaborative cluster. Therefore, the same number of users can be served simultaneously on one time-frequency resource as in single-cell transmission, while the interference between the users is minimised. In addition to linear techniques such as Zero Forcing (ZF) and MMSE (Minimum Mean Square Error) precoding, also non-linear techniques like dirty paper coding can be applied.

Ideally, the coherent joint signal processing is able to eliminate completely the interference by precoding the signals based on the instantaneous CSI at a central processing unit. However, true multi-user multi-cell precoding techniques are very challenging from the practical implementation point of view, since they require

- the user data to be made available at the cooperating transmission points
- a tight frequency synchronization of the coordinated transmitters
- complete channel state information of all jointly processed links is required at the transmitters. It can be achieved either via reverse link measurements (TDD) or feedback from user terminals (FDD)
- in case of FDD; the UT to estimate the channels from each cooperating transmission point (antenna), which imposes requirements on the reference signal design to enable such estimation with sufficient quality, or additional signal processing to be able to separate the reference signals from different cells; in addition the UT needs to be able to read the BCH channel of the neighbour cells
- a large amount of data to be exchanged on the coordination links: the CSI from the transmission points to the central entity, and the computed precoding weights from the central entity to the collaborating transmission points.

Coherent joint signal processing allows several users to be served in the same time-frequency transmission slot using space division multiple access (SDMA) methods, e.g. beamforming/precoding across several distributed antenna heads. SDMA can be used to improve the utilisation of the physical resources (space, time, frequency) by exploiting the available spatial degrees of freedom in a downlink multi-user MIMO channel, at the expense of somewhat increased complexity [TCJ08a]. Channels between user terminals and different distributed antenna heads can be highly uncorrelated. This improves multiplexing gain in LOS conditions, where the antennas at one antenna head are correlated.

3.3.1.2 Uplink

3.3.1.2.1 Dynamic network reconfiguration and coordinated scheduling

The dynamic network reconfiguration and coordinated scheduling described for the downlink in section 3.3.1.1.1 is of course also applicable for the uplink. For example, a rather simple form of CoMP on the uplink is dynamic coordinated scheduling, meaning that the scheduling of UEs are coordinated among the different transmission/reception points in such a way that the interference among them is minimised. Again, the main advantage compared to schemes involving joint reception at several reception points (see Section 3.3.1.2.2 below) is that the requirements on the coordination links are much reduced since only information on scheduling decisions need to be coordinated.

3.3.1.2.2 Coherent joint processing

A more advanced form of uplink CoMP is to coherently combine and process signals received at different reception points. The main benefits are that energy can be collected at several reception points, and also that advanced combining algorithms can be used in the receive processing in order to cancel out interference. However, this approach puts high requirements on the coordination links since the received signals need to be exchanged.

3.3.2 Achievable performance and benefits

The overall target with all coordinated multipoint transmission/reception approaches is to improve data rates and coverage for the users with worst conditions and improve overall capacity. In other words, improve cell edge data rates without degrading for others, and to distribute the user perceived performance more evenly in the network.

Of the coordination alternatives outlined above, it can be expected that all of them will provide gains compared to traditional networks. Coordinated scheduling will provide gains since it allows interference avoidance to some degree, while the best performance will be achieved with the coherent signal processing approaches, since those in principle are able to completely eliminate the negative effects of interference in the network. In the following subsections the initial performance evaluations of some CoMP approaches are briefly summarised.

3.3.2.1 Performance of Multi-cellular Distributed versus Co-located MIMO

The capacity of a traditional co-located multiple-input multiple-output (MIMO) system is often severely limited in realistic propagation scenarios, especially in the presence of interference. One remedy is to employ a distributed MIMO system. In this section, we compare the downlink performance of an OFDM based distributed MIMO system to that of a co-located MIMO system using the WINNER channel model as defined in [WIN2D112].

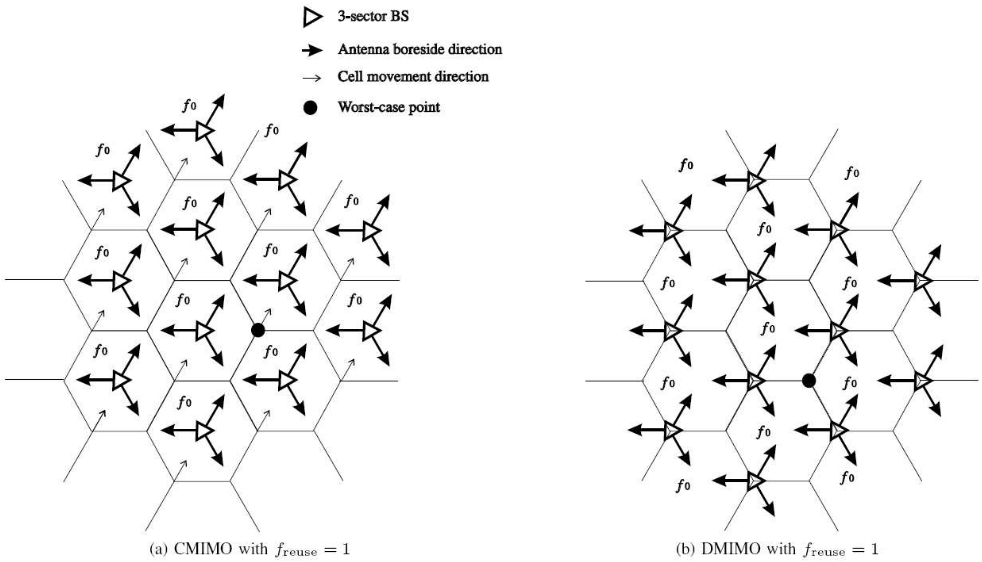


Figure 3.7: Conceptual layout of a network relying on BS collaboration (right), from a conventional network layout (left)

As illustrated in Figure 3.7, the distributed MIMO scenario (right) can be derived from the co-located MIMO scenario (left), but shifting the hexagonal grid of the cell-layout in the direction of the arrows. In the considered distributed MIMO scenario, to serve a UT the BS transmits jointly from all antenna arrays covering one cell, i.e. one large antenna array is formed, which consists of 3 sub-arrays. Vertical polarized uniform linear arrays (ULAs) are assumed at both the BS and the UTs. With M_T antennas per BS array this results in a total of $3M_T$ transmit antennas for one cell. Each UT uses M_R antenna elements to receive the signal. No further BS collaboration between different cells is considered, i.e. the cellular nature of the system is maintained.

As shown in Appendix B.4, the distributed MIMO improves the outage capacity over a large part of the cell area, and also smoothens the outage capacity over the cell. In addition, the results show that distributed MIMO increases the eigenvalues due to the inherent macro diversity. Thus, it can be concluded from the simulation results that distributed MIMO is suitable for reducing the co-channel interference in an interference limited multicell environment and thus improve the system performance.

3.3.2.2 Transceiver optimisation with coordinated multipoint processing

A generalised method for joint design of linear transceivers with coordinated multi-cell processing subject to per-BS/antenna power constraints is outlined and evaluated in Appendix B.5. The system optimisation objective can be, for example, balance the weighted SINR across all the transmitted data streams or maximise the sum rate. The general method can accommodate a variety of scenarios from coherent multi-cell beamforming across a large virtual MIMO channel to single-cell beamforming with inter-cell interference coordination and beam allocation.

- Coherent multi-cell beamforming with per BS and/or per-antenna power constraints, which requires a full phase synchronism between all BSs
- Coordinated single-cell beamforming case, where all the transceivers are jointly optimised while considering the other-cell transmissions as inter-cell interference.
- Any combination of above two, where the joint processing region may be different for each user.

In appendix B.5 the performance of different coherent/non-coherent and coordinated/non-coordinated multi-cell transmission methods with optimal and heuristic beam allocation algorithms is numerically compared in different scenarios with varying inter-cell interference. In this case, the system optimisation objective is to balance the weighted SINR, i.e., to maximise the minimum weighted SINR per stream. The coherent multi-cell beamforming greatly outperforms the non-coherent cases, especially at the cell edge and with a full spatial load. However, the coordinated single-cell transmission with interference avoidance and dynamic beam allocation performs considerably well with a partial spatial loading.

3.3.2.3 Downlink system level performance of coherent and non-coherent CoMP approaches

In appendices B.6 and B.7 initial system level performance evaluations of both non-coherent and coherent CoMP approaches are presented.

The first evaluation (presented in detail in appendix B.6) considers coherent transmission to users located close to the cell edge, also called a soft handover (SHO) region, based on a zero-forcing transmission scheme. The results with and without SHO and different power constraints are shown in Figure 3.8 below, which illustrates the complementary cumulative distribution function (CDF) of spectral efficiency per user. It can be seen that the users located in the SHO region may enjoy greatly increased transmission rates compared to the case without SHO, indicating that coherent CoMP has potential to substantially improve cell edge performance. For further details on the results, see appendix B.6.

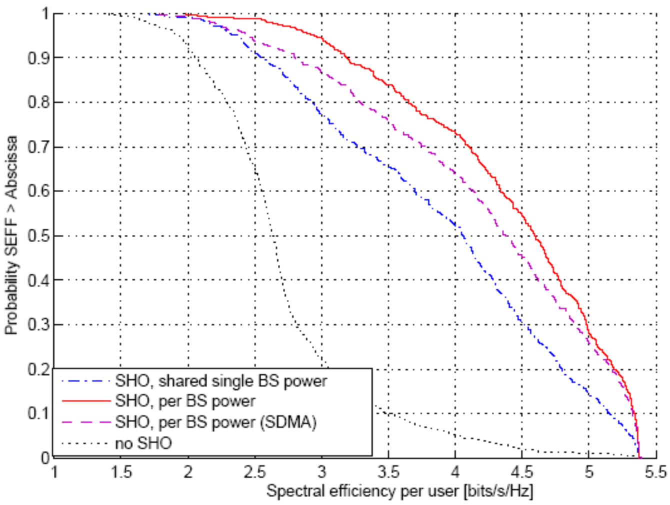


Figure 3.8: CDF of user spectral efficiency per SHO user with 30% average system load and 3 dB SHO window

In appendix B.7 the performance of a baseline LTE release 8 system is compared to that of a CoMP system employing a non-coherent approach based on coordinated scheduling and to that of a CoMP system employing a coherent approach based on zero-forcing beamforming.

The results, summarized in Table 3.1 below, show that the coherent approach achieves best performance, but that the non-coherent approach also achieves significant gains over the baseline LTE release 8 system configuration. For example, with a coordination cluster of 9 cells the coherent approach gains 67% in average throughput and 272% in cell edge user bit rate compared to the LTE release 8 system. The corresponding figures for the non-coherent approach based on coordinated scheduling are 54% and 220%, respectively. It should though be noted that the coordinated scheduling approach trade offs packet delay for user bit rate, which is not shown in these results.

Table 3.1: Summary of relative gains over the baseline LTE release 8 system configuration

Coordination cluster size	CoMP approach	Cell-edge bit rate fixed at 0.75 bps/Hz	Average throughput fixed at 2.2 bps/Hz/cell
9	Coordinated scheduling	54 % gain in average throughput	220 % gain in cell-edge bit rate
	Zero-forcing	67 % gain in average throughput	272 % gain in cell-edge bit rate
21	Coordinated scheduling	51 % gain in average throughput	200 % gain in cell-edge bit rate
	Zero-forcing	108 % gain in average throughput	500 % gain in cell-edge bit rate

Finally, it should be emphasized that the results here are based on relatively ideal assumptions and that the performance and conclusions might change as more impairments are added and when practical implementation limitations are taken into account. However, the evaluations should at least provide an indication of the technology potential of CoMP approaches.

3.4 Relaying in the framework of CoMP

The introduction of Relay Nodes (RN) which are controlled by the network allows to use them as part of a coordinated multipoint system. The RNs can be used to extend the actual coverage or to densify the actual network to enhance the user throughput at the cell edge. When the connection between relays and the Base Station (BS) uses the available cell time frequency resources, the backhauling is called "in band".

The proposed concepts consider the inband backhauling with half duplex mode and therefore one has to distinguish between two different phases: the first one concerns the link BS-RN and the second one the RN-User terminals (UT). Indeed, one can divide the cooperation frame into two time-slots. During the first time-slot the relay nodes are treated as additional UT, while during the second time-slot the BS and the relays form a distributed, virtual antenna array. Figure 3.9 illustrates an example of the downlink cooperation frame when only one RN is considered. Once the RN receives the signal from the BS, it can either amplify it and transmit (AF) or decode and transmit it (DF). When the BSs and/or RN are equipped with several antennas one can exploit the available resources in time, frequency and space more efficiently by optimizing them by at the scheduling.

In the following sections, three new concepts are proposed. The first concerns the integration of the RN resources into the scheduling process where BS and RN have multiple antennas. The second proposes a coding scheme based on the full diversity full rate block code for single antenna case. The last one is an extension of a scheduling concept previously introduced in the section 2.3.3 to the Relay Enhanced Cell (REC).

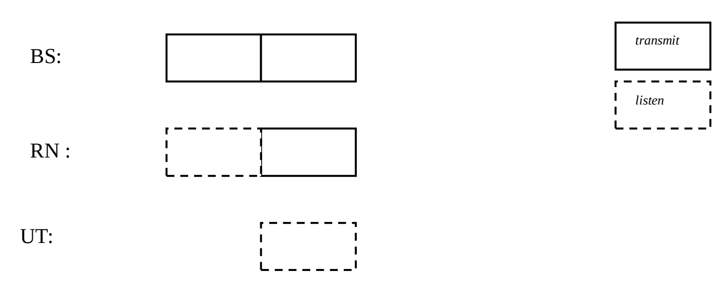


Figure 3.9: Two slot downlink cooperating frame

3.4.1 A Multi-User MIMO Relaying Approach

A multi-user MIMO relaying approach is here proposed that uses infrastructure-based half-duplex Amplify-and-Forward (AF) relays and linear precoding based block-diagonalization. The relays are assumed to be half-duplex and the communication is thus divided into two time-slots. The concept is analysed for the downlink scenario. During the first time-slot the relay nodes are treated as additional User Terminals (UTs), while during the second time-slot the Base-Station (BS) and the relays form a distributed, virtual antenna array as illustrated in Figure 3.10. In contrast to many relay applications, the purpose of the proposed scheme is not to increase diversity, but rather to increase the system throughput at the borders of a communication cell or in areas with a high user density. The performance of the proposed concept is investigated by examining the sum-capacity of the system as well as the distribution of the capacity over the cell-area.

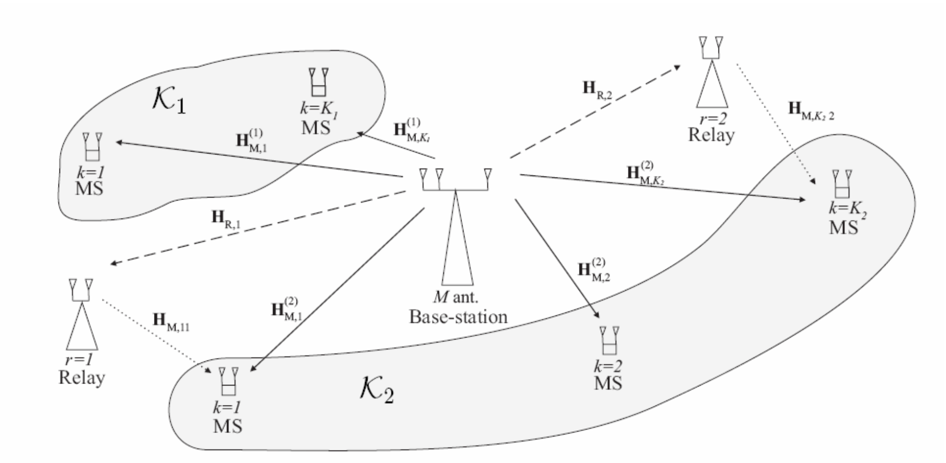


Figure 3.10: Multi-user MIMO relaying concept

By integrating the relays into the scheduling process, one can exploit the available resources in time, frequency and space more efficiently. For instance, serving relays on available spatial modes of the system instead of dedicated subcarriers or time slots avoids or at least mitigates the loss in spectral efficiency commonly associated with half-duplex relay communication. Following the notation in Figure 3.10, the BS employs an *M*-element antenna array, while each relay and UT has an *N*-element antenna array. The number of UTs served by the BS during the first and the second timeslot are denoted as *K1* and *K2*, respectively. With these assumptions, it is straightforward to show that 2*M/N* users are served over the 2 time slots independent on the number of relays in use, [WSO08].

The proposed system setup assumes a joint optimization of scheduling, relay gain, precoding, and power allocation. Scheduling here refers to the problem of deciding which terminals and which relays to serve during the two time-slots. By using two simple greedy algorithms to solve this optimization task, and linear multi-user MIMO pre-coding based on block-diagonalization, the proposed scheme increases the sum-capacity: In a first step, the *K1* set and *K2* set are chosen to maximize the sum capacity without relays, and then iteratively relays are included in case the sum capacity is increased, as described in detail in [WSO08]. Thus, the sum capacity is always larger or equal to the case without relays, i.e. the relays are not used in case they do not improve in a given usage scenario.

In Appendix B.8 it is shown that with the proposed scheme substantial sum-capacity gains can be achieved compared to a system not benefiting from a relay. Furthermore it is illustrated that the proposed scheme allows for a redistribution of the available throughput over the cell-area, while at the same time achieving a sum-capacity gain.

3.4.1.1 Impact on the overall system concept

Since the proposed relaying concept assumes a joint optimization of scheduling, relay gain, precoding, and power allocation, perfect channel state information is needed in all the involved nodes. Thus, further work is needed on this relaying concept to explore the gains under imperfect channel state information based on specific pilot and feedback schemes. In addition, the concept needs to be evaluated with a more realistic channel model, with user fairness constraints and in a multi-cellular scenario.

3.4.2 Distributed space time coding

3.4.2.1 Concept description

Several cooperative protocols have been proposed and they can be classified into two families: orthogonal and non orthogonal protocols [AES05]. By considering a back-hauling in band, the transmission between the base station and the RN will impact the evaluated rate since it consumes a part of the available cell resources. On the other hand, the receiver can listen to this first phase which can enhance the received signal quality. For example if we use the Alamouti code in a distributed way, we transmit 2 symbols on 4 time symbol and this corresponds to a rate of ½ symbol per time symbol. However, if only the direct transmission is used the rate is 1 symbol per time symbol.

We propose to use the full-rate full diversity Golden Code [BRV05] in a distributed way that will allow to increase the diversity without reducing the rate caused by the first phase of the transmission between the BS and RN. The transmission protocol is the following:

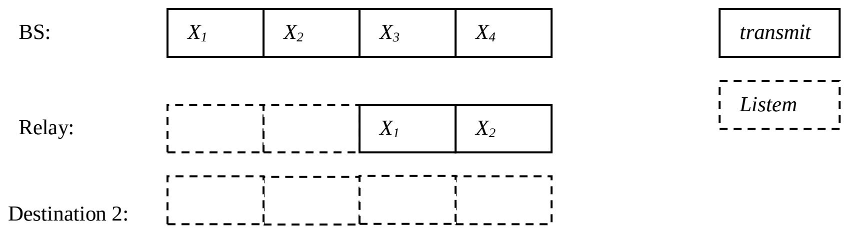


Figure 3.11: Genie aided Golden code protocol

Where X_1, X_2 , X_3 and X_3 are the elements of the space time code:

$$\begin{bmatrix} X_1 & X_2 \\ X_3 & X_4 \end{bmatrix} = \begin{bmatrix} \alpha(s_1+\theta s_2) & \alpha(s_3+\theta s_4) \\ i\bar{\alpha}(s_3+\bar{\theta}s_4) & \bar{\alpha}(s_1+\bar{\theta}s_2) \end{bmatrix}$$

And $\theta = \frac{1+\sqrt{5}}{2}, \bar{\theta} = \frac{1-\sqrt{5}}{2}, \alpha = 1+i-i\theta, \bar{\alpha} = 1+i-i\bar{\theta}$.

As we can see on the Figure 3.11, the transmission rate is 1 symbol per time symbol since the all X_i are transmitted on 4 time symbol and they contain 4 uncoded symbols (s_1..s_4). The genie aided protocol is the one that assumes a perfect decoding (with no errors) of the signal received from the BS at the relay. It represents the upper bound of the achievable rate by the protocol compared to the realistic ones using the AF or DF strategies. Indeed, the performance could be degraded by the amplification of the relay noise or the errors when decoding.

3.4.2.2 Performance evaluation

The performance of genie aided potocols is an upper bound of the expected performance. The use of AF strategy at the RN will reduce the performance. We compare the genie aided proposed scheme throughput with the ones of the following schemes:

- Genie Aided Alamouti based scheme with inband backhauling: the received signal by the relay is assumed to be perfectly decoded.
- Single link Base station-Mobile
- Single link Relay-Mobile

The system model, the Alamouti protocol description and the throughput evaluation methodology are detailed in the appendix B.9.

Simulation results are shown in Figure 3.12 for different transmitting power sets (P^1_{BS}, P^2_{BS}, P_{Rs}), where D_{rd} represents the distance between MS and the RN. The proposed protocol gives the best performance since there is no loss of the information due to the inband backhauling and it acts as a direct link when the mobile is near the base station.

Figure 3.13 shows the performance for the Amplify and Forward protocol where the link BS, RN is a Rayleigh channel. The proposed scheme outperforms the others without requirement of additional signaling to switch from a transmitting scheme to another.

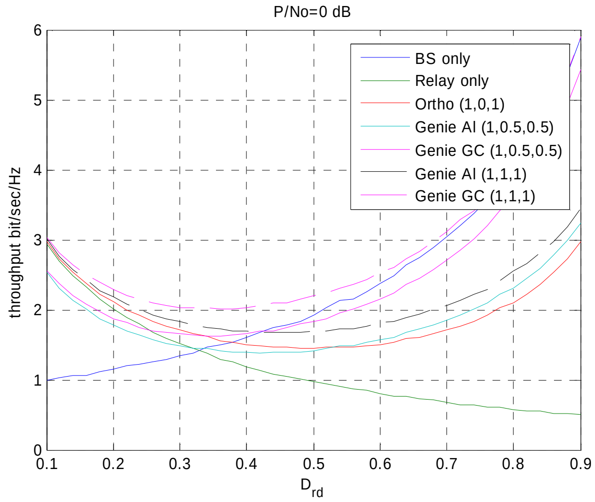


Figure 3.12: Genie aided transmission protocol performance

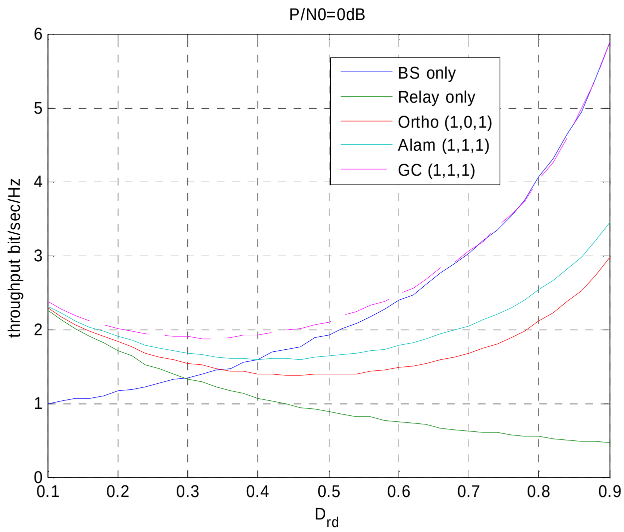


Figure 3.13: Amplify and forward transmission protocol performance

3.4.2.3 Impact on the signalling and practical considerations

If the Alamouti based protocol is used, a switching is needed to obtain the optimal performance. Indeed, depending on the location (or the average SNR) of the mobile the system will switch the transmission scheme to the direct BS link or the direct RN link. There is no important impact on the signalling. For the link adaptation procedure, the SINR is easily obtained with this space time code to estimation the link quality.

If the Golden code is decided, no switching procedure is needed since it gives the best performance for all positions. However, based on the protocol description, only amplify and forward protocol can be used in this case because the decoding of only a part of the code at the relay is tricky [HOS08]. Moreover, the receiver has to be the maximum likelihood (ML) to obtain the transmitting diversity. In this case the link adaptation metric is not obvious to obtain.

We have to notice again that these analyses are based on the assumption of inband backhauling with half duplex mode.

3.4.3 Low complexity resource allocation for multi-user SDMA in REC

3.4.3.1 Description of the concept

Based on the version for multiple base stations desribed in 2.3.3, the spatially beneficial transmitter/receiver combinations can also be estimated in a REC. When the RNs are half duplex, they can be treated as user terminals in the time slots when the RNs receive. And when they transmit, they become additional base stations for the algorithm. Full duplex relay nodes could be supported in a similar fashion. Details of the concept as well as simulation results on interference avoidance in relay enhanced cells are provided in Appendix B.10.

3.4.3.2 Expected requirements on signalling and measurements

The genie performing multi-cell coordination needs to know the channel matrices between all combinations of nodes in the system to be able to estimate interference. However, it can be safely assumed that no additional overhead may be needed to signal measurements of the channels between any RN and the BSs. These channels can be obtained with a similar PACE procedure as for the users in the single BS system: the RN could send uplink pilots without precoding and the BSs could then perform channel estimation. As a simplification, the stationarity of the RNs can be exploited in the SDMA scheme during the scheduling process as presented in [WIN2D341] Annex G.1. The only overhead stems from the necessity to signal the channels between any RN and all users back to the central intelligence. Assuming that the BSs are connected by some sort of backbone network, it may be sufficient for an RN to only signal to the nearest BS. If the RN has multiple antennas, spatial multiplexing can be used for this purpose.

4. Conclusion

This deliverable captured the first set of best innovative concepts identified in the field of Advanced Multiple Antenna Systems for potential inclusion into the WINNER+ system concept. The concepts consist of promising principles or ideas as well as detailed innovative techniques. For each concept, the associated benefits as well as the corresponding requirements on the system architecture and protocols, measurements and signalling, have been considered.

In Chapter 2, a set of innovative concepts for advanced antenna schemes in the context of conventional cellular networks were presented. The proposed concepts include several detailed SDMA signal processing solutions for improving the capacity of cellular networks employing multiple antenna base stations and terminals. The main framework of the presented schemes consists of downlink spatial user multiplexing and beamforming by means of linear transmit precoding and scheduling. Since both precoding and scheduling depend on CSI knowledge in the transmitter (CSIT), most of the proposals focus on how to make CSIT available and accurate enough.

The proposals in Section 2.1 form a realistic and promising set of improvements to the WINNER II wide-area FDD solution that employs the Grid of Beams precoding concept. The improvement arises from interference management solutions that enable either interference rejection receiver processing in terminals, or interference avoidance scheduling in the network side. These proposals are as such readily applicable to LTE as well. On the other hand, Section 2.2 introduced more revolutionary concepts. The focus there is on the careful design of CSI feedback from mobiles to the base station, in order to facilitate beam selection and efficient transmit-receive zero-forcing. Finally, in Section 2.3 a generic methodology for multiuser transmit-receiver processing under various system optimization criteria was presented. There, nearly perfect CSIT is assumed, which implies that the method is best applicable in TDD systems with low mobility users. Most of the new concepts in Chapter 2 deal with joint precoder design and user scheduling. However, in order to reduce complexity and to support more general protocols, it is beneficial to essentially decouple the scheduling from the precoder choice. Therefore, a scheduler that supports generic precoder designs and multi-cell interference avoidance was suggested Section 2.3. Due to its generality, it is a promising approach for practical networks.

The introduction of CoMP systems, namely systems where a coordination among multiple transmitters and/or receivers take place, have been proposed in this deliverable in Chapter 3 as one of the most promising techniques aiming at increasing the overall data rate of innovative radio access networks. From a theoretical point of view CoMP systems could significantly improve performances in the radio access network both in terms of average performance per cell and for users in the cell borders regions.

In order to fully exploit and take profit of the above mentioned benefits, CoMP systems have been considered as a possible innovation to be proposed and supported in future radio access systems. A close relationship with the activities on this same topic carried on in the main standardization bodies (3GPP, IEEE) has been established and the main impacts that the introduction of CoMP could have on the systems have been analyzed in Section 3.1. In the overall framework of CoMP, different architectures are suggested in Section 3.2: inter-cell coordination among base stations; coordination among Radio over Fiber connected remote units, both in inter-cell and intra-cell layouts; coordination including relaying nodes in cooperation with related base stations. For each of the proposed architectures innovative solutions are suggested and related most important impacts on the existing network are pointed out. Aiming at assessing the achievable performance obtained by means of CoMP systems, some preliminary evaluations have been performed and described in 3.3. Even if the study is still going on and many assumptions made are mostly ideal the first conclusions reached are quite promising, prompting to further investigate CoMP introduction and full exploitation. Finally, CoMP evaluations in this deliverable include also relaying schemes in cooperation with related base stations (Section 3.4). The results obtained by very simple relaying schemes suggest to further investigate this approach as one of the most promising.

Important steps forward in the CoMP area are foreseen in order to fully evaluate possible advantages CoMP could bring about. Future studies will concentrate on refining architectural CoMP proposals, in close relationship with future networks features, and on performing further link and system evaluations, including less ideal system concepts. Furthermore, in close cooperation with the activity in the standardization consortia, the final proposal for CoMP will be refined in order to impact as little as possible to the currently standardized next generation networks proposals.

5. References

[3GPP25814] 3GPP TR 25.814, “Physical layer aspects for evolved Universal Terrestial Radio Access (UTRA)”, V7.1.0, Sep. 2006.

[3GPP36211] 3GPP TS 36.211 V8.0.0, “E-UTRA - physical channels and modulation (release 8),” Sept. 2007.

[3GPP36814] 3GPP TR 36.814, "Further Advancements for E-UTRA Physical Layer Aspects", V0.2.0, Sep. 2008, available in R1-084615 (RAN1#55).

[ABE06] D. Aktas, M. Bacha, J. Evans and S. Hanly, “Scaling results on the sum capacity of cellular networks with MIMO links”, IEEE Transactions on Information Theory, vol. 52, no.7, pp. 327–337, 2006.

[AES05] K. Azarian, H.El Gamal and P. Schniter "On the Achievable Diversity-Multiplexing Tradeoff in Half-duplex Cooperative Channels", IEEE Trans. On Information Theory, Vol. 51, No. 12, December 2005.

[AG07] A. Ashikhmin and R. Gopalan, “Grassmannian Packings for Quantization in MIMO Broadcast Systems,” in IEEE International Symposium on Information Theory (ISIT), Nice, France, June 2007.

[Alc08] R1-083759, Alcatel-Lucent, ‘UE PMI feedback signalling for user pairing/ coordination’, 3GPP TSG RAN WG1 #54bis, Prague, Czech Republic, September 2008.

[BCT+07] N. Benvenuto, E. Conte, S. Tomasin and M. Trivellato, “Joint Low-Rate Feedback and Channel Quantization for the MIMO Broadcast Channel,” in IEEE Africon’07, Windhoek, Namibia, Sept. 2007.

[Ben02] M. Bengtsson, “A pragmatic approach to multi-user spatial multiplexing,” in IEEE Sensor Array and Multichannel Signal Processing Workshop, Rosslyn, VA, USA, Aug. 2002, pp. 130–134.

[BH07] F. Boccardi and H. Huang, “A near-optimum technique using linear precoding for the MIMO broadcast channel,” in IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Honolulu, Hawaii, USA, Apr. 2007.

[BHA07] F. Boccardi, H. Huang, and A. Alexiou, “Hierarchical quantization and its application to multiuser eigenmode transmissions for MIMO broadcast channels with limited feedback,” in IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Athens, Greece, Sept. 2007.

[BHT07] F. Boccardi, H. Huang and M. Trivellato, “Multiuser Eigenmmode Transmission for MIMO Broadcast Channels with Limited Feedback,” in proc. IEEE International Workshop on Signal Processing Advances for Wireless Communications (SPAWC), Helsinki, Finland, June 2007.

[BK05] A. Bayesteh and A. K. Khandani, “On the User Selection for MIMO Broadcast Channels,” in IEEE International Symposium on Information Theory (ISIT), Adelaide, Australia, Sep. 2005.

[BKK+08] K. Balachandran, J. Kang, K. Karakayali, J. Singh, “Capacity Benefits of Relays with In-Band Backhauling in Cellular Networks”, in *IEEE International Conference on Coomunications (ICC 08)*, May 2008.

[BO01] M. Bengtsson and B. Ottersten, “Optimal and suboptimal transmit beamforming,” in Handbook of Antennas in Wireless Communications, L. C. Godara, Ed. Boca Raton, FL: CRC Press, 2001.

[BO08] E. Björnson and Björn Ottersten, “Exploiting Long-Term Statistics in Spatially Correlated Multi-User MIMO Systems with Quantized Channel Norm Feedback”, in Proc. ICASSP 2008.

[Boc07] F. Boccardi, Precoding schemes for MIMO downlink transmissions, PhD Thesis, University of Padova, 2007.

[BRV05] J-C. Belfiore, G. Rekaya and E. Viterbo, “The Golden Code : A 2 × 2 Full-Rate Space-Time Code with Non-Vanishing Determinants”, IEEE Transactions on Information Theory, vol. 51, Issue 4, April 2005.

[Bru05] K. Brueninghaus et al., “Link Performance Models for System Level Simulations of Broadband Radio Access Systems”, Proc. IEEE Int. Symp. Pers., Indoor, Mobile Radio Commun. Berlin, Germany, Sep. 2005.

[BV04] S. Boyd and L. Vandenberghe, Convex Optimization. Cambridge, UK: Cambridge University Press, 2004.

[CDG01] S. Catreux, P. Driessen, and L. Greenstein, “Attainable throughput of an interference-limited multiple-input multiple-output (MIMO) cellular system,” in IEEE Transactions on Communications, vol. 49, August 2001, pp. 1307 – 1311.

[CHC04] B. K. Chalise, L. Haering, and A. Czylwik, “Robust uplink to downlink spatial covariance matrix transformation for downlink beamforming,” in Proc. IEEE ICC., vol. 5, June 2004, pp. 3010–3014.

[CM04] Lai-U Choi and Ross D. Murch, “A Transmit Preprocessing Technique for Multiuser MIMO Systems Using a Decomposition Approach,” IEEE Tran. Wireless Commun., vol. 3, no. 1, pp. 20 – 24, Jan. 2004.

[CS03] G. Caire and S. Shamai, “On the achievable throughput of a multiantenna gaussian broadcast channel,” Information Theory, IEEE Transactions on, vol. 49, no. 7, pp. 1691–1706, 2003.

[DMH06] N.H. Dawod, I.D. Marsland and R.H.M. Hafez, “Improved transmit null steering for MIMO-OFDM downlinks with distributed base station antenna arrays”, IEEE Journal on Selected Areas in Communications, vol. 24, no. 3, pp. 419–426, 2006.

[DPS+08] E. Dahlman, S. Parkvall, J. Sköld and P. Beming, “3G Evolution – HSPA and LTE for Mobile Broadband”, 2nd ed., Academic Press, 2008.

[DS05] G. Dimic and N. Sidiropoulos, “On downlink beamforming with greedy user selection: Performance analysis and a simple new algorithm”, IEEE Transactions on Signal Processing, vol. 53, no. 10, pp. 3857–3868, 2005.

[FDH05b] M. Fuchs, G. Del Galdo, and M. Haardt, ”Low complexity space-time-frequency scheduling for MIMO systems with SDMA”, to appear in IEEE Transactions on Vehicular Technology September 2007.

[FDH06] M. Fuchs, G. Del Galdo, and M. Haardt, ”Low complexity spatial scheduling ProSched for MIMO systems with multiple base stations and a central controller”, In Proc. ITG/IEEE Workshop on smart Antennas, Guenzburg, Germany, March 2006.

[FKK+07] M. Fuchs, C. Kaes, U. Korger, and M.Haardt, “Comparison of MIMO Relaying Deployment Strategies in a Manhattan Grid Scenario,” in Proc. ITG/IEE Workshop on Smart Antennas, Vienna, Austria, February, 2007.

[HKK+08] Howard Huang, Cheeni Kadaba, Kemal Karakayali, Sivarama Venkatesan, " Network MIMO for Inter-cell Interference Mitigation", Contribution to IEEE 802.16m, IEEE C802.16m-08/044r1 (Alcatel-Lucent), Jan. 2008.

[Ho01] J. Holtzman, “Asymptotic analysis of proportional fair algorithm,” in 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), vol. 2, 2001, pp. 33–37.

[HOS08] C. Hucher, G.R.-B. Othman, A. Saadani “A New incomplete Decode and Forward Protocol” IEEE conference WCNC 2008.

[HP05] R. Heath and A. J. Paulraj, “Switching between diversity and multiplexing in MIMO systems,” IEEE Transactions on Communications, vol. 53, no. 6, 2005.

[JHJ+01] V. Jungnickel, T. Haustein, E. Jorswieck, V. Pohl, and C. von Helmolt, “Performance of a MIMO system with overlay pilots,” in *Global Telecommunications Conference, 2001. GLOBECOM ’01. IEEE*, vol. 1, 2001, pp. 594–598 vol.1.

[Jin07] N. Jindal, “Antenna Combining for the MIMO Downlink Channel,” Submitted to IEEE Trans. Wireless Communications, April 2007.

[JRV05] N. Jindal, W. Rhee, S. Vishwanath, S. Jafar, and A. Goldsmith, “Sum Power Iterative Water-filling for Multi-Antenna Gaussian Broadcast Channels,” IEEE Transactions on Information Theory, Vol. 51, No. 4, April 2005.

[JTW+H08] V. Jungnickel, L. Thiele, T. Wirth, M. Schellmann, V. Venkatkumar, and T. Haustein, „Feedback Design for Multiuser MIMO Systems“, 13th International OFDM-Workshop (InOWo), Hamburg, Germany, Aug. 2008.

[KBS07] T.T. Kim, M. Bengtsson and M. Skoglund, “Quantized Feedback Design for MIMO Broadcast Channels”, in Proc. ICASSP 2007.

[KFV06] M.K. Karakayali, G.J. Foschini and R.A. Valenzuela, “Network coordination for spectrally efficient communications in cellular systems”, IEEE Wireless Communications Magazine, vol. 3, no. 14, pp. 56– 61, 2006.

[KLJ08] P. Komulainen, M. Latva-aho, and M. Juntti, “Block diagonalization for multiuser MIMO TDD downlink and uplink in time-varying channel,” in Proc. ITG Workshop Smart Antennas, Darmstadt, Germany, Feb. 2008, pp. 74–81.

[KTL+09] P. Komulainen, A. Tölli, M. Latva-aho, and M. Juntti, “Downlink Assisted Uplink Zero-Forcing for TDD Multiuser MIMO Systems,” accepted for publication in IEEE Wireless Communications & Networking Conferece, WCNC 2009, Budapest, Hungary, April 2009.

[LH04] D. J. Love and R. W. Heath Jr., “Grassmannian Beamforming on Correlated MIMO Channels,” in IEEE Global Communication Conference (GLOBECOM) 2004, Dallas, TX, USA, Dec. 2004.

[LHL+08] D. J. Love, R. W. Heath, V. K. N. Lau, D. Gesbert, M. Andrews “An overview of limited feedback in wireless communication systems”, IEEE Journal on selected areas in communications (JSAC), vol. 26, no. 8, Oct. 2008.

[LHS03] D. J. Love, R. W. Heath Jr., and Thomas Strohmer, “Grassmannian Beamforming for Multiple-Input Multiple-Output Wireless Systems,” IEEE Trans. Information Theory, vol. 49, no. 10, pp. 2735–2747, Oct. 2003.

[LZ06] K. Letaief and Y.J Zhang, “Dynamic multiuser resource allocation and adaptation for wireless systems“, IEEE Wireless Communications Magazine, vol. 13, no. 4, pp. 38–47, 2006.

[MHM+08] "Classification on Interference Management Proposals in TGm", Contribution to IEEE 802.16m, IEEE C802.16m-08/142r6 (Mediatek, Huawei, Motorola, LGE, Alcatel-Lucent, Nextwave, Mitsubishi Electric, Panasonic), Mar. 2008.

[OBS20] OBSAI V2.0 Open Base Station Architecture Initiative “BTS System reference Document”, 2006

[PBG+08] A. Papadogiannis, H. J. Bang, D. Gesbert and E. Hardouin, "Downlink Overhead Reduction for Multi-Cell Cooperative Processing enabled Wireless Networks", in Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) 2008, Sept. 2008.

[PHG08] A. Papadogiannis, E. Hardouin and D. Gesbert, "A Framework for Decentralising Multi-Cell Cooperative Processing on the Downlink", in Proc. 4th IEEE Broadband Wireless Access Workshop (GLOBECOM 2008), New Orleans, USA, December 2008.

[PNJ+05] V. Pohl, P. H. Nguyen, V. Jungnickel, and C. von Helmolt, “Continuous flat-fading mimo channels: achievable rate and optimal length of the training and data phases,” *Wireless Communications, IEEE Transactions on*, vol. 4, no. 4, pp. 1889–1900, July 2005.

[PR07] S. Plass and R. Raulefs, "The cellular Alamouti technique", in Proceedings 6th International Workshop on Multi-Carrier Spread-Spectrum (MC-SS 2007), Herrsching, Germany, May 2007.

[R1-084649] "LS on support of ACK/NACK repetition in Rel-8", 3GPP TSG RAN WG1 meeting #55, R1-084649, Nov. 2008.

[Sam06] Samsung, “Downlink MIMO for EUTRA,” 3GPP TGS RAN WG1, R1-060335, Feb. 2006.

[Sam08] R1-082886, Samsung, “Inter-cell interference mitigation through limited coordination”, 3GPP TSG RAN WG1 #54, Jeju, Korea, August 2008.

[SCW+07a] Y. Song, L. Cai, K. Wu and H. Yang, "Collaborative MIMO Based on Multiple Base Station Coordination", Contribution to IEEE 802.16m, IEEE C802.16m-07/162 (Alcatel-Lucent), Aug. 2007.

[SCW+07b] Yang Song, Liyu Cai, Keying Wu, Hongwei Yang, "Collaborative MIMO", Contribution to IEEE 802.16m, IEEE C802.16m-07/244r1 (Alcatel-Lucent), Nov. 2007.

[SFF+99] M. Speth, S. Fechtel, G. Fock, and H. Meyr, “Optimum receiver design for wireless broad-band systems using OFDM. I,” *Communications, IEEE Transactions on*, vol. 47, no. 11, pp. 1668–1677, Nov. 1999.

[SH05] M. Sharif and B. Hassibi, “On the Capacity of MIMO Broadcast Channels With Partial Side Information,” IEEE Trans. Inf. Theory, vol. 51, no. 2, pp. 506–522, Feb. 2005.

[SH07] M. Sharif and B. Hassibi, “A comparison of time-sharing, DPC, and beamforming for MIMO broadcast channels with many users”, IEEE Transactions on Communications, vol. 55, no. 1, pp. 11–15, 2007.

[SS04] Q. H. Spencer and A. L. Swindlehurst, “A hybrid approach to spatial multiplexing in multiuser MIMO downlinks,” EURASIP J. Wireless Comm. and Netw., vol. 2004, no. 2, pp. 236–247, Dec. 2004.

[SSB+06] O. Somekh, O. Simeone and Y. Bar-Ness, A. Haimovich, “Distributed multi-cell zero-forcing beamforming in cellular downlink channels”, in Proc. IEEE Global Telecommun. Conf. San Francisco, CA, USA, 2006.

[SSB+07] O. Somekh, O. Simeone, Y. Bar-Ness, A. Haimovich, U. Spagnolini and S. Shamai, “An information theoretic view of distributed antenna processing in cellular systems”, in Distributed Antenna Systems: Open Architecture for Future Wireless Communications. Auerbach Publications, CRC Press, first edition, 2007.

[SSH04] Q. H. Spencer, A. L. Swindlehurst and M. Haardt, “Zero-Forcing methods for Downlink Spatial Multiplexing in Multiuser MIMO Channels,” IEEE Trans. on Signal Processing, vol. 52, no. 2, pp. 461–471, Feb. 2004.

[SSO07] M. Sternad, T. Svensson, T. Ottosson, A. Ahlen, A. Svensson and A. Brunstrom, “Towards systems beyond 3G based on Adaptive OFDMA transmission”, Proc. of IEEE, Vol. 95, No. 12, pp. 2432-2454, Dec. 2007

[STJ+07] M. Schellmann, L. Thiele, V. Jungnickel, and T. Haustein, “A Fair Score-Based Scheduler for Spatial Transmission Mode Selection“, 41st Asilomar Conference on Signals, Systems and Computers, Monterey, USA, IEEE, Nov. 2007.

[STJ08] M. Schellmann, L. Thiele, and V. Jungnickel, “Predicting SINR conditions in mobile MIMO-OFDM systems by interpolation techniques”, 42nd Asilomar Conference on Signals, Systems and Computers, Monterey, USA, Oct. 2008.

[SWO04] P. Svedman, S. Wilson, and B. Ottersten, “A QoS-aware proportional fair scheduler for opportunistic OFDM,” in IEEE 60th Vehicular Technology Conference, 2004. VTC2004-Fall, vol. 1, 2004, pp. 558 – 562.

[SWO08] N. Seifi, A. Wolfgang and T. Ottosson, “Performance Analysis of Distributed vs. Co-located MIMO-OFDM”, Proc. COST2100 Workshop on MIMO and Cooperative Communications, Trondheim, Norway, June 3-4, 2008.

[SZV02] S. Shamai, B.M. Zaidel and S. Verdu, “On information theoretic aspects of multi-cell wireless systems”, in Proc. 4th International ITG Conference on Source and Channel Coding. Berlin, Germany, 2002.

[TBH08a] M. Trivellato, F. Boccardi and H. Huang, "On transceiver design and channel quantization for downlink multiuser MIMO systems with limited feedback," IEEE Selected Areas in Communications, IEEE Journal on , vol.26, no.8, pp.1494-1504, October 2008.

[TBH08b] M. Trivellato, F. Boccardi and H. Huang, “Zero-Forcing vs Unitary beamforming in Multiuser MIMO Systems with Limited Feedback”, In Proc. of IEEE PIMRC, Sept. 08.

[TBT07] M. Trivellato, F. Boccardi, and F. Tosato, “User Selection Schemes for MIMO Broadcast Channels with Limited Feedback,” in proc. IEEE Vehicular Technology Conference Spring (VTC), Dublin, Ireland, Apr. 2007.

[TCJ07a] A. Tölli, M. Codreanu & M. Juntti, "Compensation of Non-Reciprocal Interference in Adaptive MIMO-OFDM Cellular Systems", IEEE Transactions on Wireless Communications, Vol. 6, No. 2, pp. 545-555, Feb. 2007.

[TCJ07b] A. Tölli, M. Codreanu, and M. Juntti, “Minimum SINR maximization for multiuser MIMO downlink with per BS power constraints” in Proc. IEEE Wireless Commun. and Networking Conf., Hong Kong, pp. 1144–1149, Mar. 2007.

[TCJ08a] A. Tölli, M. Codreanu & M. Juntti, "Cooperative MIMO-OFDM Cellular System with Soft Handover between Distributed Base Station Antennas", IEEE Transactions on Wireless Communications, Vol. 7, No. 4, pp. 1428-1440, April 2008.

[TCJ08b] A. Tölli, M. Codreanu & M. Juntti, "Linear Multiuser MIMO Transceiver Design with Quality of Service and Per-Antenna Power Constraints", IEEE Transactions on Signal Processing, Vol. 56, No. 7, Jul. 2008.

[TJ05] A. Tölli & M. Juntti, “Scheduling for multiuser MIMO downlink with linear processing”, Proc. IEEE Int. Symp. Pers., Indoor, Mobile Radio Commun. Berlin, Germany, 156–160, Sep. 2005.

[TJ06] A. Tölli & M. Juntti, “Efficient user, bit and power allocation for adaptive multiuser MIMO-OFDM with low signalling overhead” Proc. IEEE Int. Conf. Commun. Istanbul, Turkey, vol. 12, 5360–5365, Jun. 2006.

[TNL+98] M. Trott A. Narula, M. Lopez and G. Wornell, “Efficient use of side information in multiple-antenna data transmission over fading channels,” IEEE J. Select. Areas Commun., vol. 16, pp. 1423 – 1436, Oct. 1998.

[Tol08] A. Tölli, “Resource management in cooperative MIMO-OFDM cellular systems”, D. Sc. Thesis, University of Oulu, Finland, 2008

[TPK08] A. Tölli, H. Pennanen, and P. Komulainen, “SINR balancing with coordinated multi-cell transmission”, IEEE Wireless Commun. and Networking Conf., Budapest, Hungary, Apr. 2008, accepted for publication.

[TSS+08] L. Thiele, M. Schellmann, S. Schiffermüller, and V. Jungnickel, W. Zirwas, “Multi-Cell Channel Estimation using Virtual Pilots,” IEEE 67th Vehicular Technology Conference VTC2008-Spring, Singapore, May 2008.

[TSW+08] L. Thiele, M. Schellmann, T. Wirth, and V. Jungnickel, “On the Value of Synchronous Downlink MIMO-OFDMA Systems with Linear Equalizers“, *IEEE International Symposium on Wireless Communication Systems 2008 (ISWCS’08)*, Oct. 2008.

[TSZ+07] L. Thiele, M. Schellmann, W. Zirwas, and V. Jungnickel, “Capacity Scaling of Multiuser MIMO with Limited Feedback in a Multicell Environment“, 41st Asilomar Conference on Signals, Systems and Computers, IEEE, Nov. 2007, invited.

[VAL+06] M. Vemula, D. Avidor, J. Ling, and C. Papadias, “Inter-cell co-ordination, opportunistic beamforming and scheduling,” in IEEE International Conference on Communications, 2006. ICC ’06., vol. 12, June 2006, pp. 5319–5324.

[VT03] P. Viswanath and D. Tse, “Sum capacity of the vector Gaussian broadcast channel and uplink-downlink duality”, IEEE Transactions on Information Theory, vol. 49, no. 8, pp. 1912–1921, 2003.

[VVH03] H. Viswanathan, S. Venkatesan and H. Huang, “Downlink Capacity Evaluation of Cellular Networks With Known-Interference Cancellation,” IEEE J. Sel. Areas Comm., vol. 21, no. 5, pp. 802–811, June 2003.

[WCM05] J. Salo, G. Del Galdo, J. Salmi, P. Kyösti, M. Milojevic, D. Laselva, and C. Schneider, “MATLAB implementation of the 3GPP Spatial Channel Model,” Tech. Rep., 3GPP TR 25.996, Jan. 2005, Available http://www.tkk.fi/Units/Radio/scm/.

[WES06] A. Wiesel, Y. C. Eldar, and S. Shamai, “Linear precoding via conic optimization for fixed MIMO receivers,” IEEE Trans. Signal Processing, vol. 54, no. 1, pp. 161–176, Jan. 2006.

[WIN2D112] IST-4-027756 WINNER II, D1.1.2, “WINNER II Channel Models”, September 2007.

[WIN2D223] IST-4-027756 WINNER II, D2.2.3, “Modulation and coding schemes for the WINNER II system”, November 2007.

[WIN2D341] IST-4-027756 WINNER II Deliverable “D3.4.1 The WINNER II Air Interface: Refined Spatial-Temporal Processing Solutions”, October 2006.

[WIN2D351] IST-4-027756 WINNER II “D3.5.1 Relaying concepts and supporting actions in the context of CGs”, October 2006.

[WIN2D61310] IST-4-027756 WINNER II, D6.13.10 V1.0, Final CG “wide area” description for integration into overall System Concept and assessment of key technologies, November 2007

[WIN2D6137] IST-4-027756 WINNER II, “D6.13.7 Test scenarios and calibration case issue 2,” December 2006.

[Win84] J. Winters, “Optimum combining in digital mobile radio with cochannel interference,” *IEEE Journal on Selected Areas in Communications*, vol. 2, no. 4, pp. 528–539, 1984.

[WSO08] A. Wolfgang, N. Seifi and T. Ottosson, “Resource allocation and linear precoding for relay assisted multiuser MIMO systems”, Proc. International ITG Workshop on Smart Antennas (WSA 2008), Darmstadt, Germany, Feb. 26-27, 2008.

[WSS06] H. Weingarten, Y. Steinberg and S. Shamai, “The capacity region of the Gaussian multiple-input multiple-output broadcast channel”, IEEE Transactions on Information Theory, vol. 52, no. 9, pp. 3936–3964, 2006.

[Wyn94] A.D. Wyner, “Shannon–theoretic approach to a Gaussian cellular multiple-access channel”, IEEE Transactions on Information Theory, vol. 40, no. 6, pp. 1223–138, 1994.

[YG06] T. Yoo and A. Goldsmith, “On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming,” IEEE J. Select. Areas Commun., vol. 24, no. 3, pp. 528 – 541, Mar. 2006.

[YL07] W. Yu, T. Lan, “Transmitter Optimization for the Multi-Antenna Downlink With Per-Antenna Power Constraints,” Signal Processing, IEEE Transactions on , vol.55, no.6, pp.2646-2660, June 2007.

[YSL+08] C. I. Yeh, Y. S. Song, S. J. Lee, B.-J. Kwak, J. Kim, and D. S. Kwon, "Frame Structure to Support Inter-cell Interference Mitigation for Downlink Traffic Channel using Co-MIMO and FFR", Contribution to IEEE 802.16m, IEEE C802.16m-08/017r1 (ETRI), Jan. 2008.

[ZMM+07] H. Zhang, N.B. Mehta, A.F. Molisch, J. Zhang and H. Dai, “On the fundamentally asynchronous nature of interference in cooperative base station systems”, in Proc. IEEE Int. Conf. Commun., Glasgow, Scotland, UK, 2007.

[ZT03] L. Zheng and D. Tse, “Diversity and multiplexing: A fundamental tradeoff between in multiple antenna channels,” IEEE Transactions on Information Theory, vol. 49, no. 5, pp. 1073–1096, May 2003.

[ZTZ+05] P. Zhang, X. Tao, J. Zhang, Y. Wang, L. Li and Y. Wang, “A vision from the future: beyond 3G TDD”, IEEE Commun. Mag., vol. 43, no. 1, pp.38– 44, 2005.

A. Appendix for Advanced Antenna Schemes

A.1 On the value of synchronous downlink: Impact of estimation errors on the throughput performance with linear receivers

A.1.1 System Model

The downlink MIMO-OFDMA transmission via N_T transmit and N_R receive antennas for each subcarrier is described by

$$\mathbf{y} = \mathbf{H}\mathbf{C}_{\omega}\mathbf{x} + \mathbf{n} \,,$$

where $\mathbf{H}$ is the $N_R \times N_T$ channel matrix and $\mathbf{C}_\omega$ the unitary $N_T \times N_T$ pre-coding matrix; $\mathbf{x}$ denotes the $N_T \times 1$ vector of transmit symbols; $\mathbf{y}$ and $\mathbf{n}$ denote the $N_R \times 1$ vectors of the received signals and of the additive white Gaussian noise (AWGN) samples, respectively.

All BSs are assumed to provide Ω fixed unitary beam sets $\mathbf{C}_\omega$, $\omega \in \{1, ...,\Omega\}$. Each beam set contains N_T fixed beams $\mathbf{b}_{\omega,u}$ with $u \in \{1,\ldots,N_T\}$. Each BS i independently selects one of these sets. In the following, we denote $\mathbf{b}_{i,u}$ as the u-th precoding vector from the beam set selected by BS i. The received downlink signal $\mathbf{y}^m$ at the UT m in the cellular environment is given by

$$\mathbf{y}^m = \underbrace{\mathbf{H}_i^m \mathbf{b}_{i,u}}_{\overline{\mathbf{h}}_{i,u}} x_{i,u} + \underbrace{\sum_{\substack{j\in C_i \\ j\neq u}} \mathbf{H}_i^m \mathbf{b}_{i,j} x_{i,j}}_{\zeta_{i,u}} + \underbrace{\sum_{\substack{\forall k,j \\ k\neq i}} \mathbf{H}_k^m \mathbf{b}_{k,j} x_{k,j} + \mathbf{n}}_{\mathbf{z}_{i,u}}$$

The desired u-th data stream transmitted from the i-th BS is distorted by the intra-cell and inter-cell interference given as $\boldsymbol{\zeta}_{i,u}$ and $\mathbf{z}_{i,u}$, respectively. The BSs may select a limited number Q_i of active beams from the set to serve the users simultaneously. Therefore, the transmit power per beam is uniformly distributed over all non-zero transmit symbols $s_{i,j}$ with p_i/Q_i, where $p_i = \sum_{j=1}^{N_T} | s_{i,j} |^2$ is the total available power for BS i. Single-stream (ss) mode selected by BS i refers to the case $Q_i = 1$, while multi-stream (ms) mode refers to $Q_i > 1$. For the pre-coding beams $\mathbf{b}_{\omega,u}$ **,**columns from the DFT matrices are used, as proposed in [3GPP36211]. For simplicity, we confine our selection to a single beam set here, i.e. there is only one unitary pre-coding matrix $\mathbf{C}_1$. We further assume all interfering sectors always to serve their terminals with multiple data streams, i.e. $Q_k = 2\ \forall k\neq i$, while the selected sector i supports a single-stream only, i.e. $Q_i=1$ and thus $\boldsymbol{\zeta}_{i,u} = 0$. Note that we allow the UTs to select their best beam for single-stream transmission, thus the system benefits from higher capacities due to selection diversity.

Assuming a linear equalizer $\mathbf{w}_u$, which is required to extract the useful signal from $\mathbf{y}^m$, yields a post-equalization SINR at the UT for stream u given by

$$\mathrm{SINR}_u \geq p_i \frac{\mathbf{w}_u^H \overline{\mathbf{h}}_{i,u} \overline{\mathbf{h}}_{i,u}^H \mathbf{w}_u}{\mathbf{w}_u^H \mathbf{Z}_u \mathbf{w}_u} \;,$$

where $\mathbf{Z}_u$ is the covariance matrix of the interference signals in $\mathbf{z}_{i,u}$, i.e. $\mathbf{Z}_u = E[\mathbf{z}_{i,u} (\mathbf{z}_{i,u})^H]$ with E[.] being the expectation operator. For equalization, the interference-aware minimum mean square error (MMSE) receiver for single-stream transmission [Win84] is used and its achievable spectral efficiency is evaluated in a downlink OFDMA multi-cellular simulation environment. The MMSE equalizer reads

$$\mathbf{w}_u^{MMSE} = \frac{p_i \mathbf{R}_{yy}^{-1} \overline{\mathbf{h}}_{i,u}}{Q_i}$$

where, $\mathbf{R}_{yy}$ denotes the covariance matrix of the received signal $\mathbf{y}^m$, i.e. $\mathbf{R}_{yy} = E[\mathbf{y}^m(\mathbf{y}^m)^H]$. For reference purpose, we compare these results with results achievable by using a MRC receiver

$$\mathbf{w}_u^{MRC} = \overline{\mathbf{h}}_{i,u}$$

Introducing channel estimation errors yields to an estimate $\hat{\overline{\mathbf{h}}}_{i,u} = \overline{\mathbf{h}}_{i,u} + \delta_{i,u}$. Here, $\hat{\mathbf{x}}$ denotes the estimate of vector $\mathbf{x}$ and $\delta_{i,u}$ denotes the zero-mean Gaussian distributed error with variance μ, being the normalized MSE for channel estimation. Thus, the MRC receiver is given by $\hat{\mathbf{w}}_u^{MRC} = \overline{\mathbf{h}}_{i,u} + \delta_{i,u}$. The post-equalization SINR at the receiver may be lower bounded by [TSW+08]

$$SINR_u^{MRC,est} \geq SINR_u^{MRC,ideal}\left(1-\underbrace{\mu\left(1-\frac{1}{N_R}\right)}_{loss}\right)$$

The achievable $SINR_u^{MRC,est}$, which is obtained from inserting the estimated $\hat{\mathbf{w}}_u^{MRC}$ into $SINR_u$ from above, is degraded by the loss caused by the estimation errors with power μ. For example, assuming $N_R = 2$ and a normalized channel estimation MSE μ=0.1 yields a maximum SINR loss of 5%.

A.1.2 Covariance estimation

For interference suppression at the UT based on the MMSE equalizer, we require to obtain the system's covariance matrix $\mathbf{R}_{yy}$. In the following two mechanisms are considered to estimate the desired matrix.

A.1.2.1 Sample covariance estimator

Knowledge on interference conditions may be obtained by estimating the covariance matrix $\mathbf{R}_{yy}$ == E[$\mathbf{y}^m$($\mathbf{y}^m)^H$] of the received signal vector $\mathbf{y}^m$ across several subsequently received data symbols. Therefore, asynchronous downlink transmission from all BSs in the system may be sufficient. By assuming data transmission of i.i.d. transmit symbols x_k across channel k and averaging over s symbols, the estimation error in $\hat{\mathbf{R}}_{yy}$ decreases with s [SFF+99], [JHJ+01]. Let the total number of transmitted data symbols across a quasi-static channel be given by S. Then

$$\hat{\mathbf{R}}_{yy} = \frac{1}{S}\sum_{\forall s}\left(\sum_{\forall k,l}\mathbf{h}_{k,l}x_{k,l}(s)+\mathbf{n}\right)\left(\sum_{\forall k,l}\mathbf{h}_{k,l}x_{k,l}(s)+\mathbf{n}\right)^H$$

A.1.2.2 Correlation-based estimator

Alternatively, we use the pilot-aided multi-cell channel estimation scheme based on virtual pilot sequences, which has been introduced in section B.1. This estimation scheme allows for optimum correlation-based estimation of the interfering channels in fully synchronized multi-cell systems. Thus, the covariance may be estimated by directly utilizing channel estimates with sequence length n.

$$\widehat{\mathbf{R}}_{yy} = \sigma_n^2\mathbf{I} + \sum_{\nu=0}^{n-1}\sum_{l=1}^{N_T}\sigma_\nu^2\overline{\mathbf{h}}_{\nu,l}\overline{\mathbf{h}}_{\nu,l}^H$$

The suggested concept enables mobile terminals to distinguish more of the strong interference channels with an increasing length of the correlation window utilized for the estimation process. It does not require higher pilot overhead than in current systems, but results in a trade-off between the mobility of the user and the ability to track interfering channels. In this way, channels of nearby base stations may be estimated at an early stage due to the provided pattern, and therefore be separated using a short correlation window, e.g. over two transmission time intervals (TTIs). Estimating the channels of distant BSs may be less important due to their higher average path loss. Therefore, these BSs are forced to use sequences that require higher correlation window lengths to enable estimation of their interfering channels at the UT.

The suggested system concept is limited to use fixed DFT-based beamforming, i.e. only one precoding matrix $\mathbf{C}_1$ is provided for downlink transmission in all cells of the system. Thus, codebook entries are known at the UTs and dedicated pilots are not necessary to obtain knowledge on effective channels.

A.1.3 Performance evaluation

The performance is investigated in a triple-sectored hexagonal cellular network with 19 BSs in total. For simplicity, we employ the time-division multiple access (TDMA) round-robin scheduler for all UTs in the inner cell. Performance is evaluated for the sum throughput in a sector. This value is normalized by the signal bandwidth, yielding a sector's spectral efficiency. The achievable rates are determined from a quantized rate mapping function [WIN2D223], representing achievable rates in a practical system. For comparison three different measures are of major relevance.

Case A: The achievable spectral efficiency with perfectly known variables, i.e. equalization vector $\mathbf{w}_u$, desired and interfering signals $\mathbf{h}_{i,u}$ and $\mathbf{z}_i$, respectively.

$$\mathrm{SINR}_u \geq p_i \frac{\mathbf{w}_u^H \overline{\mathbf{h}}_{i,u} \overline{\mathbf{h}}_{i,u}^H \mathbf{w}_u}{\mathbf{w}_u^H \mathbf{Z}_u \mathbf{w}_u}$$

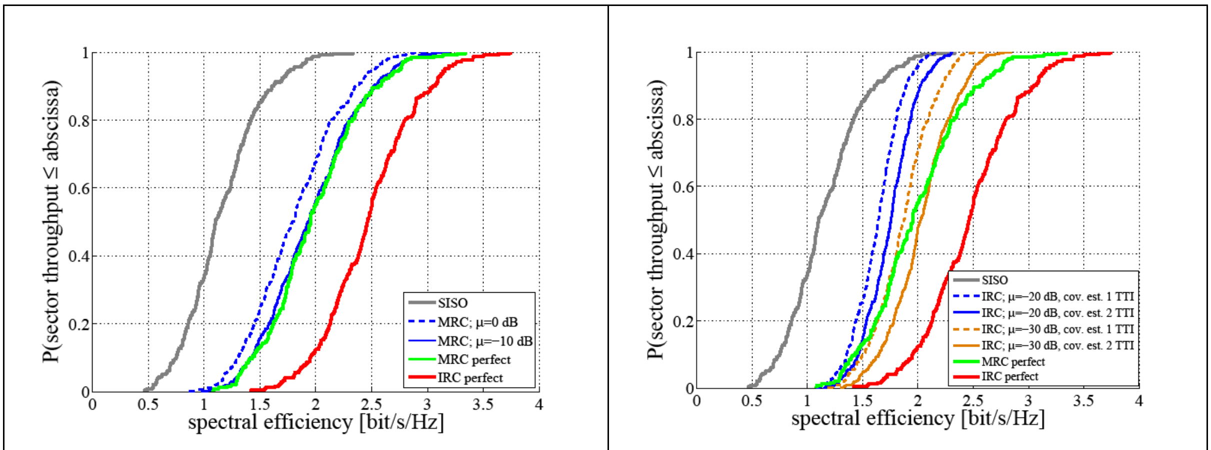
Case B: The resulting spectral efficiency utilizing the estimated equalization vectors $\hat{\mathbf{w}}_u$, i.e. the rate which may be achieved in maximum using an erroneous estimated receiver.

$$\widehat{\mathrm{SINR}}_u \geq p_i \frac{\widehat{\mathbf{w}}_u^H \overline{\mathbf{h}}_{i,u} \overline{\mathbf{h}}_{i,u}^H \widehat{\mathbf{w}}_u}{\widehat{\mathbf{w}}_u^H \mathbf{Z}_u \widehat{\mathbf{w}}_u}$$

Case C: The difference $\Delta_{\mathrm{SINR}\ u}$ between the estimated and achievable SINR at the UT. Where the UT utilizes the estimates $\hat{\mathbf{w}}_u$, $\hat{\overline{\mathbf{h}}}_{i,u}$ and $\hat{\mathbf{Z}}_i$.

$$\Delta_{\mathrm{SINR}_u} = \frac{p_i \dfrac{\widehat{\mathbf{w}}_u^H \widehat{\overline{\mathbf{h}}}_{i,u} \widehat{\overline{\mathbf{h}}}_{i,u}^H \widehat{\mathbf{w}}_u}{\widehat{\mathbf{w}}_u^H \widehat{\mathbf{Z}}_u \widehat{\mathbf{w}}_u}}{\widehat{\mathrm{SINR}}_u}$$

Non-synchronized downlink transmission from all BSs: If utilizing the MRC receiver, the desired signal $\mathbf{h}_{i,u}$ needs to be estimated. From [PNJ+05] we assume the estimation error to be modeled by a Gaussian distribution with a variance equal to a specific MSE defined by $\mu \in \{0,-10,-20,-30\}$ dB. Figure A.1 (a) compares the sector spectral efficiencies using a TDMA round-robin scheduler for the single-input single-output (SISO) and MIMO 2 × 2 for case A. Furthermore, it may be observed that the case B performance assuming a μ = -10 dB for channel estimation is sufficient to approach 99% of the MRC performance with perfect channel estimates. Thus, the lower bound for the SINRs, which was determined to 5% based on the analytically estimate at the end of Section A.1.1, is quite close to the resulting performance from our simulations.



(a) MRC (b) IRC

Figure A.1: Case A and case B performance for MRC and IRC receivers in non-synchronized downlink transmission systems. $\overline{\mathbf{h}}_{i,u}$ is generated using the estimation loss model [PNJ+05] with a given μ; the covariance is estimated over 1 and 2 TTIs.

For Figure A.1 (b) the covariance estimator from Section A.1.2.1 is employed across 1 and 2 TTIs, i.e. 7 and 14 OFDM data symbols, yielding an estimate $\hat{\mathbf{R}}_{yy}$. In combination with the channel estimation error model, which was already introduced for MRC, it is possible to determine $\mathbf{w}_u^{MMSE} = p_i \hat{\mathbf{R}}_{yy}^{-1} \hat{\overline{\mathbf{h}}}_{i,u}$.

Comparing both figures, it may be observed that the achievable performance of the IRC receiver highly depends on the estimate $\hat{\mathbf{h}}_{i,u}$, showing hardly any gain for a μ = -20 dB compared to the MRC approach. In case of an assumed μ = -30 dB and a covariance estimation over 2 TTIs, the system outperforms the simple MRC receiver in 60% of all cases. However, these assumptions are not feasible in a system under realistic conditions. Thus, it is doubtable whether these IRC gains are still present.

Synchronized downlink transmission from all BSs: Figure A.2 compares case A and B for the correlation-based estimator, described in section.A.1.2.2. Assuming a multi-cell channel estimation over 0.5 TTIs, i.e. only one 3G-LTE slot, clearly outperforms the MRC receiver. Thus, 3G-LTE systems may already profit from higher spectral efficiencies when employing IRC using the correlation-based estimator. Therefore, any additional scrambling for common pilots symbols of different sites has to be introduced, but downlink transmission from all BSs must be synchronized. In this case the achievable median spectral efficiency reaches 94.7% of the case A performance. If the estimation is done over 1 TTI the median performance reaches 98.4% of case A. Finally, after 2 TTIs there is hardly any difference between the performance of case A and B.

Furthermore it can be observed that estimation errors caused by the correlation-based estimator only result in a constant shift of the original cumulative distribution function (cdf) with perfect channel knowledge and IRC (Figure A.2). In contrast, the estimation errors caused by the covariance estimator dramatically change the shape of the distribution, disabling high spectral efficiencies of the system and thus indicating the highly error limited behavior (Figure A.1 (b)).

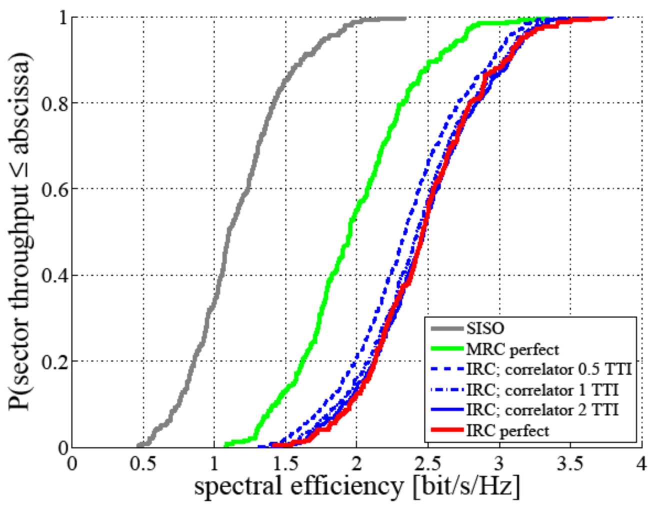


Figure A.2: Performance comparison of ideal systems (case A) and IRC using the correlation based estimator (case B) in synchronized downlink. As correlation intervals we selected 0.5, 1 and 2 TTIs.

Figure A.3 compares the resulting $\Delta_{\mathrm{SINR}\,u}$ for asynchronous and synchronous downlink transmission from all BSs in the system, while using appropriate linear equalizers at the UTs. In case of non-synchronized transmission we consider MRC as proprietary choice and thus indicate its performance for MSE μ = {-10,-20,-30} dB. It may be observed that UTs utilizing MRC receivers tend to underestimate their SINR conditions, i.e. abscissa values below zero, but with relatively high standard deviation.

Assuming a fully synchronized transmission system, one may benefit from linear equalizers, which minimize the MSE while the achievable SINR is maximized. Hence, we suggest to use the MMSE receiver for interference suppression at the terminal, which results in steeper distribution of $\Delta_{\mathrm{SINR}\,u}$ and thus clearly outperforms asynchronous systems. However, knowledge on the interference channels of good quality is required. Therefore, the correlation window length should be set to an adequate value, i.e. above 1 TTI, to ensure $\Delta_{\mathrm{SINR}\,u} \leq 3$ dB in more than 90% of all cases.

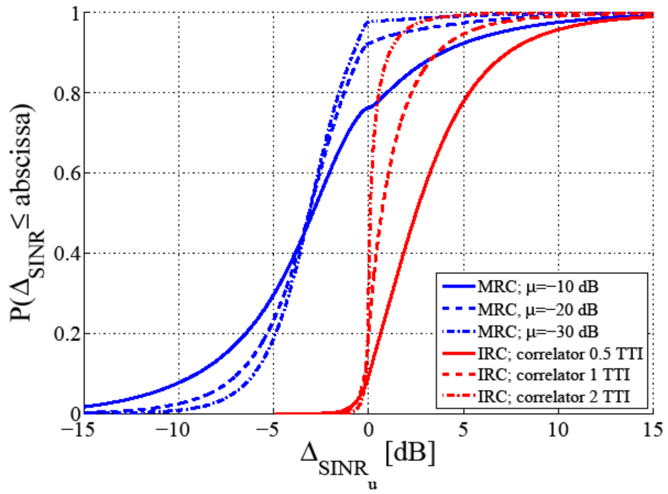


Figure A.3: Maximum $\Delta SINR_u$ (case C) of both available beams for single-stream, while assuming asynchronous and synchronous transmission from all BSs and using appropriate receivers.

A.1.4 Conclusion

We provided a comparison between the theoretical achievable spectral efficiency in a cellular OFDMA system with asynchronous and synchronous downlink transmission from all BSs. Depending on the system, different linear receivers were shown to be feasible. It was shown that the maximum ratio combining receiver is quite robust against estimation errors, if channel estimation with μ = -10 dB is sufficient to approach the upper bound given by perfect channel knowledge at the receiver. Interference suppression requires channel estimates of higher precision and therefore does not seem to be feasible in non-synchronized systems, e.g. by employing covariance estimation based on independent OFDM data symbols. Including the gains of interference suppression into cellular systems requires more precise multi-cell channel knowledge. This may be enabled by introducing synchronized downlink transmission and a multi-cell channel estimation as suggested in section B.1. We demonstrated that a 3G-LTE radio system achieves 94.7% of the spectral efficiency available with perfect channel knowledge and IRC, if fully synchronized data transmission from all base stations is introduced. Improving the knowledge of the interfering channels results in a performance close to the optimum of linear equalizers and a decreasing estimation error $\Delta_{\mathrm{SINR}\,u}$ between the estimated and the achievable SINRs.

A.2 Simulation results for intra-cell and inter-cell interference avoidance by partial CSIT sharing

A.2.1 Objective

Simulation results are shown in this appendix section for a novel signalling concept, called “Best companion”, introduced in section 2.1.3, using one mode (MU-MIMO) of the adaptive MIMO mode switching concept introduced in section 2.1.1.

The aim of the “best companion” concept is to introduce additional codebook-based channel state information in addition to existing best weight indices (called PMI in the LTE terminology) in order to reduce the interference in the overall system. Intra-cell interference will be reduced by better support of MU-MIMO pairing. For a complete description, see section 2.1.3.1.1. The results are for improving intra-cell interference in MU-MIMO (mode B)

A.2.2 Parameters and results

Single cell simulations with statistical modeling of inter-cell interference are performed based on the settings of Table A.1.

Table A.1: Simulation parameters

Scenario	FDD Downlink, codebook-based MU-MIMO, without multi-cell cooperation
Antenna configuration	BS: 4 TX uniform linear array (λ/2 element spacing), vertical polarized elements $A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right]$ θ_{3dB} = 70 degrees, A_m = 20 dB, 14dBi gain (incl. cable loss) MS: 2 RX with λ/2 element spacing
Carrier Frequency	2.1 GHz, 10 MHz bandwidth
OFDM parameters	Based on LTE FDD frame structure, FFT size 1024, 600 subcarriers used
Modulation and Coding	LTE turbo coding, 27 different MCS ranging from QPSK 1/9 to 64 QAM 9/10, Ideal link adaptation Pilot and control overhead is taken into account (≈26%)
Linear Precoding	Unitary codebook based on Householder transformation: LTE 4Tx codebook from TS36.211, subset of 7 entries suitable for beamforming
Feedback	CQI per subband, PMI (+BCI) for the whole band
Channel model	SCME: urban macro (8° angular spread) and urban micro
Scheduling	Non-frequency selective SDMA/TDMA In each subframe 2 users are paired and share 25 chunks (50 PRBs grouped to 25 subbands, thus the whole frequency band). SDMA is based on BCI – when not available, user pairing is done based on a minimum beam distance. TDMA is done in a Round Robin fashion.
Receiver	Linear Receiver with ideal channel state information with MRC combining
Intra-cell interference	Fully modeled
Inter-cell interference	Geometry obtained from 19*3 sector system level simulation with 500m inter-site-distance using interference wrap around, lognormal shadow fading with 8 dB standard deviation, path loss L_dB=128.1 + 37.6$\log_{10}$(.R), R in kilometers, Total BS Tx power 46 dBm, noise power spectral density -174 dB/Hz, used to model inter-cell interference as frequency flat and spatially white

With the above settings, the additional uplink feedback signaling required per user is 4 bit per subframe, thus e.g. 0.8 kbit/s for BCI-reporting at each 5th subframe (which is a realistic assumption). The gains of the novel reporting scheme are shown in Table A.2.

Table A.2: Simulation results: Relative gain of proposed reporting scheme

	Urban macro 8°	Urban Micro
Average cell throughput gain of “Best Companion” reporting vs. standard PMI reporting	+16 %	+22%

The SINR is measured at the output of the receive combiner, thus the decoder input. The figures below show the resulting subband-SINR distribution with and without BCI reporting. Due to reduced intra-cell interference, the SINR is improved with the help of the best companion index.

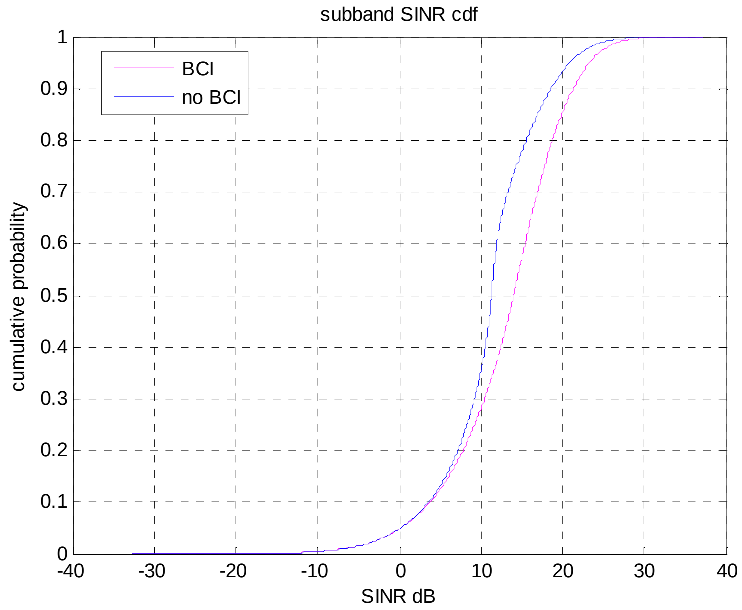


Figure A.4: Urban macro 8°: cdf of subband SINR ("per chunk")

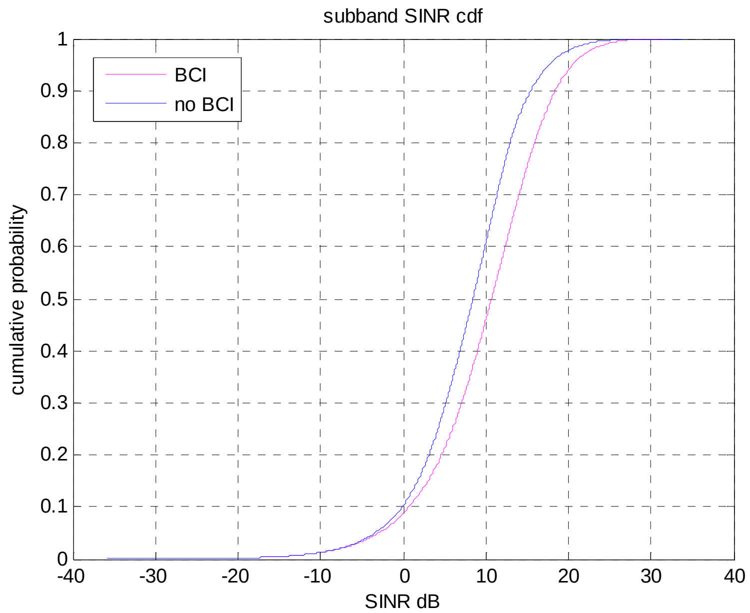


Figure A.5: Urban micro: cdf of subband SINR ("per chunk")

A.3 Joint transmit-receive optimization and user scheduling for FDD downlink

A.3.1 System Model

We consider the downlink of a cellular network with multiple hexagonal cells. Each cell is partitioned into 3 sectors and a linear array of M transmit antennas is deployed in each sector. Users are dropped uniformly in the network, and each one is assigned to the sector with maximum measured SNR. We let S_l denote the set of users assigned to sector l, with $l = 0,\ldots,L-1$ where L is the number of sectors in the entire network. Each user has N receive antennas, and assuming the kth user is assigned to cluster l=0, its received signal is:

$$\mathbf{x}_k = \mathbf{H}_{k,0}\mathbf{s}_0 + \sum_{l=1}^{L-1}\mathbf{H}_{k,l}\mathbf{s}_l + \mathbf{n}_k$$

where $\mathbf{H}_{k,l}\mathbf{s}_l$ is the N x M complex channel matrix between transmitter l and the kth user, $\mathbf{s}_l$ is the M-dimensional transmitted signal from base l, and $\mathbf{n}_k$ is the additive white Gaussian noise vector. Sectors with indices $1,\ldots,L-1$ correspond to the other bases in the network that cause interference to this user.

If N>1, each user could receive multiple spatially multiplexed data streams. Interestingly under ideal CSIT, restricting the transmission to at most a single stream per user was shown to be asymptotically optimal as the number of users in a sector $K \to \infty$ [BK05] and able to achieve a large fraction of DPC capacity even for practical values of K > M, [BH07]. Motivated by these results, under limited feedback conditions, we choose to devote all the available bits to characterize only one stream per user.

Assuming linear precoding the transmitted signal by base l is given by

$$\mathbf{s}_l = \sum_{k \in S_l}\mathbf{g}_k d_k$$

where $\mathbf{g}_k \in C^{M\times 1}$ and d_k are the precoding vector and the information symbol for user k, respectively. We assume a block fading model for the channel so that it is static over one symbol interval but subsequent channel realizations are correlated according to the time coherence of the channel. An average sum power constraint P is imposed among the M transmit antennas in each sector.

A.3.2 Finite rate FB model and user selection

The base station first transmits *common* pilot signals from each antenna so the MTs can estimate the MIMO channel. These pilots are mutually orthogonal in time, frequency, or code domain, moreover we assume perfect channel estimation. Each mobile feeds back:

1) a channel direction information (CDI) given by a quantized version of the channel matrix using a fixed number of bits,
2) an analog value called the channel quality indicator (CQI), related to its expected SINR. Notice that the feedback link is modelled as an error-free and zero-delay uplink control channel.

Using the CDI and the CQI feedback from all of the mobiles, the base station chooses a set of users to serve based on a weighted sum rate criterion. A beamforming vector is calculated for each user and *dedicated* pilots are sent to the selected users that can be used to compute a new MMSE receiver. For each transmitted data stream, a dedicated pilot signal is generated by modulating a pilot sequence with the associated beamforming vector.

A.3.3 Joint receive coefficient design and channel quantization

Given the restriction of at most one stream per user, each receiver has to 1) choose a vector in the space vector spanned by the rows of its channel matrix to feed back as CDI, 2) design a linear detector $\mathbf{u}_k^H$ for combining the N received signals and 3) choose a CQI.

Assume the kth user is assigned to base l=0. Its effective received signal after linear combination of the N received signals with $\mathbf{u}_k^H$, $\|\mathbf{u}_k^H\|^2 = 1$, is

$$\mathbf{r}_k = \mathbf{u}_k^H\mathbf{x}_k$$

where $\mathbf{x}_k$ is the received signal. In the following, for ease of notation we drop the index l of the base. After the combining process, we get an equivalent multi-input single-output formulation and the achievable SINR for the kth user reads

$$SINR_k = \frac{p_k \left|\mathbf{u}_k^H \mathbf{H}_k \mathbf{w}_k\right|^2}{\sigma_k^2 + \sum_{i \in S \setminus \{k\}} p_i \left|\mathbf{u}_k^H \mathbf{H}_k \mathbf{w}_i\right|^2}$$

where $\mathbf{g}_k = p_k \mathbf{w}_k$ is the beamforming vector for user k and $\mathbf{w}_k$ is the ZF precoder vector for the kth user. We consider an average sum-power constraint and impose equal power-allocation for the selected users, i.e. $p_k = \frac{P}{|S| \|\mathbf{w}_k\|^2}$.

We define $\mathbf{v}_k^H = \mathbf{u}_k^H \mathbf{H}_k$ as the equivalent MISO channel for the kth user and assume that $\hat{\mathbf{v}}_k^H$ is its unit norm quantized version, we choose to send back as CDI. This vector is chosen from a codebook C=$\mathbf{c}_1, \dots, \mathbf{c}_{2^B}$ of 2^B unit norm vectors known a priori both at transmitter and receivers.

Assuming a fully loaded system and zero forcing beamforming, an approximated lower bound for the expected SINR is given by

$$E\left[SINR_k\right] \underset{\approx}{>} \frac{\gamma_k}{\|\mathbf{w}_k\|^2} = \tilde{\gamma}_k$$

where we defined

$$\gamma_k = \frac{\mathbf{u}_k^H \mathbf{A}_k \mathbf{u}_k}{\sigma_k^2 + \mathbf{u}_k^H \mathbf{B}_k \mathbf{u}_k}$$

as the CQI FB with $\mathbf{A}_k = \frac{P}{M}\left(\mathbf{H}_k \hat{\mathbf{v}}_k \hat{\mathbf{v}}_k^H \mathbf{H}_k^H\right)$ and $\mathbf{B}_k = \frac{P}{M}\left[\mathbf{H}_k\left(\mathbf{I} - \hat{\mathbf{v}}_k \hat{\mathbf{v}}_k^H\right)\mathbf{H}_k^H\right]$. We choose the linear detector $\mathbf{u}_k^H$ and the codebook vector $\hat{\mathbf{v}}_k^H$ jointly according to

$$\mathbf{u}_\mathrm{k}, \hat{\mathbf{v}}_\mathrm{k} = \underset{\mathbf{u}_\mathrm{k} \in C^N, \|\mathbf{u}_\mathrm{k}\|^2 = 1, \mathbf{c}_i \in C}{\arg\max} \gamma_k\left(\mathbf{u}_{k,} \mathbf{c}_i\right)$$

The maximizing arguments can be determined in a straightforward manner by considering all quantization vectors and computing for each of them the linear detector that maximizes γ_k. We refer to the scheme as the *maximum expected SINR combiner* (MESC). The estimated weighted sum rate is given by

$$\mathrm{R} = \sum_{\mathrm{k} \in S} \alpha_k \log_2\left(1 + \tilde{\gamma}_k\right)$$

A.3.4 User selection and precoding design at the transmitter

For a given set of active users *S* we collect the quantized vectors of these users in

$$\Lambda(S) = \left[\hat{\mathbf{v}}_1, \dots, \hat{\mathbf{v}}_{|S|}\right]^H$$

and we define the matrix as

$$\mathbf{W}(S) = \left[\mathbf{w}_1, \dots, \mathbf{w}_{|S|}\right] = \mathbf{\Lambda}(S)^\dagger = \mathbf{\Lambda}(S)^H \left(\mathbf{\Lambda}(S)\mathbf{\Lambda}(S)^H\right)^{-1}$$

The precoding matrix is designed using only the CDIs of the selected users and assuming equal power distribution. The ZF-BF vector $\mathbf{g}_k$ of the kth user is represented by the kth column of the matrix where $\mathbf{p} = \left[p_1, \dots, p_{|S|}\right]$.

The user selection algorithm adds one user at a time, up to a maximum of M if the estimated achievable weighted throughput is increased.

A.3.5 LBG-based codebook

We use a codebook based on the Lloyd-Max algorithm proposed by Linde, Buzo, and Gray (LBG). The codebook is designed to match the statistics of a given channel model and results in a tree structure that can be used in time correlated MIMO channels to reduce FB overhead. More in details, if the MIMO channel is changing sufficiently slowly, the mobile CDI FB could be aggregated over multiple FB intervals so that the aggregated bits index a larger codebook, which generally implies more accurate knowledge of the MIMO channel at the transmitter and improved throughput. This can be done by arranging the codewords in a hierarchical tree structure so that the FB on a given interval is an index of codewords that are the "children nodes" of a codeword indexed by previous FB. The LBG algorithm can be modified to generate a codebook with this binary tree structure. With the designed codebook, quantization can be performed with a binary search on the tree, thus requiring a lower computation complexity than conventional quantization, at the expense of a larger memory and a little decrease in quantization performance compared to a maximum likelihood (ML) brute force search.

A binary representation (codeword) of each precoding vector is obtained by associating a bit to each of the two branches exiting a node and identifying a node at level i with the i bits on the branches leading from the root to the node itself. As a consequence, all nodes of the subtree departing from a node at level i have the same i most significant bits. Moreover, slight changes of the channel in subsequent time slots most probably lead to codewords with the same most significant bits. Hence instead of feeding back the most significant B bits in each coherence interval (referred as Basic Feedback (BFB)), we use the available feedback bits to update the previous channel vector. We refer to [TBH08a] for more details about the proposed technique.

A.3.6 Simulation results

We assume a cellular network with 19 adjacent hexagonal cells (L=57 sectors), where each sector uses M=4 antennas. The channel coefficient between each transmit and receive antenna pair is a function of distance-based pathloss, shadow fading, and Rayleigh fading. We let the (n,m)th element of the kth user's MIMO channel matrix $\mathbf{H}_{k,l}$ from base l be given by:

$$\left\{\mathbf{H}_{k,l}\right\}^{n,m} = \beta_{k,l}{}^{n,m}\sqrt{A\left(\vartheta_{k,l}\right)\left[\mu_{k,l}/\mu_0\right]^{\gamma}\rho_{k,l}\Gamma}$$

here $\beta_{k,l}{}^{n,m}$ is the independent Rayleigh fading, $A\left(\vartheta_{k,l}\right)$ is the antenna element response as a function of the direction from the lth base to the kth user (all antennas in a sector are assumed to “point” in the same direction) $\mu_{k,l}$ is the distance between the lth base and the kth user, μ_0 is a fixed reference distance, $\gamma = 3.5$ is the path loss coefficient, and $\rho_{k,l}$ is the lognormal shadowing between the lth base and kth user with standard deviation 8 dB. Since shadowing is caused by large scatterers we assume that antennas of the same cell are close enough to be characterized by the the same shadowing effect. The variable $\Gamma = 20\ dB$ is the reference SNR defined as the SNR measured at the reference distance $\mu_0 = 1$ km, assuming a single antenna at the cell center transmits at full power, accounting only for the distance-based pathloss.

We model the antenna element response as an inverted parabola that is parameterized by the 3 dB beamwidth ϑ_{3dB} and the sidelobe power A_{S} measured in dB:

$$A\left(\vartheta_{k,l}\right)\Big|_{\mathrm{dB}} = -\min\left\{12\left(\vartheta_{k,l}/\vartheta_{\mathrm{3dB}}\right)^2, A_{\mathrm{S}}\right\}$$

where $\vartheta_{k,l} \in \left[-\pi, \pi\right]$ is the direction of user k with respect to the broadside direction of the antennas of the lth sector, $\vartheta_{\mathrm{3dB}} = 70\pi/180$, and $A_{\mathrm{S}} = 20$. The broadside direction is the same for the M antennas in each sector.

Users are dropped uniformly over the entire network, and the average number of users per sector is 20. Users are assigned to the base with the highest received SNR, accounting for distance-based pathloss and shadow fading. To provide fairness in the network we adopt a multiuser proportional fair scheduler with fairness factor 0.1. Cell wraparound is employed in order to make interference statistics uniform over the entire network. In particular intercell interference is modelled with a two-phase methodology. In the first phase, the resource allocation and transmit covariance calculations are performed assuming the intercell interference is spatially white and estimating the achievable SINR assuming all bases transmit at full power and accounting for pathloss and shadowing. In the second phase, the actual achievable rates are computed assuming that the transmit covariances are colored according to sample covariances generated from the first phase. The assumption of spatially white noise in the first phase is the worst-case noise and results in a somewhat pessimistic rate. This methodology circumvents the problem of resource allocation when the statistics of the colored spatial noise is not known.

Figure A.6 considers a static spatially uncorrelated channel and compares the proposed scheme (ZF-BF-BFB) and PU^{2}RC [Sam06] in terms of mean cell throughput as a function of the number of feedback bits

B. All schemes benefit from the additional degrees of freedom provided by multiple receive antennas thanks to MMSE receiver that attenuates multiuser interference. While cell throughput for ZF-BF-BFB increases with B the performance of PU^2RC degrades with high feedback rate. Indeed for a given number of users in the network, increasing B has two opposite consequences: i) higher channel quantization accuracy ii) increment of the probability that some vectors of each unitary matrix are not selected by any user. While i) is beneficial for the achievable throughput, with ii) each base station serves with high probability less than M users reducing the multiplexing gain of the system. For a practical number of users in the network i) is dominant for small B, but eventually, when increasing the FB rate, ii) causes a performance degradation.

Figure A.7 compares ZF-BF-BFB, PU^2RC, ZF-BF-HFB (where the mentioned LGB-based codebook with hierarchical structure is used) and ZF-BF with perfect CSIT (ZF-BF-PCSIT) in terms of cell throughput for different speeds of the mobile terminals. Spatial and time correlation of the channel is modelled as spatial channel model [WCM05] assuming transmit antennas spaced 10 lambda with lambda the transmission wavelength. The time slot is T = 0.5 ms and mobile terminals speed is either v = 3, or 50 km/h. All limited feedback schemes use 4 bits and 12 is the maximum number of levels in the LBG-tree codebook. We note that While ZF-BF-BFB and PU2RC have comparable performance, ZF-BF-HFB is able to exploit the time correlation of the channel and thanks to hierarchial indexing achieves approximately a 50% improvement in median cell throughput. We refer to [TBH08b] for a more detailed description of these simulation results.

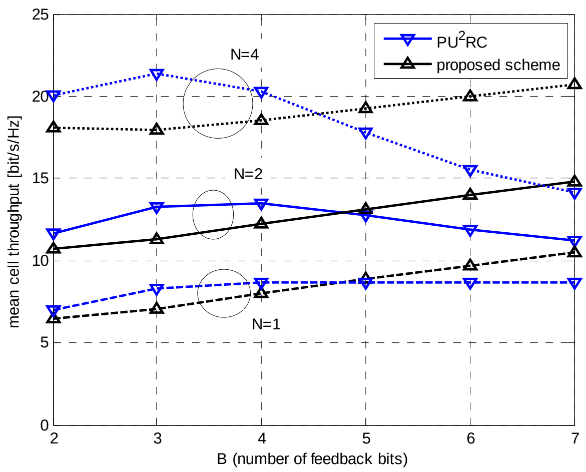


Figure A.6: Mean cell throughput as a function of the feedback rate. M=4, K=20 users on average.

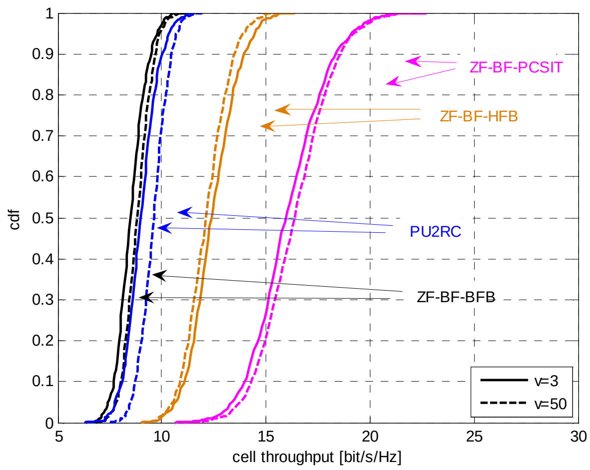


Figure A.7: Cdf of the cell throughput

A.4 Efficient feedback schemes combining long term and short term information

A.4.1 System Model

A communication system with n_T antennas at Base Station and K users, each with n_R receive antennas, is considered. The $n_R \times n_T$ channel matrix for the k^{th} user is denoted as $\mathbf{H}_k$. It is assumed that the rows of $\mathbf{H}_k$ denoted as $\mathbf{h}_{k,\,i}$ are complex circularly symmetric zero mean Gaussian vectors with covariance matrix $\mathbf{R}_k$. This means that the channel is correlated at the transmitter. We further assume uncorrelated channels at the receiver. The transmitter uses the beamforming vector $\mathbf{w}_k$ for k^{th} user and the receiver beamformer is denoted by the matrix $\mathbf{V}_k$. The eigenspace of $\mathbf{R}_k$ is divided as

$$\mathrm{Eig}(\mathbf{R}_k) = [\mathbf{u}_k^{\mathrm{D}}, \mathbf{U}_k^{\mathrm{N}}, \mathbf{U}_k^{\mathrm{I}}]$$

where $\mathbf{u}_k^{\mathrm{D}}$ corresponds to the maximum eigenvalue, $\mathbf{U}_k^{\mathrm{I}}$ corresponds to the interference sensitive subspace (having non-negligible eigenvalues) and $\mathbf{U}_k^{\mathrm{N}}$ corresponds to interference insensitive subspace (having negligible or zero eigenvalues). The dimensionality of $\mathbf{U}_k^{\mathrm{N}}$ and $\mathbf{U}_k^{\mathrm{I}}$ are considered as design parameters.

It is assumed that the transmitter knows $\mathbf{R}_k$ for all users while the k^{th} receiver knows $\mathbf{H}_k$ and $\mathbf{R}_k$.

A.4.2 Choice of Transmit and Receiver Beamformers

The transmit beamformer should have a large component along $\mathbf{u}_k^{\mathrm{D}}$. Since the interference needs to be considered as well, a zero-forcing beamformer is employed at the transmitter for each user. Obtain the matrix $\mathbf{F}_k$ by stacking the dominant eigenvectors of users (except user k) from a pre-defined index set. The transmit beamformer is then obtained as,

$$\mathbf{w}_k = \alpha_k \mathbf{F}_k^{\perp} \mathbf{u}_k^{\mathrm{D}}$$

where $\mathbf{F}_k^{\perp}$ is the projection onto orthogonal complement of $\mathbf{F}_k$ and α_k is a scaling used to normalize $\|\mathbf{w}_k\|$ to 1. The choice of the index set is a design parameter. The receiver beamformer is chosen so as to mitigate the interference while retaining the signal power. Since the users know $\mathbf{R}_k$ and the channel $\mathbf{H}_k$, the receiver beamformer is chosen so as to satisfy

$$\mathbf{V}_k \perp \mathbf{H}_k \mathbf{U}_k^{\mathrm{I}}$$

where $\perp$ refers to orthogonality. Clearly the receiver beamformer acts as an interference suppressor.

A.4.3 User Scheduling

A greedy scheduler maximizing the weighted sum rate is considered. This, in turn, requires the SINR of k^{th} user, which is given as,

$$\mathrm{SINR}_k = \mathrm{S}_k / (\mathrm{I}_k + \mathrm{N}_k)$$

where $\mathrm{S}_k = \mathrm{p}_k \|\mathbf{V}_k^{\mathrm{H}} \mathbf{H}_k \mathbf{w}_k\|^2$, $\mathrm{I}_k = \sum_{l \neq k} \mathrm{p}_l \|\mathbf{V}_k^{\mathrm{H}} \mathbf{H}_k \mathbf{w}_l\|^2$, p_k and N_k are the power and noise variance of k^{th} user respectively. It should be noted that the transmitter does not know the effective channel ($\mathbf{V}_l^{\mathrm{H}} \mathbf{H}_l$) and hence is unable to evaluate SINR_k. Instead, MMSE estimates of instantaneous signal and interference power can be used. These estimates can be considerably improved by utilizing feedback of the effective channel norm, $\|\mathbf{V}_k^{\mathrm{H}} \mathbf{H}_k\|^2$. Further to avoid overestimation of SINR_k (which can cause outage in turn), a design parameter is chosen and the MMSE estimate of SINR_k is denoted as,

$$\mathrm{SINR}_{\mathrm{est},\,k} = (\mathrm{S}_{\mathrm{est},\,k} - \alpha \mathrm{B}_k) / (\mathrm{I}_{\mathrm{est},\,k} + \alpha \mathrm{C}_k + \mathrm{N}_k)$$

where $\mathrm{S}_{\mathrm{est},\,k} = \mathrm{p}_k E(\mathrm{S}_k \mid \rho_k)$, $\mathrm{B}_k = \mathrm{STD}(\mathrm{S}_k \mid \rho_k)$, $\mathrm{I}_{\mathrm{est},\,k} = \mathrm{p}_k E(\mathrm{I}_k \mid \rho_k)$, $\mathrm{C}_k = \mathrm{STD}(\mathrm{I}_k \mid \rho_k)$, $\rho_k = \|\mathbf{V}_k^{\mathrm{H}} \mathbf{H}_k\|^2$, $E()$ denotes expectation operation and STD( ) denotes standard deviation. A closed form expression for $\mathrm{SINR}_{\mathrm{est},\,k}$ is obtained in [BO08]. This analytical result is exploited by the scheduler.

A.4.4 CQI feedback

The probability density function of the effective channel norm is exploited to obtain the decision boundaries and quantization levels for a given feedback budget. The quantizer designed further has the property that closed form expressions for $SINR_{est,\,k}$ can be obtained even with limited feedback.

A.4.5 System Operation and Preliminary Results

Assuming a block fading model for the channel, the following operations are performed cyclically:

- Each user estimates the current channel realization based on pilot signals and computes $\mathbf{V}_k$
- The resulting norm $\rho_k = \|\mathbf{V}_k^H \mathbf{H}_k\|^2$ is then quantized by each user and fed back.
- The base station combines $\mathbf{R}_k$ and ρ_k to obtain $SINR_{est,\,k}$ as a function of $\mathbf{w}_k$
- The scheduler uses these estimates to iteratively allocate resources to various users.

Preliminary results presented in Figure 2.7 show significant gains compared to opportunistic beamforming, using as little as 1 bit of short-term CQI, when combined with long-term CSI.

A.5 Resource allocation with linear transceiver processing

This contribution considers the linear precoder design together with a sub-optimal user/beam selection/allocation per each frequency, time and space dimension. Linear transceiver processing accommodates conventional single-user channel coding and modulation methods. A general iterative method for joint design of the linear TX and RX beamformers for several optimisation criteria subject to per antenna or antenna group (BS) power constraints is presented. A more detailed description of the theory and the proposed algorithms can be found in [TCJ08a, TCJ08b, Tol08]. Alternatively, the block-zero forcing principle can be further used to decouple the TX precoder design from power allocation.

First part of this contribution presents the proposed framework for linear multiuser MIMO transceiver design with a fixed user allocation. Second part deals with the user/beam selection problem and the results are shown for the block ZF transmission case.

A.5.1 Linear multiuser MIMO transceiver design with quality of service and per antenna power constraints

Joint design of linear multiuser MIMO transceiver subject to different quality of service (QoS) constraints per user and with per antenna or antenna group power constraints is considered. Solutions for various linear transceiver optimization problems are proposed, such as weighted sum rate maximisation, balancing the weighted signal-to-interference-plus-noise ratio (SINR) per data stream and balancing the weighted rate for each scheduled user with minimum rate requirements per user. The proposed joint transceiver optimization algorithms are compared to corresponding optimal non-linear transmission methods as well as to generalised zero forcing transmission solutions.

Unlike the optimal non-linear schemes, the optimization problems employed in the linear multiuser MIMO transceiver design are not convex in general. However, by utilizing the recent results on the precoder design via conic optimization [WES06] and signomial programming [BV04], the non-convex problem is divided into convex subproblems that can be optimally solved by using standard convex optimization tools [BV04]. The proposed iterative algorithms are shown to provide very efficient solutions. However, the global optimality cannot be guaranteed due to non-convexity of the original problem.

A multi-user MIMO-OFDM downlink channel with N_C sub-carriers, K users, each equipped with N_R antennas, and a single base station having N_T antennas is considered. The input-output relation for the downlink channel is described as $\mathbf{y}_{k,c} = H_{k,c}\mathbf{x}_c + \mathbf{n}_{k,c}$, where $\mathbf{H}_{k,c}$ is the channel matrix for user k at sub-carriers c , $\mathbf{x}_c$ is the transmitted signal vector, $\mathbf{y}_{k,c}$ is the signal vector received by user k, and $\mathbf{n}_{k,c}$ represents the noise-plus-interference vector. The elements of $H_{k,c}$ are modelled as independent zero mean complex Gaussian random variables and normalized to have unitary variance. The channel state information (CSI) is assumed to be perfectly known both at the transmitter and the receivers of all users.

The focus here is on linear transmission schemes, where the BS sends S independent data streams, $S \leq \min(N_T, K\,N_R)$. The transmitted vector is generated as $\mathbf{x} = \mathbf{Md}$, where $\mathbf{M} = [\mathbf{m}_1, \dots, \mathbf{m}_S]$ is the pre-coding matrix and $\mathbf{d} = [d_1, \dots, d_S]$ is the vector of normalized complex data symbols. $\mathbf{M}$ is further factorised to $\mathbf{M} = \mathbf{VP}^{1/2}$, where $\mathbf{V}$ contains the normalized TX beamformers and $\mathbf{P} = \mathrm{diag}(p_1, \dots, p_S)$ controls the powers allocated to S streams. For each data stream s, the scheduler unit associates an intended user k_s. More than one stream can be assigned to one user.

Assume a MIMO-OFDM system which transforms the frequency selective channel into N_C parallel independent MIMO sub-channels. A separate beamformer is assigned to each sub-channel c and each scheduled data stream s at the transmitter and at the receiver. As an example of an optimisation problem, we consider a system that has to provide different services to different users. Each user $k \in U$ may have different rate allocation priorities β_k, and the subset U_{GBR} from the full user set U includes users with minimum bit rate requirements r_k^{min}. The achievable rate per stream is modelled as $\min(\log_2(1 + \Gamma\gamma_s), r_{max})$, where Γ describes the SNR gap to the channel capacity, γ_s is the SINR of stream s and r_{max} is the maximum rate limit, both imposed by a set of some practical modulation and coding schemes. The objective is to maximise the weighted common rate of all users while guaranteeing the minimum bit rate requirements for the guaranteed bit rate (GBR) users. The optimisation problem can be formulated as follows:

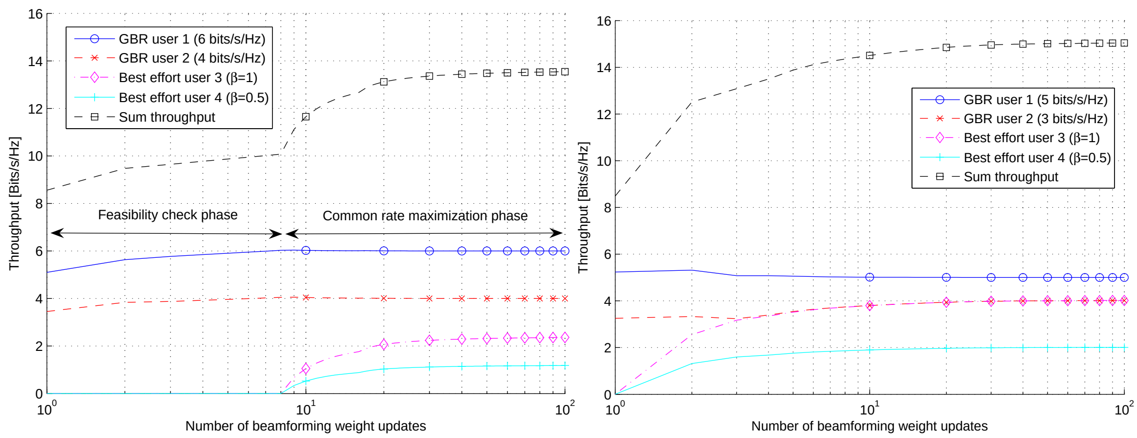
$$
\begin{aligned}
\text{maximise} \quad & r_o \\
\text{subject to} \quad & \sum_{c=1}^{N_C} \sum_{s \in \mathcal{P}_{k,c}} \log_2\left(1 + \Gamma \gamma_{s,c}\right) \geq \beta_k r_o, \; k \in \mathcal{U} \\
& \sum_{c=1}^{N_C} \sum_{s \in \mathcal{P}_{k,c}} \log_2\left(1 + \Gamma \gamma_{s,c}\right) \geq r_k^{\min}, \; k \in \mathcal{U}_{\mathrm{GBR}} \\
& \gamma_{s,c} \leq \frac{p_{s,c}\left|\mathbf{w}_{s,c}^{\mathrm{H}} \widetilde{\mathbf{H}}_{k_s,c} \mathbf{v}_{s,c}\right|^2}{1 + \sum_{i=1, i \neq s}^{S} p_{i,c}\left|\mathbf{w}_{s,c}^{\mathrm{H}} \widetilde{\mathbf{H}}_{k_s,c} \mathbf{v}_{i,c}\right|^2}, \; \forall\, s, c \\
& \gamma_{s,c} \leq \gamma_{\max}, \; \forall\, s, c \\
& \sum_{c=1}^{N_C} \sum_{s=1}^{S} p_{s,c} \left\|\mathbf{v}_{s,c}^{[n]}\right\|_2^2 \leq P_n, \quad n = 1, \ldots, M \\
& \left\|\mathbf{w}_{s,c}\right\|_2 = 1, \left\|\mathbf{v}_{s,c}\right\|_2 = 1, \; \forall\, s, c
\end{aligned}
$$

where the variables are common rate r_o, TX beamformers $\mathbf{v}_{s,c}$, LMMSE receivers $\mathbf{w}_{s,c}$, TX powers $p_{s,c}$ and SINR per stream $\gamma_{s,c}$. M is the number of antenna groups, $P_{k,c}$ is a subset of data streams assigned to the user k at sub-carrier c and γ_{max}=2^(r_{max}-1) / Γ.

Linear MIMO transceiver optimisation problems cannot be solved directly, in general. Thus, iterative procedures are required, where transmit beamformers are optimised at the BS in an iterative manner. The general iterative algorithm for solving any optimisation problem is the following:

1) Initialize TX beamformers $\mathbf{m}_{s,c}$ such that antenna group power constraints are satisfied. Let j = 1.
2) Compute LMMSE receive beamformers $\mathbf{w}_{s,c}$ for each streams s
3) Check the feasibility and/or solve any optimisation problem with fixed receive beamformers by using an appropriate reformulation (second order cone program and/or geometric program, see more details in [TCJ08a, TCJ08b, Tol08]). Check the stopping criterion. If it is not satisfied, let j = j +1 and go to Step 2, otherwise STOP.

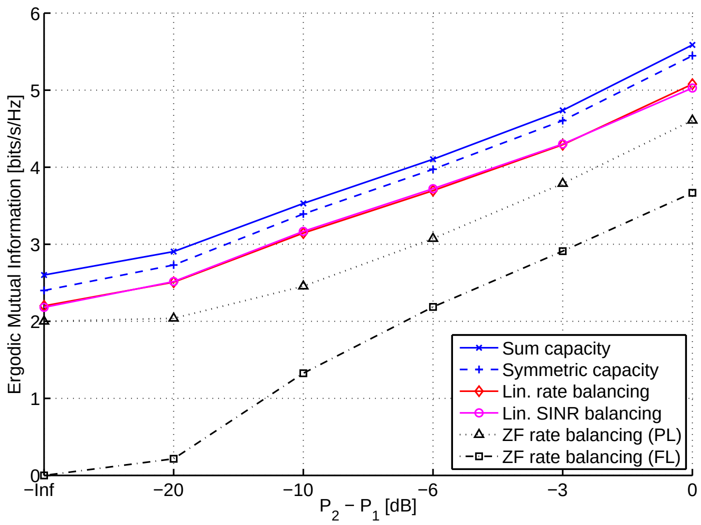
First, we consider a MIMO-OFDM system with 16 sub-carriers, where 2-4 users are served simultaneously by a BS. The number of antennas is fixed to {N_T, N_R} = {4, 2}. The TX antennas are divided into two groups of two antennas, each with separate power constraint. Let us now consider a 4-user case, where two guaranteed bit rate (GBR) users have 6 and 4 bits/s/Hz normalised guaranteed throughput requirements, while 2 best effort users have priority weights 1 and 0.5, and a single stream is allocated per user. Figure A.8:(a) illustrates the behavior of the algorithm for a single random channel realization in such a scenario. The SNR per antenna group is P_1 = P_2 = 10 dB. It is seen from Figure A.8:(a) that the initial beamformer configuration is not feasible for this particular channel realization and eight beamforming weight updates are required for the GBR users to reach a feasible starting point. The common rate maximization phase is then initiated with the feasible beamformer configuration and the user rates converge close to their final values after 20-30 iterations. In Figure A.8:(b), the behavior of the algorithm with slightly modified minimum throughput requirements (5 and 3 bits/s/Hz) is depicted for the same channel realization. Now, the initial beamformer configuration can support the minimum rate requirements, and hence, the feasibility check phase is not required.



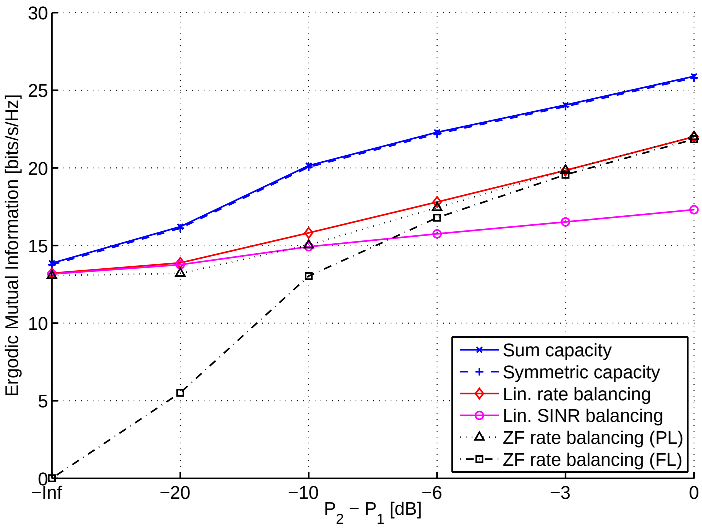
a) b)

Figure A.8: User rate evolution for a single channel realisation in {N_T, N_R, N_C, K} = {4, 2, 16, 4} system with 10 dB SNR per antenna group

Figure A.9 illustrates the ergodic 2-user sum rate in a flat fading scenario where the power constraint P_1 for antenna group 1 is fixed to 0 dB and 20 dB, respectively, and the power constraint P_2 for antenna group 2 gets values $P_2=P_1-\{0, 3, 6, 10, 20, \infty\}$. This resembles a distributed MIMO antenna setup, where the users are connected to two adjacent BSs both with two TX antennas and the received power imbalance from the BSs is varied between 0 and ∞. The sum rate is depicted for the user rate balancing algorithm and the corresponding ZF method. Furthermore, the sum rate of the linear SINR balancing algorithm (labelled as 'lin. SINR balancing') with a single stream per user is plotted for a comparison.



a) P_1=0 dB, $P_2=P_1-\{0, 3, 6, 10, 20, \infty\}$ dB



b) P_1=20 dB, $P_2=P_1-\{0, 3, 6, 10, 20, \infty\}$ dB

Figure A.9: Ergodic sum of user rates of $\{N_T, N_R, N_C, K\} = \{4, 2, 1, 4\}$ system with per antenna group power constraints

In the given scenario, the SINR balancing solution provides nearly identical results with the user rate balancing algorithm at low SNR and with high power imbalance. This is due to the fact that the user rate balancing algorithm is also likely to allocate only a single stream per user in such situations. At high SNR, however, the user rate balancing algorithm utilizes all the available dimensions to maximize the rate per user, thus providing a higher sum rate. The ZF solution is depicted for two scenarios: fully loaded (FL) case and partially loaded (PL) case, where the number of streams providing the highest common rate among all possible combinations is selected for each channel realization. The ZF solution with full spatial load results in rather poor performance, especially at low SNR range. On the other hand, it performs reasonably well with partial loading even at low SNR and approaches the user rate balancing algorithm at high SNR.

Rate region with linear transceiver processing

The behaviour of the two rate maximization (sum and common rate) algorithms in a 2-user (K=2) channel with 10 dB and 7 dB power constraints per 2 antenna groups (M=2) is depicted in Figure A.10:. The rate pairs corresponding to different weight vectors and the rate regions are plotted for a single random channel realisation per user and with a per BS power constraint. The beamformer initialisation has an impact on the performance of the algorithm, due to the non-convexity of the problem. This example demonstrates the near optimality of the proposed algorithms for linear precoder design. Furthermore, it is shown that the achievable rate region boundaries, which are plotted as convex hulls of all the achievable rate pairs, are identical for both rate maximisation algorithms with linear processing. However, all the rate pairs with a weighted common rate constraint that deviate from the convex hull cannot be claimed as local optima, unlike in the weighted sum rate case. This is due to the different objectives of the two optimisation criteria. The linear part of the convex hull can be achieved only via time sharing.

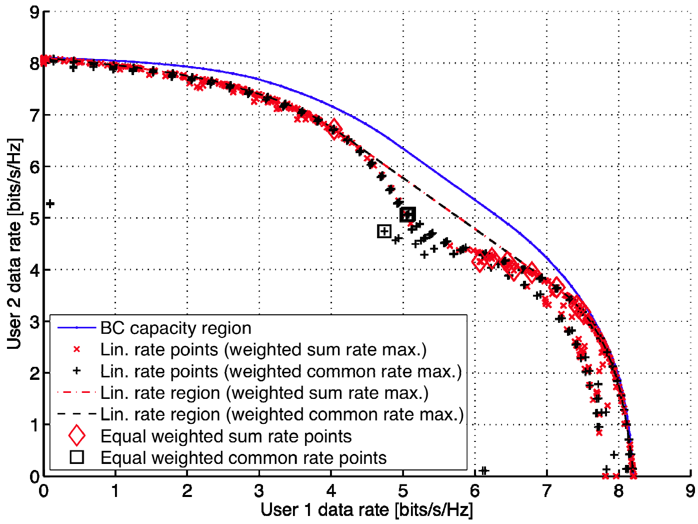


Figure A.10: Broadcast capacity region and rate region with linear processing for $\{N_T, N_R, K, M\} = \{4, 2, 2, 2\}$ **system with per antenna group power constraint**

A.5.2 TX-RX zero-forcing with scheduling

In Figure A.11, with block diagonalization (BD) method with coordinated TX-RX processing, the performance of the greedy scheduling algorithm is compared with other scheduling criteria. Since the transmitter vectors, and thus, the corresponding receiver vectors at each user are affected by the set of selected users, it is impossible to know the actual receiver structure at the transmitter before the final beam allocation. An obvious candidate for an intelligent initial guess of the receiver matrix, and the one used in the proposed algorithm, is the optimum single user receiver, i.e. the left singular vectors of user channel matrices. Three user scheduling criteria are used in the simulations:

- *Greedy scheduling* (GS): At most N_T beams are selected such that they create a small amount of interference to each other while having large channel eigenvalues. The first beam is selected based on the largest channel eigenvalue. The greedy beam selection algorithm is described in more detail in [TJ05, TJ06, Tol08].
- *Maximum eigenvalue* (ME) scheduling: The eigenvalues of the equivalent channel matrices of each user are sorted and at most N_T beams providing the maximum sum rate are selected for the transmission at any time instant. Spatial compatibility with other beams is not considered.
- *Best user scheduling*: A single user with the maximum channel norm is selected at any time instant.

The performance of the proposed algorithms is studied by simulations in a single-cell environment. The single user capacity with and without CSI at the transmitter is plotted for comparison (dotted curves in the figures). Two different spatial loading scenarios are considered in the simulations:

- Fully loaded: N_T beams are always allocated for each channel realisation (plotted with dashed curves in the figures).
- Partially loaded: the optimal number of beams is selected for the scheduling. These results are plotted with solid curves in the figures.

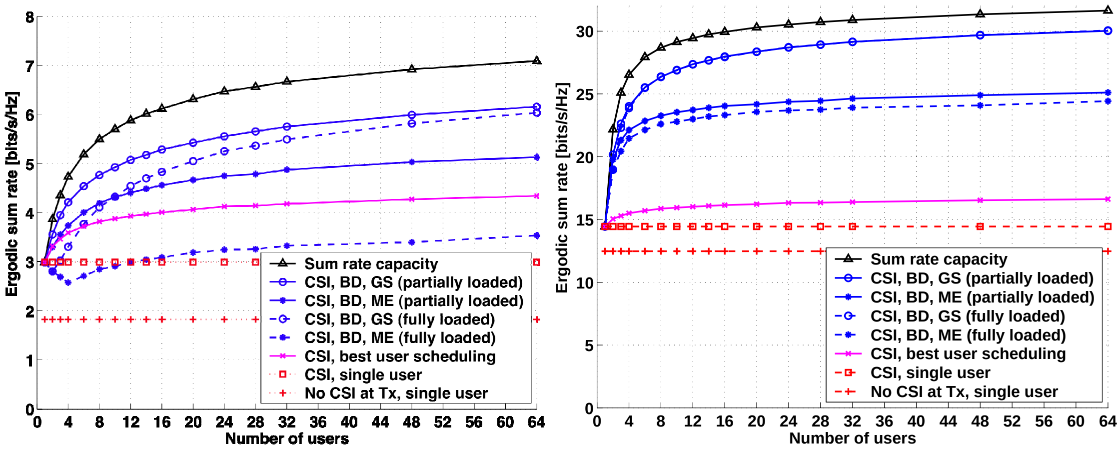


Figure A.11: Sum rate for {N_T, N_R, N_c, K} = {4, 2, 1, 1-64} with 0 dB and 20 dB

The results indicate that the BD method with greedy scheduling approaches the sum rate capacity in the high SNR region as the number of users present in the system becomes large. However, in the low SNR region the capacity loss from the noise amplification can be significant as can be seen by comparing the curves labelled as 'fully loaded' to 'partially loaded' cases. The BD method suffers from the noise amplification in the fully loaded case. Therefore, it is often beneficial to allocate fewer beams than the spatial dimensions available allow in order to reduce the noise amplification, especially in the low SNR region and with a low number of users.

A.6 Downlink-assisted uplink zero-forcing

The signal processing chain for multiuser MIMO downlink Tx-Rx zero-forcing is shown in Figure A.12. The ZF criterion is $\mathbf{F}_k^{\mathrm{H}}\mathbf{H}_k\mathbf{C}_i=\mathbf{0}$, $i\neq k$, where $\mathbf{C}_k$, $\mathbf{H}_k$, and $\mathbf{F}_k$ are a transmit processor, channel and receiver processor matrices for user k. The proposed transmit precoding for the uplink relies on the reciprocity of the MIMO channel and the reversal of the downlink signal processing chain; the orthonormalized receive beamformers can be used in turn as transmit precoders. The preferred Tx-Rx zero-forcing solution is obtained by an iterative algorithm [SS04], where the starting point for iteration is the selected set of user-specific eigenbeams. The same active set of beams is used for both uplink and downlink.

Iterative zero-forcing algorithm
1) Initialize $\mathbf{F}_k$ for each user k with the L_k left singular vectors (chosen by the beam selection algorithm) of the channel matrix $\mathbf{H}_k$
2) Transmitter adaptation: find a matrix $\mathbf{C}_k$ with orthonormal columns for each user k so that $\mathbf{F}_k^{\mathrm{H}}\mathbf{H}_k\mathbf{C}_i=\mathbf{0}$, $i\neq k$
3) Receiver adaptation: calculate SVD, $\mathbf{H}_k\mathbf{C}_k = \mathbf{U}_k\mathbf{\Lambda}_k\mathbf{V}_k^{\mathrm{H}}$ and set $\mathbf{F}_k = \mathbf{U}_k^{(1)}$, where $\mathbf{U}_k^{(1)}$ contains the L_k first column vectors from $\mathbf{U}_k$
4) If $\mathbf{F}_k^{\mathrm{H}}\mathbf{H}_k\mathbf{C}_i \approx \mathbf{0}$, $i\neq k$ with sufficient accuracy, stop the iteration. Otherwise repeat steps 2 to 4.
5) Select the transmit precoders as $\mathbf{C}_k\mathbf{V}_k^{(1)}$, where matrix $\mathbf{V}_k^{(1)}$ consists of the L_k first column vectors from $\mathbf{V}_k$

After the final steps 3-5, the received downlink stream responses for user k become $\mathbf{R}_k = \mathbf{H}_k\mathbf{C}_k\mathbf{V}_k^{(1)} = \mathbf{U}_k^{(1)}\mathbf{\Lambda}_k^{(1)}$, where $\mathbf{\Lambda}_k^{(1)}$ is a diagonal matrix including the L_k largest singular values from matrix $\mathbf{\Lambda}_k$. Thus the final receiver matrix $\mathbf{F}_k = \mathbf{U}_k^{(1)}$ is a set of matched filters. Since the optimal downlink receivers are matched filters, ideally, the terminals need not actively suppress interference.

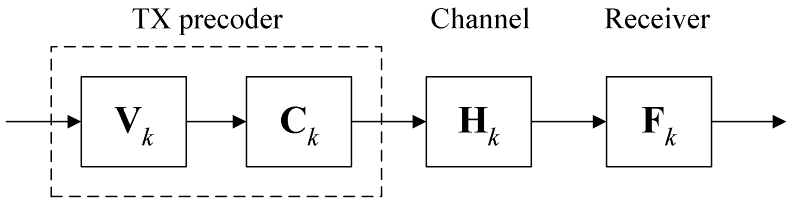


Figure A.12: Downlink signal processing chain for iterative zero-forcing

Pilot symbols transmitted with beamforming via the same precoders as data are necessary in order to facilitate coherent detection. However, unlike data, the pilots should have equal power allocation per stream. This way the channel gains can be correctly observed from the received signal without getting mixed with the transmit amplitude adjustment, and the pilot responses can be utilized for the purpose of transmit precoding as well. The base node carries out the multi-user processing, and thus it is necessary that the uplink pilots of each user fully span the N_{u}-dimensional transmit signal space, where N_{u} is the number of antennas in the terminal, even when the number of per-user allocated data streams L_k is lower. This can be achieved by appending the L_k uplink pilot streams associated with data streams by another N_{u}-L_k pilot streams so that the pilot precoder matrix becomes unitary. On the other hand, in the downlink it suffices to transmit just as many pilot streams as there are data streams.

Figure A.13 depicts the effect of non-ideal channel estimation on the achievable rates of uplink-downlink iterative zero-forcing with greedy beam selection, in a setup of one four-antenna BS with four two-antenna mobiles. Here, the uplink always employs a zero-forcing receiver while the non-idealities of the downlink are compensated by least-norm receivers in the terminals. The power allocation constraints are the same for uplink and downlink, so that each user is granted with a share of the total cell Tx power proportional to the number of beams it was allocated with. Here, data SNR = $\Sigma_k P_k/N_0$ and channel estimate SNR = $N_{\mathrm{pilot}}\ \Sigma_k P_k/N_0$. The performance of the proposed concept is compared against two other schemes: best-user SVD and non-precoded UL. In the first comparison scheme, the user with the strongest MIMO channel is always chosen for SU-MIMO transmission, and in the latter one, two strongest users are chosen for non-precoded two-stream UL transmission each. SU-MIMO is inefficient in the sense that it cannot utilize more than two out of the four degrees of freedom available, while the non-precoded scheme does not take advantage of transmit CSI. As can be seen, the capacity gain offered by the proposed concept is in the order of 35% against the best-user MIMO and 70% against the non-precoded method.

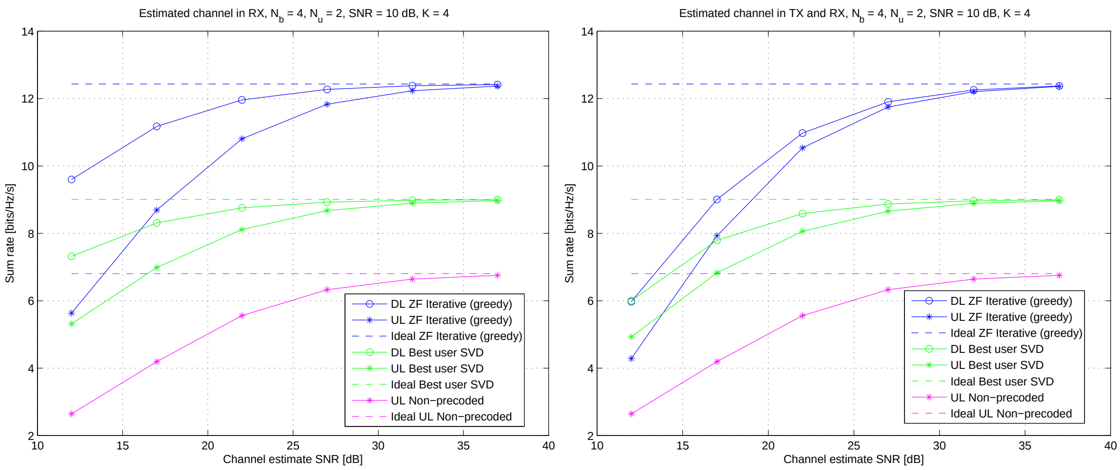


Figure A.13: Multiuser MIMO UL-DL ZF with noisy channel estimates: estimated channel in RX only vs. estimated channel in both TX and RX

B. Appendix for Coordinated MultiPoint Systems

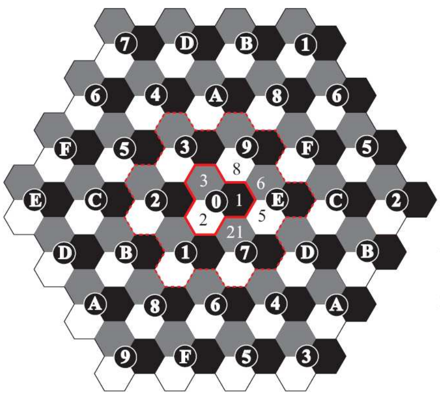
B.1 Multi-cell channel estimation based on virtual pilots

The virtual pilot concept shown in Figure B.1 is proposed. This concept helps keeping the pilot overhead low, at the costs of reduced mobility [TSS+08]. Sector pilots are assumed to be orthogonal and each BS is identified by an orthogonal sequence; common pilots are scrambled by this sequence over time. In 3GPP LTE, one would use all pilots in a slot and multiply them with a given chip from the sequence. Pilots in the next slot are multiplied with the next chip.

In the proposed concept, a particular sequence assignment to base stations is provided. Those sequences are defineded as time-domain scrambling sequences, which are pre-defined and known to the UTs. Each common pilot symbol is multiplied with the next chip of the given sequence pattern. Figure B.1 (right) indicats these sequences for a maximum window length of 16 (horizontal direction). The different sequence classes, i.e. given in vertical direction, are denoted as hexadecimal numbers and should be arranged according to cellular grid.

This multi-cell channel estimation based on virtual pilots enables the UTs to independently estimate the channels from their closest BSs, i.e. providing the desired signal and the most severe interfering signals. The idea is based on partial correlation. For some sequences families with length *L*, e.g. Hadamard or DFT, there are certain subsets of sequences which are mutually orthogonal already for correlation lengths being an integer fraction of *L*. In general, we identify closer base stations by sequences being orthogonal already in a shorter correlation window while more distant base stations use sequences which need a longer window.

Consider the hexadecimal sequence numbers at the sequence list in Figure B.1 and their assignment in the cellular grid. The proposed scheme maximizes the distance between cells using the same Hadamard sequence. After 4 cells in a row the same sequence is assigned. That applies to the horizontal and both diagonal alignments. All cells in a radius of 4 have orthogonal sequences to the cell in the middle of the scheme. The assignment of the Hadamard sequences to cells is completely defined by an arbitrary rhombus containing 16 cells each one using another pilot sequence. The rhombus is repeated to fill an infinite plane. One possible rhombus in Figure B.1 is enclosed by cells E,0,1,7. Note that each permutation of the assignment would affect the channel estimation mean square error (MSE). In the suggested scheme it is guaranteed that the mean channel estimation error of a UT is independent of the cell where it is placed, i.e. with symmetric conditions for all cells. The scheme is scalable in sequence length, thus the size of the correlation window may chosen according to the mobility of the UTs.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1
2	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1
3	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1
4	1	1	1	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1
5	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
6	1	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1
7	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1	1	-1
8	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1
9	1	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1
A	1	1	-1	-1	1	1	-1	-1	-1	-1	1	1	-1	-1	1	1
B	1	-1	-1	1	1	-1	-1	1	-1	1	1	-1	-1	1	1	-1
C	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1
D	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	1	-1	1	-1
E	1	1	-1	-1	-1	-1	1	1	-1	-1	1	1	1	1	-1	-1
F	1	-1	-1	1	-1	1	1	-1	-1	1	1	-1	1	-1	-1	1

Figure B.1: Left: Pilot reuse pattern based on orthogonal code sequences, e.g. Hadamard, in a 3-fold sectorized cellular system. Decimal numbers indicate the sector index. Right: Hadamard sequences spread over space (rows) and time (columns) domain. Hex-base numbers indicate sites with the same virtual pilot sequence.

At the UT, a correlation-based estimator is used to separate the channels $\mathbf{h}_{k,l}$ for the *n* distinct groups. The main reason to use the correlation-based estimator is its moderate computational complexity. The correlation-based estimator is given by

$$\tilde{\mathbf{h}}_\nu = \frac{1}{n}\sum_{p=0}^{n-1} c_\nu^*(p)\mathbf{y}^m(p), \text{ with } \nu = \{0,\ldots,n-1\}$$

where $c_\nu(p)$ and $\mathbf{y}^m(p)$ denote the code symbol and the received signal vector at a given discrete time index p, respectively.

Figure B.2 shows the MSE, normalized by the receive power of the associated sector. It compares the different performance in the channel estimation process using virtual pilots based on pseudo-random (Figure B.2 (a)), randomly arranged Hadamard (Figure B.2 (b)) and Hadamard sequences (Figure B.2 (c)) arranged in the suggested sequence pattern shown in Figure B.1. In these figures, the achievable MSE is given for top-N strongest sectors showing instantaneously the five highest receive powers at the MT. It turns out that using virtual pilots based on randomly arranged orthogonal sequences, e.g. Hadamard (Figure B.2 (b)), cannot reduce the MSE compared to the case of using pseudo-random sequences. However, the suggested sequence reuse pattern assigning Hadamard sequences to the BSs does clearly show a superior performance compared to the random arrangement of sequences.

The mean square error (MSE) of the two strongest signals is below -20 dB with a correlation length of 8, which corresponds to 4 ms in LTE (Figure B.2). During this time, the channel should be almost static to ensure proper estimation.

If the five strongest channels need to be estimated with a MSE below -20 dB, it is necessary to use a correlation length 16, i.e. 8 ms (Figure B.2). Again, the channel needs to be quasi-static over this duration to ensure proper estimation. Further results on channels with constant phase rotation are provided in [TSS+08].

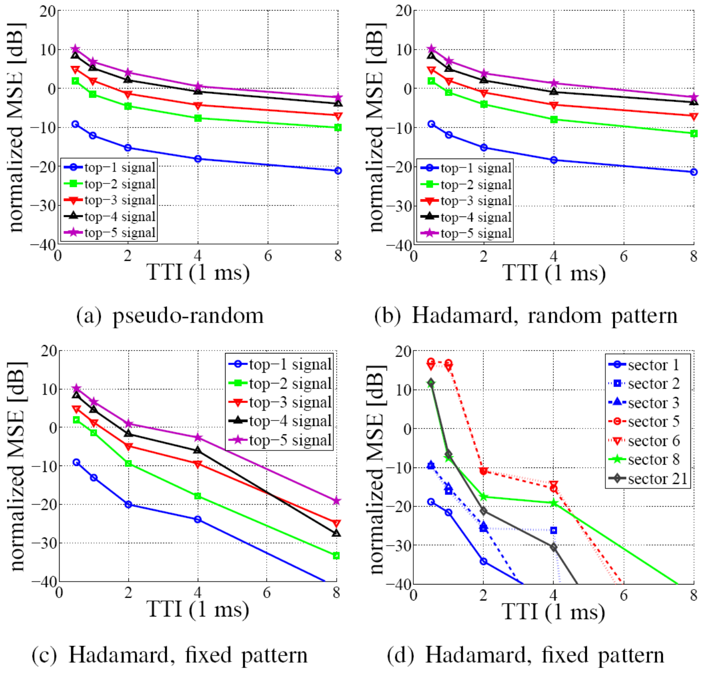


Figure B.2: Normalized MSE obtained for the correlation estimator, in case of a static channel, for the five strongest (a,b,c) and inner sectors (d)

B.2 Decentralised coordinated multi-cell transmission

A decentralised framework has been described in Section 3.2.1.2, which allows CoMP to be implemented in mobile networks without requiring a central entity to take joint scheduling decisions, nor low-latency links to connect the cooperating BSs. Hence, the structure of the conventional systems can undergo minimal changes in order for the coordinated multi-cell transmission to be incorporated [PHG08].

The main obstacle associated with the decentralised collaborative framework is the handling of errors on the different feedback links. This affects both channel information (CI, referring to both CSI and PMI) and CQI feedback and HARQ ACK/NACK reports. Under the decentralised framework, error patterns can be different on each feedback link, since CI, CQI and ACK/NACK are fed back to all collaborating BSs (the number of feedback links used is equal to the number of collaborating BSs). Under a typical CoMP framework only one radio link is utilised per UT for feedback transmission and therefore there is only one error pattern affecting feedback information per UT. In the following paragraphs, we discuss the impact of feedback errors on the system performance with respect to CI and CQI feedback and ACK/NACK reports, and propose solutions to robustify decentralised coordinated multi-cell transmissions.

B.2.1 Impact of errors on feedback information

B.2.1.1 Impact of errors on CI and CQI feedback

In the centralised framework, CI and CQI feedback errors may lead to the selection of UTs that do not maximise the scheduler's objective function. In the decentralised framework, CI and CQI feedback errors may lead also to the selection of terminals by each BS not maximising the scheduler's objective function. Furthermore, BSs might end up selecting different terminals since the error patterns associated with each scheduling point are different. Consequently the decentralised framework could be more sensitive to scheduling degradations caused by errors in the received CI and CQI. A robust scheduling strategy against feedback errors is round-robin scheduling, since terminal selection is not based on the received CI and CQI.

Apart from UT selection, CI feedback errors also impact the design of the transmission parameters, i.e. the design of the pre-coding matrix if linear beamforming is chosen as the transmission strategy. In a preliminary evaluation of the impact of CI feedback errors under zero-forcing beamforming (assuming round-robin scheduling and an analogue modelling of feedback transmission), it has been shown that both the centralised and the decentralised frameworks perform almost the same under the presence of feedback errors [PHG08].

B.2.1.2 Impact of errors on ACK/NACK feedback

UTs feedback ACK/NACK reports which are being input to the scheduler and define if a data packet intended to a specific UT needs to be retransmitted or not. Therefore ACK/NACK signals affect scheduling priorities and errors in the reception of these signals can lead to a potential malfunction of the scheduler operating in a distributed fashion (i.e. independently at every cooperating BS). Indeed, it is crucial that all the involved BSs receive and decode the same HARQ information in order for the scheduling to perform well (the same UTs need to be selected by all BSs). Since each UT feeds back ACK/NACKs to all cooperating BSs using several radio links, different error patterns can be introduced as mentioned above. Therefore, the operation of the distributed scheduling need to be stabilised under potentially corrupted ACK/NACK information at a subset of the cooperating BSs.

For addressing this issue there are three categories of solutions that can be employed. We name the first category of techniques "*malfunction prevention schemes*", the second "*check schemes*" and the third "*malfunction detection and recovery schemes*". The first refers to schemes that robustify the UT to BS feedback by decreasing the probability of errors on the fed back information and therefore reduce the probability that BSs acquire diverging feedback information, which is a potential source of malfunction. The second refers to schemes which verify that the system operates properly (i.e. malfunctions are avoided) and the distributed scheduling function is stable. The third category contains some techniques that detect a potential operational anomaly that can impair a smooth operation of the distributed scheduling. Hence if a malfunction is detected, system operation can be reset and scheduling stability can be recovered. These categories of solutions can be deployed individually or combined in order for a very high operational reliability to be established. Thereafter follows a more detailed description of these schemes.

B.2.2 Solutions for enhancing the robustness of decentralised CoMP

B.2.2.1 Malfunction prevention schemes

In order to robustify feedback (FB) information (CI, CQI, ACK/NACK) against different error patterns that can be introduced by the different radio link utilised, efficient Forward Error Correction (FEC) schemes can be employed with an increased coding rate. This reduces the Block Error Rate (BLER) of the control information and therefore the occurrence of error patterns that may vary. Furthermore time diversity can also be exploited in order to augment the probability that the fed back information is correctly received by the collaborating BSs. For example feedback can be repeatedly transmitted over several TTIs. Schemes that enhance feedback reliability are available in LTE specifications (e.g. ACK/NACK repetition, see [R1-084649]), which could be used in order to meet the requirements of decentralised collaborative processing. This family of schemes has the consequence of increasing the feedback overhead in the uplink.

B.2.2.2 Check schemes

This category of schemes is responsible for ensuring that the collaborating BSs do not possess erroneous or diverging FB information in order to avoid potential system malfunctions.

If CRC is employed after control information encoding, the BSs can send to the UTs ACK/NACK signals depending on whether they have correctly received the UTs HARQ messages. Thus if the UT receives ACK signals from all BSs it then can feed back an OK signal indicating that scheduling and transmission can continue in the next time slot by taking into account this UT. On the contrary if the UT receives a NACK it feeds back a NOK signal indicating that it should not be considered for scheduling and transmission in the following time slot since there is a discrepancy regarding ACK/NACK information between the different collaborating BSs. This discrepancy could lead to non-identical scheduling decisions and therefore to a potential system malfunction. The OK/NOK messages can be transmitted with a very high coding rate in order to maximise the probability that they are correctly received by the BSs.

In case CRC is not employed by the BSs, they can just retransmit their received ACK/NACK messages to the UTs. If the UTs receive the HARQ messages they have transmitted by all collaborating BSs, they feed back an OK signal, else a NOK one.

In addition to signalling overhead in both the DL (for the BS ACK/NACK transmission) and the UL (for OK/NOK transmission), this technique adds a delay of at least to TTIs to the round trip time: one TTI for the BS to transmit ACK/NACK to the UTs and another one for the UTs to transmit the OK/NOK to the BS. Processing delays may increase this delay further.

B.2.2.3 Malfunction detection and recovery schemes

This group of techniques is responsible for detecting an operational malfunction and restoring stability in case the previous schemes fail to prevent the occurrence of a malfunction in the system. A potential operational anomaly may be detected either by the UTs or by the involved BSs. For instance, if the BSs receive mainly NACKS from the UTs, that might signify a problem preventing the good reception of packets targeted to specific UTs. If a system malfunction is detected, the scheduling operation needs to be restarted possibly by the use of a special signal exchanged through the X2 inter-BS communication interface.

In case the UT knows the cooperating BSs from which it is to receive useful signals, it can be the entity that detects an improper system function. For instance, if each collaborating BS allocates specific resources to each scheduled UT and communicates them to it, then a UT can immediately detect if a wrong number of BSs has allocated resources to it. In this case it can signal that a system error has occurred and the scheduling operation can be restarted.

B.2.3 Conclusion

Three types of techniques have been proposed in order to stabilise the operation of the distributed coordinated multi-cell scheduling under potentially corrupted ACK/NACK information: malfunction prevention schemes, check schemes and malfunction detection and recovery schemes. It should be noted that the malfunction prevention and check schemes can also be utilised in order to robustify CI feedback. The improvement of the feedback reliability through the malfunction prevention and check schemes is obtained at the price of increased feedback overhead and/or increased delay, whereas the malfunction detection and recovery schemes do not imply such drawbacks since they are only triggered in case of system malfunction.

By enabling a safe network behaviour in the presence of distributed scheduling, the proposed techniques allow coordinated multi-cell transmission to be introduced without low-latency links between the collaborative BSs, nor central entity to control the cluster behaviour.

B.3 Coordination based on RoF architectures

The use of optical fiber links to distribute signals from a central location to remote antenna units is the basis of RoF technology. In communication systems, signal processing functions in the digital and in the analogue domain are performed at the BS, and signals immediately fed the antenna. RoF makes it possible to centralise the signal processing functions in one shared location (Central Base Station), and then to use optical fiber to distribute the signals to the remote antenna units.

In general, Radio over Fiber technology could be implemented using Digital or Analogue approach. In the digital approach the baseband signal is transmitted from/to a Central Unit to/from a Remote Unit that includes digital to analogue and analogue to digital converters. In the analogue approach, the RF signal is directly modulated and sent over the fiber from/to the Base Station so that the Remote Unit does not need any digital to analogue and up-frequency conversion.
The main characteristics of the digital RoF are:

- applicability to different radio systems (from 2G to 4G) by using semi-proprietary transmission standards (CPRI/OBSAI), with slightly different features for every radio system;
- potentially very efficient network and capacity optimizations achieved by shifting some baseband signal processing at physical layer towards the antenna and also by antenna-related signals multiplexing on the same optical carrier;
- more complex remote units than in the case of analogue RoF but cheaper hardware components (laser, photo-diodes) and no linearity problems;
- high efficiency and wide signal dynamic range allowed, greater fiber distances covered

The main characteristics of the Analogue Radio over Fiber are:

- system independent remotization, with higher bandwidth enabling different systems on the same fiber link (multi-system transmission over fiber);
- centralized baseband signal processing only in distributed architectures and, as a consequence, less freedom than in the case of digital RoF, in optimization network process for what regards remote units;
- simple remote units with only RF amplification;
- less efficiency and signal dynamic range allowed with respect to digital RoF;
- vendor-independent implementations possible.

Analogue Radio over Fiber applications are losing momentum in the product portfolio since most of the manufacturers are now focusing on digital Radio over Fiber, mainly for the advantages in the remote signal processing allowed by the latter.

As mentioned above digital RoF has been partly specified by some international consortia, such as CPRI and OBSAI. Specifications are mainly dedicated to the transport of baseband signals over the fiber, introducing new paradigm in the overall architecture of a radio base station ([OBS20] introduces OBSAI base station architecture, as a possible example).

B.3.1 RoF based CoMP architecture

Digital RoF technology is considered as an important enabler of innovative architectures such as distributed antenna systems, with the highest possible level of reconfiguration of the network. A centrally located unit and a multiplicity of remote antenna units are easily connected by means of fiber links. The architecture that could enable an efficient RoF based architecture is the one in Figure 3.3.

Transmission of data along the fiber is managed following one of the specifications introduced (CPRI, OBSAI or similar) and is considered therefore on a cell basis which means that one antenna-carrier contains all the information for a cell transmission.

This arrangement leads to a partial interoperable behaviour of the remote units with the central unit. The manufacturers, however, maintain a certain level of customization in the implementation of the AxCs and this prevents the full interoperability among central unit and remote units produced by different O&Ms.

Transmission of aggregated data simplifies the architecture of the remote units. They only have to convert digital to analogue signals, amplify and transmit them to the antenna(s) in the downlink chain (for the uplink the received signals are amplified, converted to digital and sent via the fiber connection to the central unit). Of course, in case of beamforming, a signal processing performed over the digital AxCs could be introduced.

The physical layer processing of the LTE system is partitioned into the functional blocks shown in the Figure B.3. In particular, the figure shows the layer 1 functional partitioning of a multi-antenna LTE transmitter.

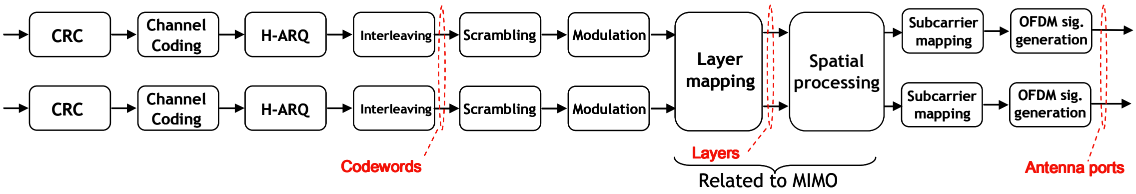


Figure B.3: Functional blocks of physical layer processing in LTE

The baseband modem receives at the input the Transport Blocks with size of TBS bits from the MAC (Medium Access Control) layer and provides at the output the OFDM baseband signal.

The baseband signal processing operations include: CRC insertion, channel coding, hybrid-ARQ processing, channel interleaving, bit scrambling, modulation, layer mapping, spatial processing (precoding, spatial multiplexing, transmit diversity, beamforming, CDD), mapping to assigned resources/antenna ports and finally OFDM signal generation (i.e. the IFFT operation with cyclic prefix insertion).

The baseband OFDM signal containing all the information for a given cell, is sampled at the frequency Fs and transmitted to the remote units over the fiber.

The network layout when a cell data transmission over the fiber link occurs is reported in Figure 3.4, focussing on the downlink path (the uplink is straightforward). Remote units receive the cell data and perform cell data processing (in order to execute the reconfiguration of the remote unit, as explained in the following) before transmitting data to each of the K antennas they are equipped with. If fiber link capacity is sufficiently high, more than a single AxC can be managed by the remote unit, enabling signal multiplexing.

In order to assess this feature, the overall data rate to be supported over the fiber must be estimated. If the sampling process of the I/Q time signals is performed using a number of bit equal to Nbit for each signal component (I/Q), the above mentioned data rate theoretically is

$$T_{data,RU} = 2 \cdot F_s \cdot N_{bit}$$

according to the sampling theorem. An example is given in the following table, where the number of bit Nbit has been set equal to 10 and reference is made to LTE system bandwidths.

LTE bandwidth [MHz]	**1.4**	**3**	**5**	**10**	**15**	**20**
Fs [MHz]	1.92	3.84	7.68	15.36	23.04	30.72
N_{bit}	10	10	10	10	10	10
$T_{data,RU}$ [Mbit/s]	38.4	76.8	153.6	307.2	460.8	614.4

As it is clear from the example, the number of AxCs that can be transmitted over the fiber link depends on the radio system bandwidth and, additionally, on the overall capacity supported by the connection. Currently consortia such as CPRI and OBSAI specify format and allocation of data over the fiber connection. OBSAI, in particular, has introduced also specifications for LTE systems. In these specifications it can be found that 16 bits are used to sample downlink and uplink LTE signals, with no oversampling. Moreover, CPRI and OBSAI indicate the number of antenna carriers that can be transported over a fiber link of a given overall capacity.

Presently OBSAI available line rates are 768, 1536, 3072 and newly introduced 6144 Mbit/s, following the development of new and more efficient optical transmitters and receivers. In the case of a line rate equal to 3072 Mbit/s OBSAI indicates that up to 8 antenna carriers transporting 5 MHz LTE signals are allowed (4 antenna carriers are manageable with a bandwidth of 10 MHz, 2 antenna carriers with 15 MHz and 20 MHz bandwidth, always according to OBSAI specifications).

Besides the cell data, control data shall be transmitted over the fiber as well, in order to perform the cell processing in the remote units. These data can be multiplexed in the currently existent data formats (CPRI, OBSAI or others) exploiting overhead data allocation.

B.3.2 Reconfigurable remote units

A feasible architecture based on digital RoF distributed antenna systems can include newly-introduced so-called reconfigurable antennas in the remote antenna units. A system capable of making digital beam forming so as to optimize the beam for the cell can be called reconfigurable antenna. Reconfigurable antennas can be effectively used in cellular network planning. In fact by means of an optimization procedure, it is possible to define a set of beam patterns that the reconfigurable antennas can radiate in order to maximize several output parameters like coverage, signal to interference ratio, capacity, etc.

When working conditions change, a new optimization procedure has to be run in order to keep the value of the output parameters to the desired level.

These concepts can be easily transformed into an automatic process:

- the information coming from the network (quality of service, number of lost calls, traffic counter, etc.) are provided to a CoMP Management entity (see);
- this entity drives the optimization procedure and determines new beamforming weights;
- this entity sends new weights to the reconfigurable antenna that discards the old configuration and sets the new one.

If the remote unit is equipped by a reconfigurable antenna array the amount of control data (or reconfiguration data) that are to be exchanged between the central unit and the remote units via the fiber link is very low.

As stated above, control data shall be multiplexed with cell data in the overall data stream carried over the fiber link (according to CPRI, OBSAI or other standards). The data streams to be transmitted over the fiber link (generally a fiber ring) to realize a reconfigurable scheme are reported in Figure B.4, where a feasible architecture is reported as well.

In that architecture, based on a fiber ring to exemplify, a double ring-fiber connection is considered. A first ring can be intended as the “main” ring transporting downlink data together with reconfiguration control data and collecting uplink data while crossing the remote units over the ring. A second ring performs the same operation in the opposite direction (e.g., counter-clockwise instead of clockwise) ensuring redundancy and resilience against possible failures along the ring. Other architectures, based on bus-like topologies to exemplify as well, present different management strategies, straightforward to be inferred from those presented here.

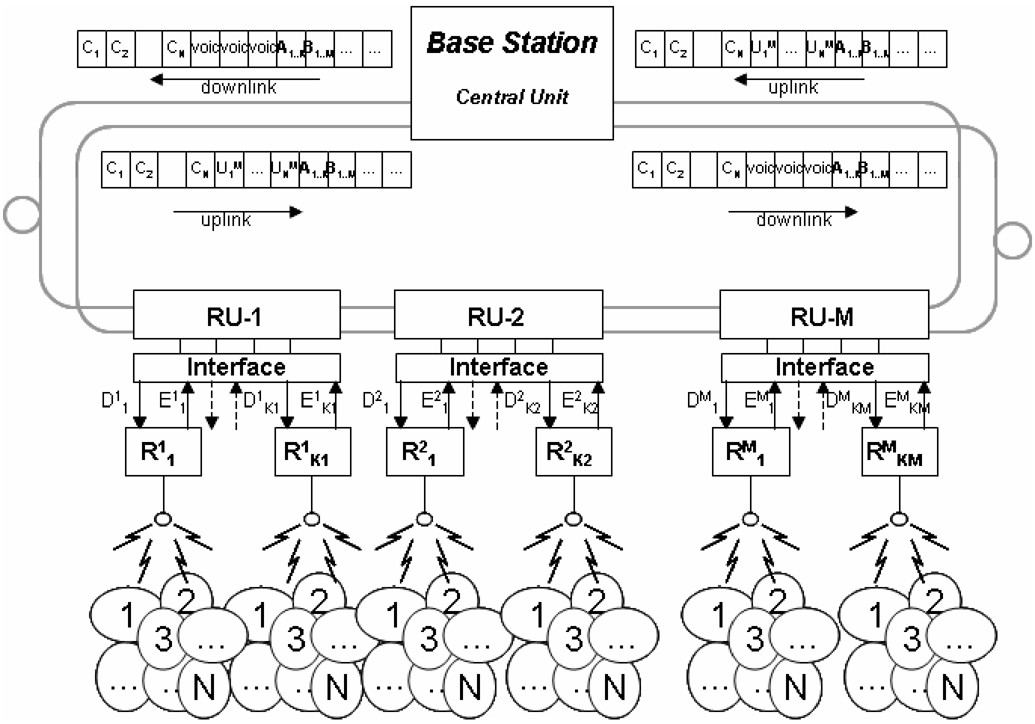


Figure B.4: Double fiber RoF based CoMP

In the architecture, the notation adopted is as follows:

- N,M, Km are the above defined parameters (number of antenna carriers, number of remote units, number of antenna elements per remote unit)
- C_i is the i-th antenna carrier in the downlink channel in the CoMP
- U^j_i is the i-th antenna carrier in the uplink channel referred to the j-th remote unit in the CoMP
- D^j_l is the l-th antenna element signal in the j-th remote unit in the CoMP, in the downlink channel
- E^j_l is the l-th antenna element signal in the j-th remote unit in the CoMP, in the uplink channel

The data stream in downlink, exiting from the base station central unit, can be organized as reported in the Figure B.5, to be considered as a general data stream, complying to CPRI and/or OBSAI or other possible standard specifications.

In the data stream there are the antenna carriers (C_i) and the control data, which are in the form of matrixes:

- A_j is the downlink control matrix of j-th remote unit
- B_j is the uplink control matrix of j-th remote unit

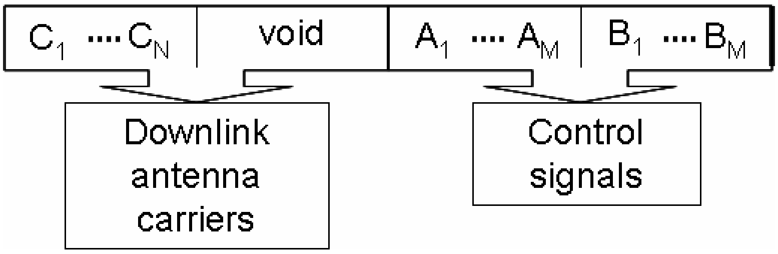


Figure B.5: Data stream exiting from the CU in a double fiber RoF CoMP

After crossing all the M remote units the data stream is slightly different, and can be considered as follows in the final connection towards the central unit.

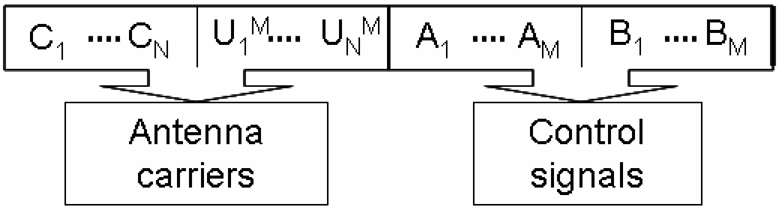


Figure B.6: Data stream entering the CU in a double fiber RoF CoMP

With respect to the firstly-generated data stream there are also the uplink antenna carriers, which are collected passing through the M remote units in the CoMP. If this arrangement of the data streams is adopted, the same data stream in the downlink connection, while passing through the remote units, collects the uplink data stream as well.

On the other hand, if a bus topology is preferred, a similar approach can be envisaged exploiting the first fiber of the bus to transport downlink antenna carriers and reconfiguration matrixes and the second fiber to collect uplink antenna carriers towards the base station central unit. However, a bus scenario does not ensure resilience against failures, at least for a subset of remote units. The bus architecture can handle a data format with double capacity with respect to the ring architecture described above: no uplink void antenna carriers are needed since uplink and downlink data stream are physically separated in a bus architecture scenario.

Matrixes A are used to perform the following operations:

$$\begin{bmatrix} D_1^j \\ D_2^j \\ \\ \\ D_K^j \end{bmatrix} = \begin{bmatrix} A_{11}^j & A_{12}^j & \cdots & \cdots & A_{1N}^j \\ A_{21}^j & \ddots & & & \\ \vdots & & A_{li}^j & & \\ \vdots & & & \ddots & \\ A_{K1}^j & & & & A_{KN}^j \end{bmatrix} \cdot \begin{bmatrix} C_1 \\ C_2 \\ \\ \\ C_N \end{bmatrix}$$

Making reference to the j-th remote unit, A transforms the antenna carriers in the useful signals for the l-th antenna element (j runs from 1 to M, l from 1 to Km).

The reconfiguration process is related to the values assigned to the elements of matrix A. A_{li}^{j} is the coefficient of matrix A related to the i-th antenna carrier Ci, to the j-th remote unit and generating the signal for the l-th antenna array element. A_{li}^{j} is therefore the "weight" for the l-th antenna element, calculated in the "CoMP Management" in order to generate the most useful radiation diagram.

In a simplified arrangement A_{li}^{j} can simply be considered as a trigger to activate/deactivate a remote unit in a CoMP. As an example, if Km, for a given remote unit, is equal to 1, A_{li}^{j} can assume 0/1 values only. In that case, if A_{li}^{j} is 0 the corresponding remote unit is switched off, if A_{li}^{j} is 1 it is turned on.

Matrix A can therefore be considered either the "beamforming" matrix, when its elements are full beamforming coefficients for the remote units' antenna arrays, or a simpler "reconfiguration" matrix, controlling the activation/deactivation of the CoMP remote units.

In this sense the "reconfiguration" in the CoMP assumes a double meaning: reconfiguration of the cell resources assigned to the remote units, and reconfiguration of the radiating diagrams of their antennas. Network planning procedures can exploit the two reconfiguration options given, enhancing quality and capacity in the area of the CoMP. While reconfiguration of the radiation diagram is a straightforward and an already-known approach, reconfiguration of the radio resources paves the way to coordinated transmission schemes, as it will be explained in the following.

Regarding uplink instead of matrix A the same role is played by matrix B, which is different because reconfiguration in uplink is not necessarily the same as in downlink. From a mathematical point of view the operations are as follows

$$\begin{bmatrix} U_1^j \\ U_2^j \\ \\ \\ U_N^j \end{bmatrix} = \begin{bmatrix} U_1^{j-1} \\ U_2^{j-1} \\ \\ \\ U_N^{j-1} \end{bmatrix} + \begin{bmatrix} B_{11}^j & B_{12}^j & \cdots & \cdots & B_{1K}^j \\ B_{21}^j & \ddots & & & \\ \vdots & & B_{il}^j & & \\ \vdots & & & \ddots & \\ B_{N1}^j & & & & B_{NK}^j \end{bmatrix} \cdot \begin{bmatrix} E_1^j \\ E_2^j \\ \\ \\ E_K^j \end{bmatrix}$$

Signals E_l^j are coming from the l-th antenna element of the antenna array of the j-th remote unit; they are processed by means of matrix B, thus obtaining the uplink antenna carrier to be transmitted to the central unit. In the above reported approach a sum occurs in each remote unit of the signals pertaining to the same antenna carrier Ui. This implies that a certain level of coordination and synchronization must be guaranteed among the remote units so as that the "sum" operation can be performed consistently. If the synchronization among the scattered remote units cannot be maintained no sum will occur in the remote units but each U_i^j signal will be transmitted to the base-band processor in the central unit, where the proper multiplexing of all the U_i^j will take place, similarly to what currently happens in case of delay diversity approaches. The above reported approach (with sums occurring in the remote units) is the most convenient in terms of fiber capacity savings, since the same data structure carrying downlink antenna carriers is able to house uplink signals as well, "collecting" them while passing through each remote unit. If the sums occur centrally in the base station each remote unit would need a separate fiber link for the uplink connection to the central unit, not allowing any kind of antenna carriers multiplexing over the fiber link.

B.3.3 RoF CoMP applications

Reconfigurable or adaptive antennas can be used in the remote antenna units in order to fully achieve network flexibility.

B.3.3.1 Intra-cell and inter-cell scenarios

Different CoMP concepts are introduced depending on the intra-cell or inter-cell approach. In the suggested architecture, based on reconfigurable or adaptive remote units, it is easy to manage both the architectures, either intra- or inter-cell one. When intra-cell behaviour is requested the antenna carriers transport information related to the same cell, easily implementing repeating schemes. On the other hand antenna carriers pooling in the central unit paves the way to inter-cell CoMP.

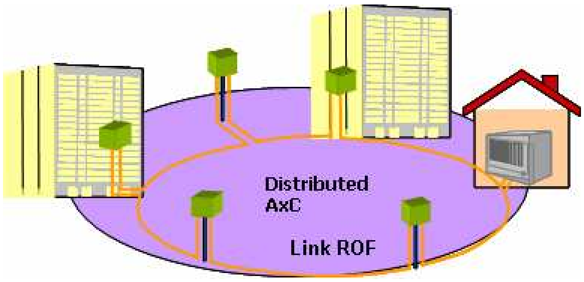


Figure B.7: Intra-cell scenario in RoF CoMP

The intra-cell approach is reported in the picture above (Figure B.7). In this case the same antenna carrier is shared among all the transmitters (micro or even macro-cells) extending the coverage area of the original base-station. A straightforward evolution of this first scenario paves the way to the inter-cell coordination, when all the transmitters manage a different antenna carrier; resources are pooled in the central unit, where a control processor ("CoMP Management") is located (see Figure B.8).

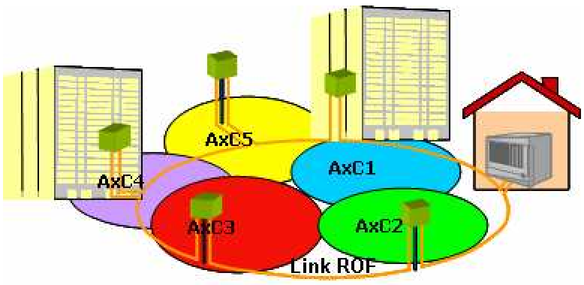


Figure B.8: Inter-cell scenario in RoF CoMP

Moreover, multilayer evolution could be considered as well, with a common antenna carrier sharing and remote unit specific antenna carriers to reinforce coverage/quality in smaller areas (Figure B.9).

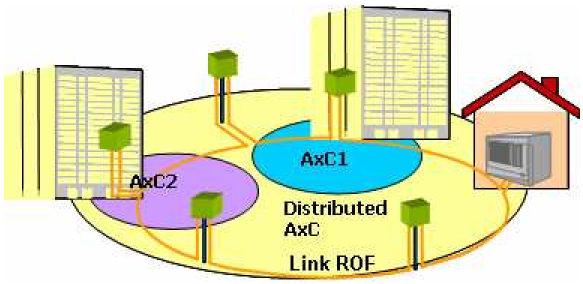


Figure B.9: Multi-layer scenario in RoF CoMP

B.3.3.2 Network reconfiguration

The suggested CoMP based on RoF links allows an easy reconfiguration of the radiation diagrams of the array antennas in the remote units. Moreover, radio resources reconfiguration, as stated above, is possible as well.

Dynamic management of remote units and remote units resources

The easiest reconfiguration scheme envisaged is that of turning on/off the remote units in the CoMP, according to network planning or traffic constraints. When needed, the planner could easily turn on/off a remote unit in order to upgrade/downgrade the overall coverage and/or capacity in the area. This option is particularly well suited for microcells in the CoMP, generally intended as complementary cells in a radio planning project.

The network reconfiguration offered by the CoMP architecture based on ROF links can be exploited to adapt the network characteristics to the traffic requirements. In fact, there are various application scenarios in which the traffic may present very significant variations in time. An exemplary case is that of stadiums or other sports and show venues and facilities. For example, a considerable mass of people may

crowd a stadium for a short period of time (e.g. for a few hours or little longer) for an event. In such a case the capacity of the network can be locally increased by providing a larger number of antenna carriers to the remote units that serve the considered venue for the correspondent period of time.
The more generic “on/off reconfiguration” of the radio resources in the CoMP is quite straightforward. A more complex form of reconfiguration can be based on an effective transmit power management. As an example, the coefficient in the A (and/or B) matrixes in the data formats described above, could be not only 0/1 stating that the corresponding remote unit is turned off/on respectively. They can also be a value between 0 and 1 stating the percentage of power that the designed remote unit shall transmit. In this way it is very easy to implement transmit power schemes to mitigate interference between remote units or also to improve the coverage for users that experience bad channel conditions (e.g. cell edge users, indoor users served by an outdoor remote unit, etc).

The possibility of reconfiguring the resources allocated to remote units in a RoF scenario can be exploited also for a transmit selection scheme of the remote units based on users locations and interference reduction. In the transmit selection scheme only a single distributed antenna module RU is selected for transmission by a certain criterion such as the criterion of minimizing propagation path-loss, maximizing SINR or maximizing capacity. This scheme is competitive in terms of simplicity and it minimizes the required transmit power (and hence the interference caused to other cells). This scheme exploits macroscopic selection diversity and is expected to additionally reduce Inter Cell Interference (ICI) because the number of ICI sources is reduced. In this case ICI is reduced and the SINR improved especially for users near cell boundaries, which normally are performance limiting users, compared to conventional cellular systems in an interference-limited multi-cell environment.

Coordination between remote units

Advanced form of reconfiguration enables also network coordination algorithms that operate on each user data stream separately, involving two or more remote units simultaneously, as shown in the Figure B.10.

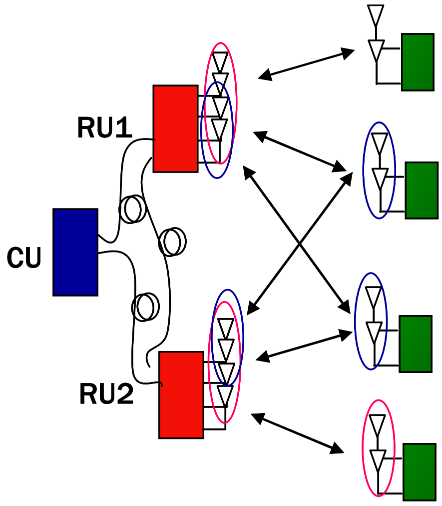


Figure B.10: Coordination in RoF architecture

In particular, each user data stream is elaborated in the central unit, it is multiplexed with the other users and transmitted to the remote units in the data format described previously. Any kind of processing, involving physical layers or even L2/L3 layers coordination, can be performed in the central unit and the processed cell data are then transmitted over the fiber link to the cooperating remote units.

MU-MIMO in reconfigurable RoF

The full exploitation of multi-user MIMO starting from a reconfigurable RoF architecture is straightforward.

Simple MIMO schemes are obtained considering each remote unit separately from the others in the RoF architecture, performing its MIMO with the assigned UEs in its coverage area. Making reference to the above picture that case is represented by the antennas i.e of RU2 implementing a 4x2 MIMO with RU2-served users.

Otherwise more complex MIMO schemes are possible, comprising antenna elements from different RUs. Always considering the above picture such a MIMO scheme can be realized with two antennas of RU1 and two of RU2 altogether introducing a 4x2 MIMO scheme for the users that are in the boundary region between RU1 coverage area and RU2 coverage area. Cell data for each of the involved antenna elements of the two involved RUs are transmitted from the CU so as to implement the MIMO scheme from spatially separated transmitting points. Of course an high level of synchronization between the transmitting points is required in order to make MIMO schemes from multiple RUs work properly.

Linear precoding in reconfigurable RoF

Simplest coordination algorithms are based on linear precoding. Precoding is the procedure consisting in taking some performance advantage from multiplying the layered signal (to transmit over a MIMO system) for a matrix, called precoding matrix or simply precoder.

The linear precoding matrix is a function of the Channel State Information (CSI), which is, in general, only available at the user terminal receiver. Thus, the required information to select the optimum precoding matrix must be fed back to the CU over a feedback link to be identified in the fiber transmission format.

The basic idea in linear precoding is that the precoding matrix is chosen from a finite set of precoding matrices, called “codebook”, known to both the receiver and the transmitter. The user terminal receiver chooses the optimal precoding matrix from the codebook as a function of the current CSI and sends the binary index of this matrix to the transmitter over a limited capacity feedback channel. The matrix index is denoted as Precoding Matrix Index (PMI).

In case of MIMO-OFDM based systems the PMI feedback must be provided for each subcarrier or at least for each group of adjacent subcarriers due to the frequency selectivity of the channel. This means that the signalling overhead may become significant and, thus, methods have been studied to reduce such feedback by exploiting, for instance, the correlation of the optimal precoding matrix over adjacent subcarriers.

In case of cooperative precoding two or more RU cooperate by transmitting the same data layer to the user terminal and uses its own optimum precoding vector whose index is provided back by the user terminal. Moreover each RU should be provided with orthogonal Reference Signals in order to enable the user terminal to separately estimate the channel of the different cooperating RUs.

B.4 Performance investigation of multi-cellular distributed versus co-located MIMO

In this section we show the evaluation results of the OFDM based cellular distributed MIMO scenario as compared to a co-located MIMO scenario, as described in Section 3.3.2.1.

In addition to the assumptions mentioned in Section 3.3.2.1, slow fading is assumed and outage capacity C_{out} is chosen for the performance analysis. In the evaluation results, M_R=M_T=2 antenna elements are assumed and a frequency reuse factor of 1. In order to model the interference two tires of interference are considered and the OFDM cyclic prefix is assumed to fully cover the delay spread. Further simulation assumptions can be found in [SWO08].

In Figure B.11, the 10% outage capacity has been evaluated as a function of the normalized distance from the cell center when moving towards the worst case point marked in Figure 3.7 in Section 3.3.2.1. It can be seen that after a normalized distance of about 0.4, the distributed MIMO system outperforms the conventional system in terms of outage capacity, and a more uniform capacity distribution is achieved over the cell.

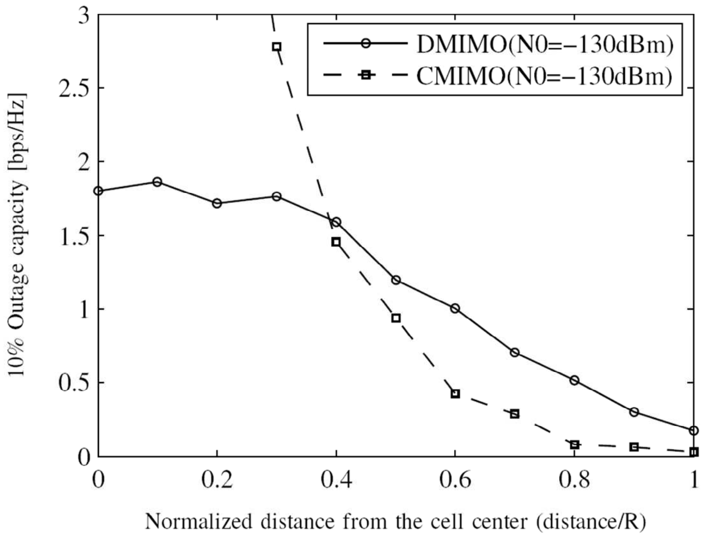


Figure B.11: 10% outage capacity when moving from cell center towards the worst case point

In Figure B.12, the area of performance improvement for distributed MIMO is shown in terms of 10% outace capacity difference C_{diff} in bits/s/Hz. The differently shaded areas represent different amount of outage capacity difference, where distributed MIMO outperforms co-located MIMO. In the unshaded area of the cell, co-located MIMO outperforms distributed MIMO. Under the assumption of a uniform user distribution, in about 84% of the cell area the distributed MIMO system performs better than the co-located MIMO system.

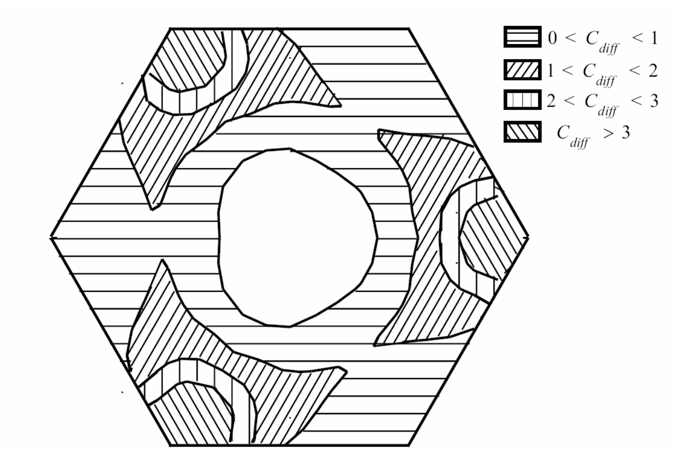


Figure B.12: Difference in outage capacity for distributed and co-located MIMO over their respective cell definition areas

Note that the gains shown in Figure B.11 and Figure B.12 are mainly due to reduced inter-cell interference resulting in an SINR gain. Additional multiplexing gain was not exploited. To show the potential multiplexing gain, the probability distribution functions of the largest and smallest of the eigenvalues at the worst case points marked in Figure 3.7 in Section 3.3.2.1 are plotted in Figure B.13.

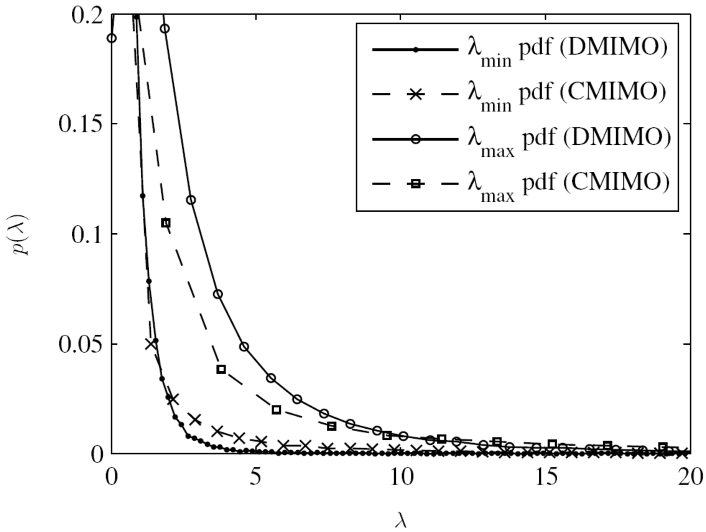


Figure B.13: Distribution of largest and smallest eigenvalues for distributed MIMO and co-located MIMO at respective worst case point

As seen the pdfs of the largest eigenvalue have a higher mean for the distributed MIMO case. This is owing to the fact that the distributed MIMO system benefits from the inherent macro-diversity, which increases the rank of the channel. It is also noted that in the distributed MIMO system, co-channel interference is also transmitted by distributed arrays which have lower large-scale correlation with respect to co-located arrays in co-located MIMO systems. This effect increases the rank of the interference correlation matrix which also contributes to the improvement of eigenvalue distributions.

Further details on this study can be found in [SWO08].

B.5 Transceiver optimisation with coordinated multi-cell processing

B.5.1 Introduction

Coordinated multi-cell processing facilitates multi-user precoding techniques across several distributed antenna heads, which can be used to improve the utilisation of the physical resources by exploiting the available spatial degrees of freedom in a multi-user multiple-input multiple-output (MIMO) channel [Wyn94], [SZV02], [KFV06], [TCJ08a]. Assuming linear transceiver processing, a coordinated multi cell system with N antennas would ideally be able to accommodate up to N streams/beams without becoming interference limited. Mutual interference between the streams can be controlled or even completely eliminated by a proper selection of transmit weight vectors. This is especially true in the coherent multi-cell MIMO case, where user data is conveyed from multiple BS antenna heads over a large virtual MIMO channel [KFV06], [TCJ08a].

The coherent multi-user multi-cell precoding techniques, however, have high requirements in terms of signalling and measurements. In addition to the complete channel knowledge of all jointly processed links, carrier phase synchronisation across the transmitting nodes and centralised entities performing scheduling and computation of joint precoding weights are required. A large amount of data needs to be exchanged between the network nodes. Thus, high speed links, such as optical fibers or dedicated radio links are needed.

Another form of coordinated transmission is a dynamic multi-cell scheduling and interference avoidance, where the network nodes coordinate their transmissions (precoder design, scheduling) in order to minimise the inter-cell interference. The phase coherence between the transmit nodes is not required, since each data stream is transmitted from a single BS node. Thus, the non-coherent coordinated multi-cell transmission approaches have somewhat looser requirements on the coordination and the backhaul, but could potentially still need centralised resource management mechanisms. Also, full channel knowledge of all jointly processed links is still needed for the ideal interference avoidance.

In this study, a generalised method for joint design of the linear transceivers with coordinated multi-cell processing subject to per-BS/antenna power constraints is proposed. The system optimisation objective in this paper is to provide an equal weighted SINR for the transmitted data streams, i.e., to maximise the minimum weighted SINR per stream. The optimisation problem is quasiconvex for receivers with a single antenna or with a fixed receive beamformers [WES06], [TCJ08b]. Thus, the optimal solution can be found for those configurations.

The generalised method can accommodate two special cases previously available in the literature: coherent multi-cell beamforming with per BS power constraints, which requires a full phase synchronism between all BSs [TCJ07b]; and coordinated single-cell beamforming case, where all the transceivers are jointly optimised while considering the other-cell transmissions as inter-cell interference (see solution in [BO01] for the minimum power beamformer design). Furthermore, the model can handle any combination of the aforementioned cases, where the number of jointly transmitting nodes may vary between users.

In the coordinated single-cell beamforming case, each stream is transmitted from a single BS. In such a case, a user is typically allocated to a cell with the smallest path loss. Near the cell edge, however, the optimal beam allocation strategy may also depend on the time varying properties of the channel. Thus, large gains from fast beam allocation (cell selection) algorithms are potentially available for the cell edge users. The optimal cell or BS assignment per beam is a difficult combinatorial problem and it requires an exhaustive search over all possible combinations of beam allocations. This is clearly computationally prohibitive for a large number of users and BSs. Therefore, a set of sub-optimal heuristic allocation algorithms is proposed.

The presented methods require complete channel knowledge between all pairs of users and BSs, and hence, the solutions represent an absolute upper bound for the less ideal solutions with incomplete channel knowledge. The performance of coherent and non-coherent coordinated transmission with different beam allocation algorithms, as well as, non-coordinated transmission and inter-cell interference free scenario with time division multiple access (TDMA), is numerically compared in different operating scenarios with varying inter-cell interference. Even though the model is presented for the general case with multiple receiver antennas per user, the numerical results are shown only for the single antenna receiver case for simplicity.

B.5.2 System model

The cellular system consists of N_B BSs, each BS has N_T transmit antennas and user k is equipped with N_{R_k} antennas. A set U with size $K = U$ includes all users active at the given time instant, while a subset $U_b \subseteq U$ includes the users allocated to BS b, $k \in U_b$. Each user k can be served by M_k BS's which define the joint processing set B_k for the user k, and $B_k \subseteq B = \{1, \ldots, N_B\}$. The signal vector $\mathbf{y}_k \in \mathbb{C}^{N_{R_k}}$ received by the user k consists of the desired signal, intra-cell and inter-cell interference, and it can be expressed as

$$\mathbf{y}_k = \sum_{b \in B_k} a_{b,k} \mathbf{H}_{b,k} \mathbf{x}_{b,k} + \sum_{b \in B_k} a_{b,k} \mathbf{H}_{b,k} \sum_{bi \neq k} \mathbf{x}_{b,i} + \sum_{b \in B/B_k} a_{b,k} \mathbf{H}_{b,k} \mathbf{x}'_b + \mathbf{n}_k \tag{1}$$

where the vector $\mathbf{x}_{b,k} \in \mathbb{C}^{N_T}$ is the transmitted signal from the b'th BS to user k, $\mathbf{x}'_b \in \mathbb{C}^{N_T}$ denotes the total transmitted signal vector from BS transmitter b, $\mathbf{n}_k \sim CN(0, N_0 \, \mathbf{I}_{N_{R_k}})$ represents the additive noise sample vector with noise power density N_0, and $a_{b,k}\, \mathbf{H}_{b,k} \in \mathbb{C}^{N_{R_k} \times N_T}$ is the channel matrix from BS b to user k with large-scale fading coefficient $a_{b,k}$. The entry $[\mathbf{H}_{b,k}]_{r,t}$ represents the complex channel gain between TX antenna t and RX antenna r. The elements of $\mathbf{H}_{b,k}$ are normalised to have unitary variance, i.e., $\mathrm{E}\left\{\left|[\mathbf{H}_{b,k}]_{r,t}\right|^2\right\} = 1$. The total transmitted vector $\mathbf{x}'_b$ from BS b consists of transmissions to all the users in the user set U_b, $\mathbf{x}'_b = \sum_{k \in U_b} \mathbf{x}_{b,k}$.

The transmitted vector for user k is generated at BS b as

$$\mathbf{x}_{b,k} = \mathbf{M}_{b,k} \mathbf{d}_k \tag{2}$$

where $\mathbf{M}_{b,k} \in \mathbb{C}^{N_T \times m_k}$ is the pre-coding matrix, $\mathbf{d}_k = [d_{1,k}, \ldots, d_{mk,k}]^T$ is the vector of normalized complex data symbols, and $m_k \leq \min(N_T M_{k,} N_{R_k})$ denotes the number of active data streams.

The total power transmitted by the BS b is

$$\mathrm{Tr}\left(\mathrm{E}\left[\mathbf{x}'_b \mathbf{x}'^{\mathrm{H}}_b\right]\right) = \mathrm{Tr}\left(\sum_{k \in U_b} \mathbf{M}_{b,k} \mathbf{M}^{\mathrm{H}}_{b,k}\right). \tag{3}$$

Consequently, the power per transmit antenna is given as $\left[\sum_{k \in U_b} \mathbf{M}_{b,k} \mathbf{M}^{\mathrm{H}}_{b,k}\right]_{n,n}$, $n = 1, \ldots, N_T$.

We focus on linear transmission schemes, where the N_B transmitters send S independent streams, $S \leq \min(N_B N_{T,} \sum_{k \in U} N_{R_k})$ per transmit dimension. Per data stream processing is considered, where for each data stream s, $s = 1, \ldots, S$ the scheduler unit associates an intended user k_s, with the channel matrices $\mathbf{H}_{b,k_s} \in \mathbb{C}^{N_T \times N_{R_{k_s}}}$, $b \in B_s$. Note that more than one stream can be assigned to one user, i.e. the cardinality of the set of scheduled users, $U = \{ k_s \mid s = 1, \ldots, S\}$, is less than or equal to S. Let $\mathbf{m}_{b,s} \in \mathbb{C}^{N_T}$ and $\mathbf{w}_s \in \mathbb{C}^{N_{R_{k_s}}}$ be arbitrary transmit and receive beamformers for the stream s. The SINR of the data stream s can be expressed as

$$\gamma_s = \frac{\left|\sum_{b \in B_s} a_{b,k_s} \mathbf{w}_s^{\mathrm{H}} \mathbf{H}_{b,k_s} \mathbf{m}_{b,s}\right|^2}{N_0 \|\mathbf{w}_s\|_2^2 + \sum_{i=1, i \neq s}^{S} \left|\sum_{b \in B_i} a_{b,k_s} \mathbf{w}_s^{\mathrm{H}} \mathbf{H}_{b,k_s} \mathbf{m}_{b,i}\right|^2}. \tag{4}$$

B.5.3 Generalised SINR balancing with coordinated BS processing

In this section, a general method for solving SINR balancing problem with coordinated BS processing is presented. The generalised method can accommodate the following special cases:

- Coherent multi-cell beamforming ($B_s = B_k = B \ \forall \ s,k$) with per BS and/or per-antenna power constraints, which requires a full phase synchronism between all $b \in B$ [TCJ08a]
- Coordinated single-cell beamforming case ($|B_s| = 1 \ \forall \ s$), where all the transceivers are jointly optimised while considering the other-cell transmissions as inter-cell interference. (similar to solution in [BO01], [Ben02] for the minimum power beamformer design).
- Any combination of above two, where $|B_k|$ and $|B_s|$ may be different for each user k and/or stream s.

Note that the presented method requires a complete channel knowledge of $a_{b,k}$ $\mathbf{H}_{b,k}$ between all pairs of k and b, and hence, the solution represent an absolute upper bound for the less ideal solutions with an incomplete channel knowledge.

The system optimisation objective is to keep the SINR per data stream γ_s in fixed ratios in order to guarantee fairness between streams/users, i.e. $\gamma_s / \beta_s = \gamma_0$, and γ_s has to be maximised subject to per BS power constraints. This can be formulated as maximisation of the minimum weighted SINR per stream:

$$\max \min_{s=1,\dots,S} \frac{\beta_s^{-1} \left| \sum_{b \in \mathrm{B}_s} a_{b,k_s} \mathbf{w}_s^{\mathrm{H}} \mathbf{H}_{b.k_s} \mathbf{m}_{b,s} \right|^2}{N_0 \|\mathbf{w}_s\|_2^2 + \sum_{i \neq 1, 1=s}^{S} \left| \sum_{b \in \mathrm{B}_s} a_{b,k_s} \mathbf{w}_s^{\mathrm{H}} \mathbf{H}_{b.k_s} \mathbf{m}_{b,i} \right|^2}$$

$$s.t. \sum_{s \in S_b} \|\mathbf{m}_{b,s}\|_2^2 \leq P_b, b = 1,\dots,N_B$$

where the optimisation variables are $\mathbf{m}_{b,s} \in \mathbb{C}^{N_\mathrm{T}}$ and $\mathbf{w}_s \in \mathbb{C}^{N_{\mathrm{R}k_s}}$, $s = 1, \dots, S$, and S_b includes all streams allocated to BS b, i.e., $S_b = \{s \mid k_s \in U_b|\}$. The weights, $\beta_s > 0$, $s = 1, \dots, S$, are used to prioritise the data streams of different users differently. Problem (5) is not jointly convex in variables $\mathbf{m}_s$ and $\mathbf{w}_s$. However, for a fixed $\mathbf{m}_{b,s}$, $s = 1, \dots, S$, (5) has a unique solution given by the LMMSE receiver

$$\mathbf{w}_s = \left(\sum_{i=1}^{S} \sum_{b \in B_i} a_{b,k_s}^2 \mathbf{H}_{b,k_s} \mathbf{m}_{b,i} \mathbf{m}_{b,i}^{\mathrm{H}} \mathbf{H}_{b,k_s}^{\mathrm{H}} + N_0 \mathbf{I}_{N_{\mathrm{R}_k}} \right)^{-1} \sum_{b \in B_s} a_{b,k_s} \mathbf{H}_{b,k_s} \mathbf{m}_{b,s}$$

which provides the maximum SINR for stream s. Furthermore, for a single antenna receiver or a fixed $\mathbf{w}_s$, (5) is quasiconvex in $\mathbf{m}_{b,s}$ [WES06], [TCJ08b]. Thus, it can be solved with any accuracy $\varepsilon > 0$ by the bisection method [BV04] presented in *Algorithm 1* [TPK08]. The optimal objective value γ_0 for fixed $\mathbf{w}_s$ (i.e., *Algorithm 1*) is indeed unique, but the resulting $\mathbf{m}_s$, $s = 1, \dots, S$ is not guaranteed to have a unique solution in general, due to the the quasi-convexity of the original problem [WES06], [TCJ08b]. Therefore, global optimality of the above method can only be guaranteed for the single-antenna receiver case.

B.5.4 Heuristic beam allocation algorithms

The aim of any beam-to-cell allocation algorithm is to select such BSs that the resulting beamformers mutually interfere as little as possible while providing large beamforming gains towards the intended users. A set of heuristic allocation algorithms for the coordinated single-cell beamforming case ($|B_s| = 1 \ \forall \ s$) are proposed in the following:

1. Greedy selection: The algorithm consecutively selects at most min ($\sum_k N_{R^k}$, N_T,) channels from the total set of $\sum_k$ min (N_{R^k}, N_T,) channels. First, the strongest channel among all channels $\operatorname{argmax}_{b,k,l} \ \mathbf{h}_{b,k,l}$ is selected. Subsequently, on each step of the selection process, the channel with the largest component orthogonal to the previously selected set of beams is chosen. See similar beam allocation approaches, e.g., in [TJ05], [YG06].
2. Maximum eigenvalue selection}: The eigenvalues (norms) of the virtual channel vectors $\mathbf{h}_{b,k,l}$ are simply sorted and at most N_T streams are allocated per cell. Spatial compatibility with other channels is not considered.
3. Eigenbeam selection using max rate criterion}: A simplified exhaustive search is carried out over all possible combinations of user-to-cell and stream/beam-to-user allocations, B_k and $S_b = \{s$

$| k_s \in U_b\}$, where the beamformer $\mathbf{m}_{b,s}$ for each stream s is matched to the virtual channel vector $\mathbf{h}_{b,k,l}$, i.e., $\mathbf{m}_{b,s} = \mathbf{v}_{b,ks,ls}\sqrt{P_T/S_b}$. For each allocation, the receivers $\mathbf{w}_s$ and the corresponding SINR values γ_s, $s = 1, \ldots, S$ are calculated as in (6) and (4), respectively. Finally, the selection of the optimal allocation is based on the maximum rate criterion, i.e., $\underset{b,k,l}{\operatorname{argmax}} \sum_{s=1}^{S} \log_2(1+\gamma_s)$.

4. Eigenbeam selection using maxmin SINR criterion: Same as above expect that the selection is based on maxmin SINR criterion, i.e., $\underset{b,k,l}{\operatorname{argmax}} \min_{s=1,\ldots,S} \gamma_s$.

Note that the usage of the greedy approach is rather limited since it can only be used when $S \le N_T$. Thus, it cannot be applied to the interference limited scenarios, $S > N_T$.

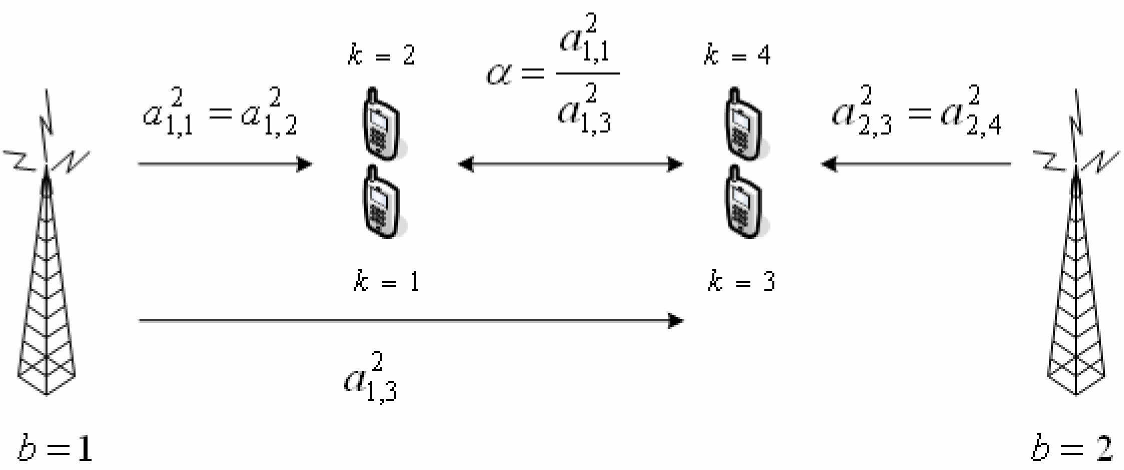


Figure B.14: Simulation scenario

B.5.5 Simulation results

Simulation results from SINR balancing with coordinated BS processing are presented. The performance of different coherent/non-coherent and coordinated/non-coordinated multi-cell transmission methods with optimal and heuristic beam allocation algorithms is numerically compared in different scenarios with varying inter-cell interference.

A flat fading multiuser MIMO system is considered, where K=2-4 users are served simultaneously by 2 BSs. The number of antennas at BSs and terminals were $\{N_{T,} N_{Rk}\} = \{2 – 4, 1\}$. For simplicity, the BSs were assumed to have an equal maximum power limit $P_{T,}$ *i.e.* $P_b = P_T \; \forall \; b$. The SNR for each user k was based on the smallest pathloss among N_B BSs and defined as $\text{SINR}_k = P_T \max_{b\in B} a^2_{b,k}/N_0$. In the simulations, the elements of the channel matrices $\mathbf{H}_{b,k}$ were modelled as i.i.d. Gaussian random variables. The simulation scenario is depicted in Figure B.14. For simplicity, we assume that the users are divided into N_B groups where the users have identical large scale fading coefficients $a_{b,k}$. Furthermore, the distance between different user groups, as well as, SNR per user were kept at identical values. The distance is defined by a parameter α which fixes the ratio of path losses between the different user groups. When the parameter α is fixed at 0 dB, all K users are located exactly on the cell border. On the other hand, cells are completely isolated when α = ∞.

We study the sum rate achievable using the maximisation of the minimum weighted SINR per data stream criterion with a per BS power constraint. Equal weighting of data streams $\beta_s = 1 \; \forall \; s$ is used in the SINR balancing algorithm. Since the optimal balanced SINR for each stream s is identical $\gamma_s = \gamma_0 \; \forall \; s$, the resulting sum rate can be expressed as $S \log_2 (1+ \gamma_0)$. The following cases were compared by simulations:

1. Coherent multi-cell MIMO transmission ($B_s = B \; \forall \; s$) with per BS power constraints.
2. Coordinated single-cell transmission ($|B_s| = 1 \; \forall \; s$)
   - o Exhaustive search over all possible combinations of beam allocations. The SINR balancing algorithm is recomputed for each allocation.

- Fixed allocation, i.e., user k_s is always allocated to a cell b with the smallest path loss, $\underset{b\in B}{\operatorname{argmax}}\, a_{b,k_s}$.
- Eigenbeam selection both with max rate and maxmin SINR allocation criteria.
- Greedy selection (can be applied when $S \le N_T$).

3. Non-coordinated single-cell transmission where the other-cell interference is assumed to be white Gaussian distributed
4. Single-cell transmission with time-division multiple access (TDMA), i.e., without inter-cell interference.

Figure B.15 and Figure B.16 show the ergodic sum rate of $\{K, N_B, N_T, N_{Rk}\} = \{4,2,2,1\}$ system for different TX processing methods as a function of the distance between different user sets, and for 0 and 20 dB single link SNR, respectively. It can be seen that coherent multi-cell beamforming greatly outperforms all other simulation cases when the distance between different user sets is finite. This is due to the fact that the coherent multi-cell beamforming can fully eliminate the inter-cell interference unlike the single-cell beamforming methods. The sum rates of non-coordinated and coordinated schemes become asymptotically equivalent as the distance approaches the infinity ($\alpha = \infty$), i.e., there is no gain from the coordinated multi-cell processing.

As the distance α approaches zero, the single-cell beamforming cases with four scheduled users becomes spatially overloaded, i.e., interference limited. For example, the achievable SINR per data stream s becomes sub-unitary at $\alpha = \infty$ dB and the resulting maximum achievable rate is, $4 \log_2 (1+ \gamma_s) \le 4$ with a fixed beam allocation in the high SNR region, as seen from Figure B.16. Near the cell edge, the optimal beam allocation strategy depends on the properties of channel realisations $\mathbf{H}_{b,k}\ \forall\ b,k$. Large gains from different beam allocation (cell selection) algorithms are available for the cell edge users. The heuristic eigenbeam based selection with maxmin SINR criterion performs nearly the same as the optimal cell assignment per beam with an exhaustive search. Also, a simple maximum eigenvalue based selection largely outperforms the fixed allocation case. Note that there only eight allocation alternatives for the exhaustive search in the scenario of Figure B.15 and Figure B.16. However, the number of combinations increases very rapidly as the number of users and BSs increases, e.g., 90 alternatives for 3 BSs and 6 users.

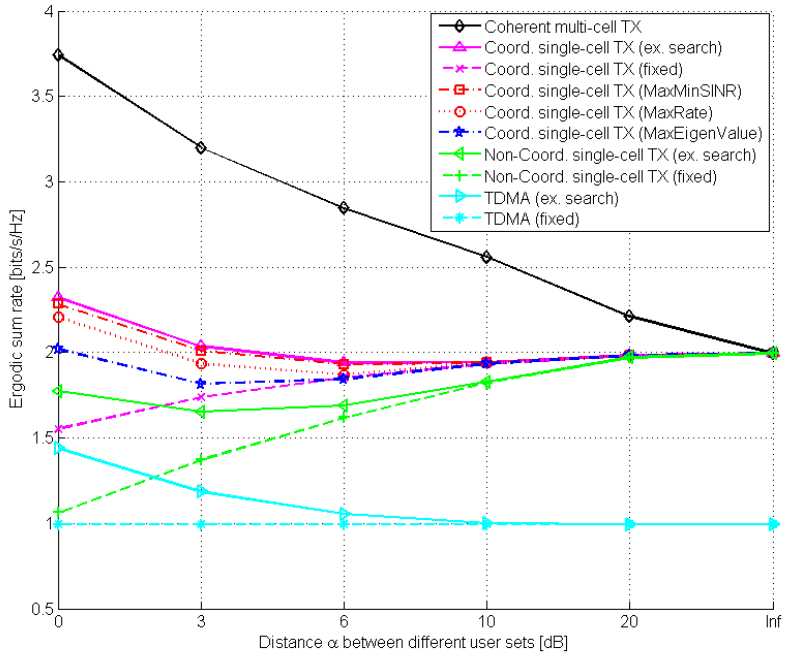


Figure B.15: Ergodic sum rates of $\{K, N_B, N_T, N_{Rk}\} = \{4,2,2,1\}$ systems at 0 dB single link SNR

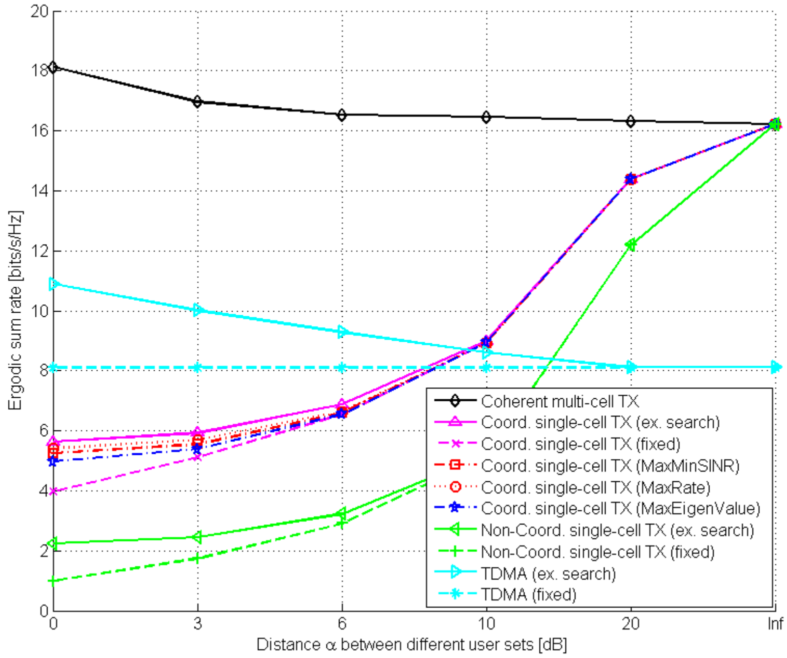


Figure B.16: Ergodic sum rates of $\{K, N_B, N_T, N_{Rk}\} = \{4,2,2,1\}$ systems at 20 dB single link SNR

The inter-cell interference is omitted in the precoder design both in the non-coordinated TX processing case and in the TDMA case, and thus the resulting beamformers are identical for both cases. All the coordinated TX processing techniques outperform the corresponding cases with non-coordinated single-cell TX processing. In the TDMA case, the transmission is time multiplexed between the BSs, and hence the reception is interference free. The TDMA case with an exhaustive search has better performance than non-coordinated TX processing with fixed allocation. As the distance between users sets approaches infinity the ergodic sum rate of both TDMA methods (exhaustive search and fixed) approaches 1 bits/s/Hz, which obviously is just half of the sum rate provided by the coherent and coordinated/non-coordinated TX processing methods.

The relative gain from the coherent multi-cell beamforming as compared to the coordinated single-cell transmission methods is greatly increased when the single link SNR is increased from 0 to 20 dB, as seen from the Figure B.16. At $\alpha = 0$, the ergodic sum rate is at least three times higher than that of coordinated single-cell beamforming with an exhaustive search of beam allocations. One can see that even the TDMA approach provides a higher sum rate than any coordinated single-cell TX processing method when $\alpha < 8$ dB. It is noteworthy, however, that the coherent multi-cell processing does not increase significantly the sum rate (maxmin SINR) at high SNR as compared to the case where the cells are completely isolated ($\alpha = \infty$). Some other optimisation criterion such as sum rate maximisation used with coherent multi-cell beamforming would result in significantly larger increase in the sum rate as α approaches zero.

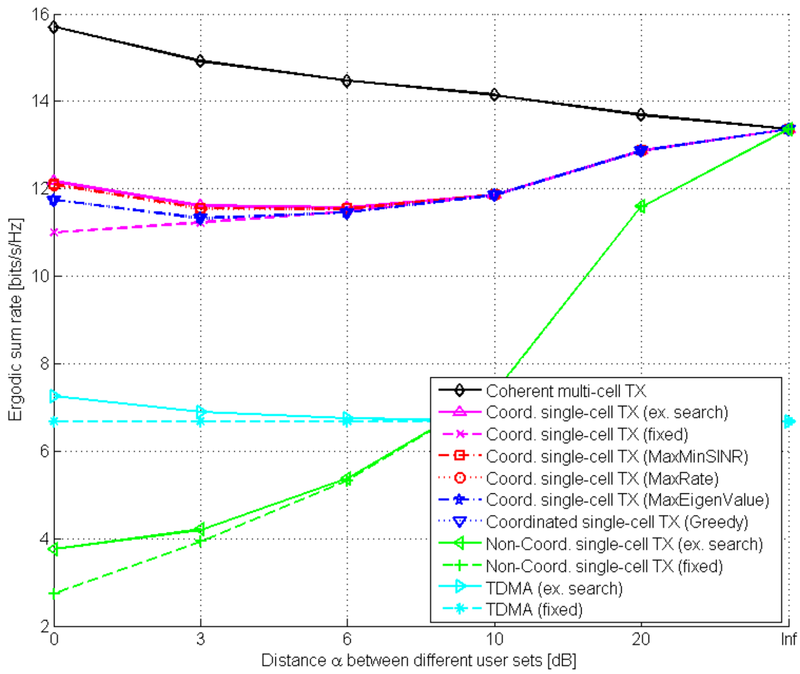


Figure B.17: Ergodic sum rates of {K, N_B, N_T, N_{Rk}} = {2,2,2,1} systems at 20 dB single link SNR

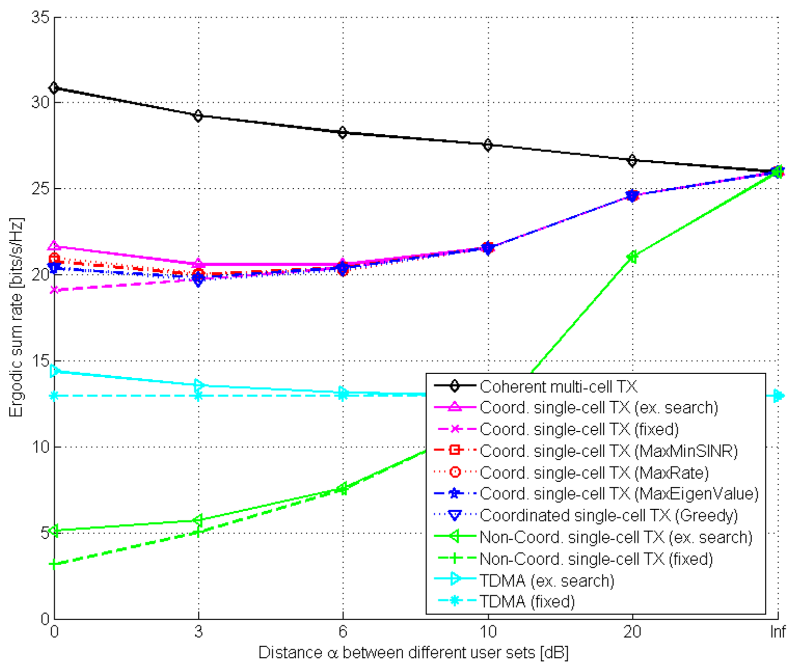


Figure B.18: Ergodic sum rates of {K, N_B, N_T, N_{Rk}} = {4,2,4,1} systems at 20 dB single link SNR

Let us now consider two cases where either K is reduced to half {K, N_B, N_T, N_{Rk}} = {2,2,2,1} or N_T is doubled {K, N_B, N_T, N_{Rk}} = {4,2,4,1}, and both BSs serve only one or two users in the single cell transmission cases, respectively. Now, neither scenario is any longer interference limited in the coordinated single-cell beamforming case, i.e., $S \leq N_T$. Therefore, the performance of the coordinated single-cell beamforming case is greatly improved, as illustrated in Figure B.17 and Figure B.18 for 20 dB SNR. Furthermore, the common SINR value is greatly improved due to increased spatial degrees of freedom available in both scenarios.

B.5.6 Conclusion

A generalised method for joint design of the linear transceivers with coordinated multi-cell processing subject to per-BS/antenna power constraints was proposed for the weighted SINR balancing optimisation objective. The method can accommodate a variety of scenarios from coherent multi-cell beamforming across a large virtual MIMO channel to a single-cell beamforming with inter-cell interference coordination and beam allocation. The performance of different coherent/non-coherent and coordinated/non-coordinated multi-cell transmission methods with optimal and heuristic beam allocation algorithms was numerically compared. The coherent multi-cell beamforming was shown to greatly outperform the non-coherent cases especially at the cell edge and with a full spatial load. However, the coordinated single-cell transmission with interference avoidance and dynamic beam allocation performed relatively well with a partial spatial loading.

B.6 System level gains from coherent CoMP processing

This section presents some system level simulation results of coordinated MIMO-OFDM cellular system which perform coherent transmission from distributed base station antennas to users located close to the cell edge, also called as a soft handover region [TCJ08a]. System level impact of the coherent multi-cell beamforming is first considered for a single user TDMA case where only one user can be allocated to a single time slot, and occupies the entire bandwidth. In this case, space division multiple access (multiuser MIMO transmission) is not enabled. The simulated system is based on HIPERLAN/2 assumptions with 20 MHz bandwidth. Modulation schemes used in the simulations are QPSK, 16QAM and 64QAM. Half rate turbo code is used for channel coding. Target quality of service per user is 10% FER.

The system model is equivalent to the one presented in Section B.5, extended to the frequency selective case with MIMO-OFDM transmission with 64 sub-carriers. In this simulation study, each user k can be also served by M_k BS's which define the joint processing set B_k for the user k, and $B_k \subseteq B = \{1, . . . , N_B\}$. The size of the joint processing set (SHO active set, AS) is defined by the pathloss ratio between adjacent BS antenna heads, similarly to WCDMA system. A user is served by multiple BSs if the pathloss ratio between the strongest cell and the adjacent cell(s) is within a certain limit, i.e., SHO window.

Figure B.19 illustrates the simulation scenario of a realistic multi-cell environment with 57 (19 3-sector antenna sites) cells. It is assumed for simplicity that the cooperative SHO processing of the transmitted signal is possible between any of the 57 BS’s. The number of both TX and RX antennas is fixed at 2. For simplicity, it is assumed that all the base stations have equal maximum power limit P_T. Linear transmitter and receiver processing is applied.

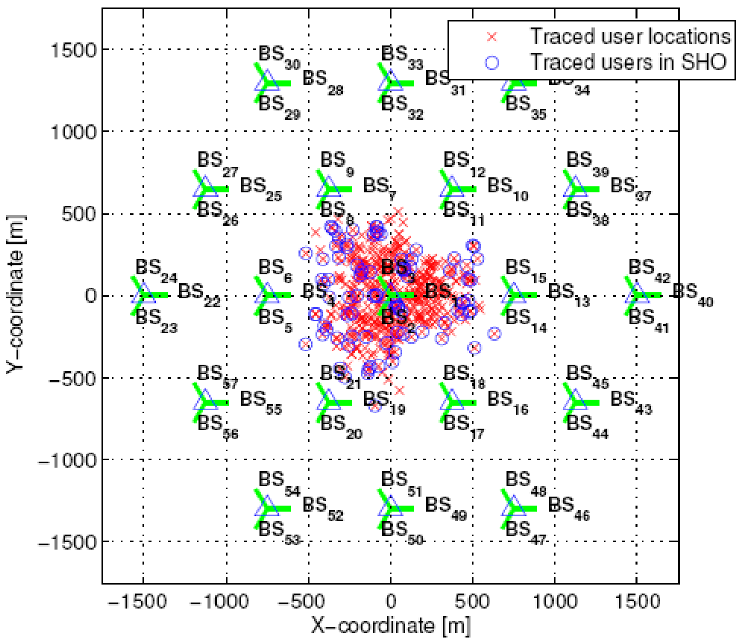


Figure B.19: System level simulation scenario

In Figure B.20, the cumulative distribution function (CDF) of spectral efficiency per user with different SHO window sizes (±3 dB and ±6 dB) and power constraints is presented. All the traced users are included in the statistics. The system load is measured as an average time slot occupancy (in the case without multi-cell transmission), and 30% load is used in the simulations. With higher average load the blocking and dropping due to increased inter-cell interference begin to dominate (see more details in [TCJ08a]). As one can see from Figure B.20, significant system level gains from the cooperative SHO processing are available, especially with a large SHO window. However, the 6 dB SHO window becomes too large without SDMA when the time slot occupancy increases further from 30% due to the increased outage probability.

In Figure B.20, the impact of two different power constraints, i.e., per BS power and shared single BS power are also compared. The per BS power constraint implies that the power consumption at BSs may be increased due to the SHO overhead. Any BS in SHO active set can use up to P_T TX power per time slot depending on the users’ received signal strength, imbalance between the SHO BSs, etc. Also, more inter-cell interference is potentially generated. Therefore, it is interesting to compare it to the case of shared single BS power where the power consumption is maintained the same on average, independent of the SHO parameters used. Since the TX power P_T of a single BS is shared between M transmitters, the shared single BS power constraint does not increase the power consumption at the transmitters even if the SHO overhead is high. In addition, the inter-cell interference generated from a single BS is reduced with the same ratio. In spite of generating more inter-cell interference, the per BS power constraint outperforms the shared single BS power constraint in terms of overall system performance.

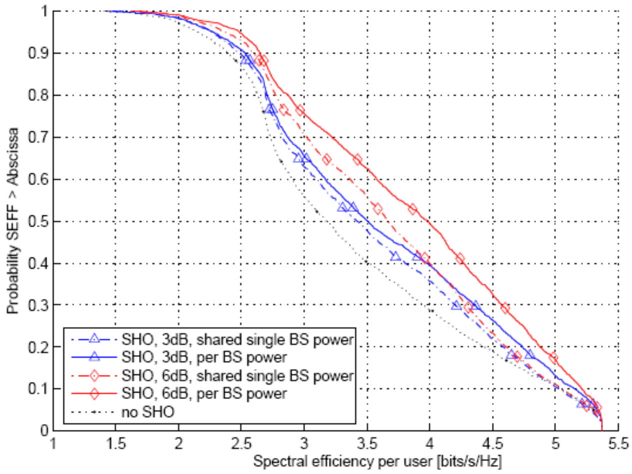


Figure B.20: CDF of user spectral efficiency per user with 30% average system load and max. AS size 3

As one can see from Figure B.21, the users located at the SHO region may enjoy greatly increased transmission rates. Figure B.21, shows also the spectral efficiency distribution for the case where SDMA is enabled. The SDMA method used in these simulations is iterative block diagonalisation [SSH04]. Some performance penalty from using the ZF method is caused by its inherent noise amplification property. Also, the transmit power is shared between the users allocated to the same time slot. However, the overall reduction is rather small due to independent fading at each BS antenna site. In addition, less inter-cell interference is generated. On the other hand, SDMA reduces significantly the time slot occupancy allowing higher average system load.

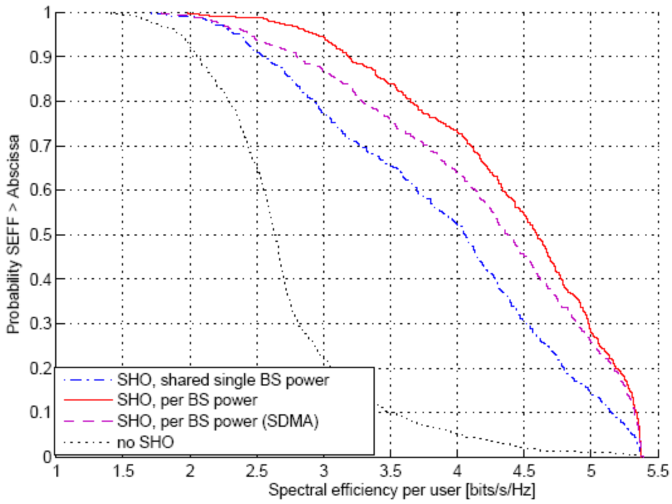


Figure B.21: CDF of user spectral efficiency per SHO user with 30% average system load, max. AS size 3 and 3 dB SHO window

B.7 System level performance evaluation of different CoMP approaches

The goal of the study presented in this appendix is to give some hints on the achievable performance with different CoMP approaches. We consider two different approaches, one coherent approach and one non-coherent approach based on coordinated scheduling. It should though be pointed out that the simulated schemes rather should be seen as exemplary configurations than schemes suitable for implementation in a practical system. However, in order to give some hints on the technology potential of CoMP they fulfill their purpose.

The performance of the schemes is evaluated by means of dynamic system level simulations, focusing on the downlink in an urban macro scenario. The considered performance metrics are average system throughput as well as cell edge user throughput, and we discuss the impact of parameters such as size of coordination clusters (the number of cells that are coordinated), channel estimation errors, and also briefly touch upon the overhead/complexity of the schemes.

B.7.1 Considered CoMP approaches

In this study, we focus on coordinated multipoint transmission over a number of traditional cell sites, which are controlled by one eNB. The area covered by the cell sites which are controlled by this eNB we refer to as a *coordination cluster*. The underlying assumption is that the cell sites within the coordination cluster are connected to the eNB via high-speed connections in order to allow for the fast coordination.

As mentioned above, two different approaches are considered in the study. The first one is an example of a coherent approach, and is based on traditional zero-forcing (ZF) precoding [CS03]. Conceptually we view all the transmit antennas at the different cell sites within the coordination cluster as one giant transmit antenna array. With knowledge of all the instantaneous MIMO channels within the coordination cluster, the weight vector of the giant transmit antenna array is selected so that the transmission to one particular UE causes as little interference as possible to antennas at other UEs within the coordination cluster, considering a power constraint per transmit antenna.

The main drawback of the coherent approaches, e.g. the one above, is that they typically require that the instantaneous MIMO channels between all the UEs and cell sites be communicated to the eNB which put extreme requirements on the backhaul. It is therefore of interest to also consider other approaches that not put these extreme reuirements on the backhaul. Hence, the second scheme should rather be seen as a comparison; instead of doing the coordination in the signal processing domain, it is done in the scheduling domain. It is based on the same architecture as the coherent scheme, but with less information to be communicated over the backhaul from the cell sites to the eNB. The scheme is based on dynamic scheduling coordination, meaning that UEs are scheduled to be served by their attached cells in a manner such that the mutual interference among them (within the coordination cluster) is minimized. The coordination takes place on a fast time scale (TTI basis), hence the scheme can be considered as an extended and faster version of the ICIC functionality available in LTE release 8 [DPS+08].

B.7.2 Simulation setup

The simulations were performed with a radio network simulator with a regular cell plan and hexagonal cell layout. The overall assumptions follow to a large extent the deployment scenario and system parameters as specified for the so-called 3GPP case 1, which is an urban macro scenario defined in [3GPP25814]. Further details of the used models and assumptions will follow below, whereas a condensed summary of them are given in Table B.1.

The studied deployment comprises 21 sites, each with three sectors (cells) per site, which means in total 63 cells are simulated. A wrap-around technique was used to avoid border effects. Each sector is equipped with an antenna array comprising four elements separated 10 wavelengths. The UEs have two antenna elements separated half a wavelength and employs an ideal Minimum Mean Square Error (MMSE) receiver with additionally Successive Interference Cancellation (SIC) functionality. The downlink transmission scheme is 4x2 MIMO on all links, and as reference case LTE Release 8 downlink with fast codebook switching [DPS+08] is simulated.

Table B.1: Simulation assumptions

Carrier frequency	2 GHz
Transmission bandwidth	5 MHz
Subcarrier spacing	15 kHz
Number of subcarriers	320
Frequency reuse	1
Number of cells	63
Number of users per cell	Varied between 0.1 and 5 (on average)
Site-to-site distance	500 m
Wrap-around	Yes
Interference modelling	All links modeled
Cell antenna configuration	4-element ULA, antenna element separation 10 λ
UE antenna configuration	2-element ULA, antenna element separation 0.5λ
UE velocity	3 km/h
Channel model	3GPP case 1 [3GPP25814] + indoor UEs
Coding	Practical turbo codes
Modulation	QPSK, 16QAM, 64QAM
Link adaptation	Ideal
UE receiver	Ideal MMSE-SIC
Data traffic model	Full buffer

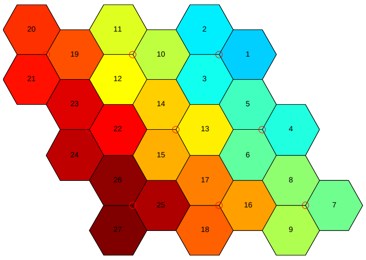
The layout for the reference LTE Release 8 system is depicted in Figure B.22a, where each cell (a numbered hexagon) acts independently. To reflect the fact that each cell acts independently, each cell is depicted in a different color. The locations of the sites are represented by red circles. In Figure B.22b the layout for a CoMP system with a coordination cluster size of 9 cells (i.e. the transmissions within these 9 cells are coordinated) is illustrated. The cells belonging to the the same coordination cluster are depicted in the same color. Similarily, Figure B.22c illustrates a layout where each coordination cluster consists of 21 cells. Again, the cells belonging to the same coordination cluster are depicted in the same color.

All users are assumed to have full buffers, and the average number of users per cell is varied from 0.1 to 5. The users are uniformly distributed across the simulated area, and each user moves at the speed of 3 km/h and are assumed to be indoors (modeled with a 20 dB additional path loss). For the coherent transmission scheme and the baseline LTE release 8, round robin TDMA scheduling is used, i.e., in each frame a single user per sector is assigned to the entire transmission bandwidth of 5 MHz. This is not optimal, but makes it easier to understand and compare the results.

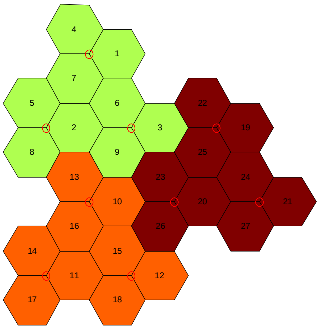
There are three available modulation schemes (QPSK, 16QAM, and 64QAM) and six different channel code rates (1/10, 1/3, 1/2, 2/3, 3/4, and 8/9). The transport format is selected to maximize the expected throughput. Packet decoding error probability is modeled according to a mutual information based link-to-system interface [Bru05].

The simulations assume perfect channel and interference estimation at the UE. The OFDM transmission is further modeled as perfectly orthogonal and any potential intersymbol or intercarrier interference caused by channel time dispersion exceeding the cyclic prefix is neglected. Overhead such as reference signals, e.g. for channel and interference estimation, or protocol headers are neither accounted for. On the other hand, in order to assess the impact of non-ideal channel knowledge on the coherent transmission scheme, a rather detailed model for this has been used in the simulations.

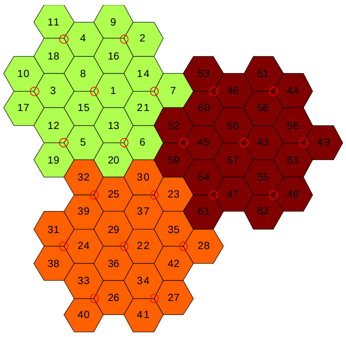
The used performance measures are the system throughput measured in bps/Hz/cell, and the cell edge user bit rate (the 5th percentile user bit rate) measured in bps/Hz. The first one is focused on the system performance, while the second one may be described as a user centric performance measure and/or the fairness in the system when put in relation to the system throughput.



a) Reference layout (each cell acts independently)



b) Coordination cluster size of 9 cells



c) Coordination cluster size of 21 cells

Figure B.22: Cell layouts for different coordination cluster sizes. Note that the site-to-site distance is 500 m in all cases (i.e. the cell size is the same), and that wrap-around (not shown here) is used in the simulations in order to avoid border effects.

B.7.3 Simulation Results

Figure B.23 and Figure B.24 below presents the average throughput versus 5th percentile user bit rate for coordination cluster sizes of 9 cells and 21 cells, respectively. Four curves are shown in each figure:

1. LTE release 8, which corresponds to an uncoordinated system employing standard LTE release 8 fast codebook switching.
2. Coordinated scheduling, which is the same as LTE release 8, but with coordinated scheduling on TTI basis.
3. ZF with estimation error. Coherent transmission based on zero-forcing where downlink transmission weights are set based on uplink transmissions and utilizing reciprocity. Uplink channel estimation error model used.
4. ZF with ideal channel estimation. Coherent transmission based on zero-forcing where downlink transmission weights are set based on uplink transmissions and utilizing reciprocity. Ideal uplink channel estimation.

Overall it can be seen that the coherent transmission based on zero-forcing provides the best performance, the gain is significant both in terms of average system throughput as well as in cell edge user throughput (5th percentile user bit rate). We also note that the coordinated scheduling provides rather large gains over the baseline LTE release 8. In fact, with a coordination cluster size of 9 cells the performance of the coordinated scheduling is almost as good as for the coherent scheme. With a coordination cluster size of 21 cells, on the other hand, the performance of the coherent scheme is better than the non-coherent scheme based on coordinated scheduling. It should also be noted that the coordinated scheduling approach trade offs packet delay for user bit rate, which is not shown in the figures.

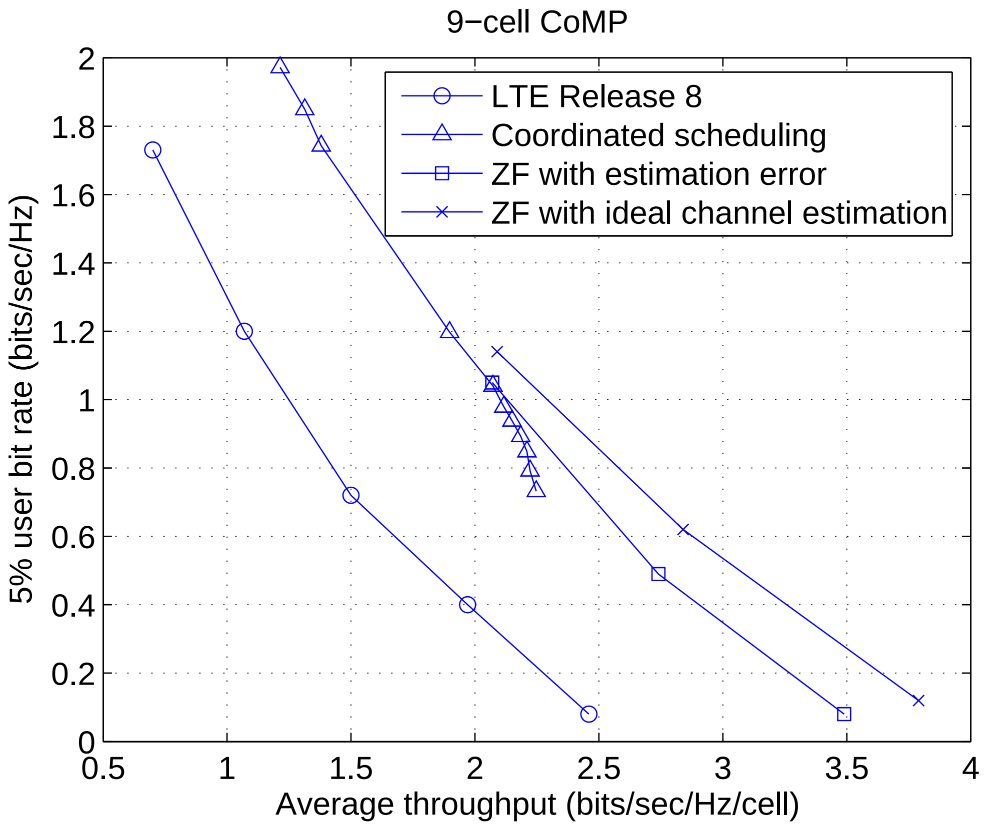


Figure B.23: Simulation results for coordination cluster size of 9 cells

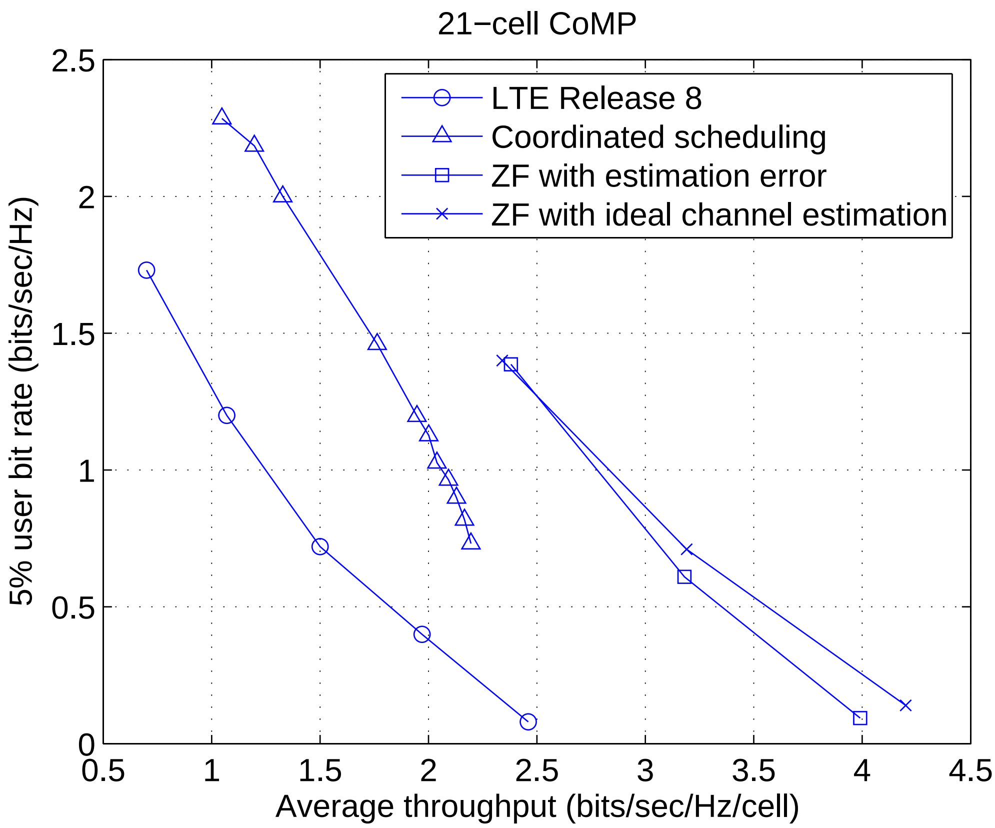


Figure B.24: Simulation results for coordination cluster size of 21 cells

By comparing Figure B.23 and Figure B.24 we can get some hints on the impact of the coordination cluster size, i.e., how many cells that are coordinated. One interesting observation that can be made is that the performance of the coordinated scheduling is almost the same in the two figures, i.e., it does not seem to matter that much whether 9 cells or 21 cells are coordinated. In fact, at low loads there is a small gain by coordinating over 21 cells compared to 9 cells, but at high loads there is in principle no difference. The reason for this is that at high load all resources are used, hence there are not so many resources for the scheduler to play around with and therefore no gain to be able to coordinate over a larger number of cells. For the coherent scheme, on the other hand, it can be seen that the performance is clearly improved when the coordination is carried out over 21 cells compared to 9 cells. This is explained by the fact that we in the case with 21 cells have a larger effective antenna array, and hence more degrees of freedom to work with. However, whether that observation also will hold in practice remains to be seen, since impairments and implementation limitations effectively will limit the achievable gains.

Regarding the coherent scheme based on zero-forcing, it can be noted that the degradation due to imperfect channel estimation is not that large, however, again it should be remembered that there still are more impairments to add, e.g. reporting/measurement delay, non-ideal link adaptation etc. which will affect the performance of the coherent scheme.

An interesting observation that can be made when it comes to the approach based on coordinated scheduling, is that at high loads it is possible to achieve a significant gain in cell-edge bit rate if it can be accepted to slightly reduce the average system thoughput.

If we want to quantify the performance of the different approaches and compare them, we use these two alternatives:

1. Assuming a given/fixed desired system throughput T_0, one can compare the 5th percentile user bit rate achieved with two different approaches, i.e. we compare (T_0, b_1) to (T_0, b_2) where b_1 is the 5th percentile user bit rate obtained when the first approach results in system throughput of T_0, and b_2 is the 5th percentile user bit rate obtained when the second approach results in system throughput of T_0.
2. Assuming a given/fixed 5th percentile user bit rate b_0, one can compare the the system throughput achieved with two different approaches, i.e. we compare (T_1, b_0) to (T_2, b_0) where T_1 is the system throughput obtained when the first approach results in 5th percentile user bit rate of b_0, and T_2 is the system throughput obtained when the second approach results in 5th percentile user bit rate of b_0.

For a fixed cell-edge bit rate (5th percentile user bit rate) of 0.75 bps/Hz and coordination cluster size of 9 cells, the average throughput of the LTE release 8 system is 1.46 bps/Hz/cell, while it reaches 2.25 bps/Hz/cell and 2.44 pbs/Hz/cell for the coordinated scheduling and zero-forcing transmission scheme, respectively. Note that it is the zero-forcing with non-ideal channel estimation that is considered in the comparisons. For the same layout and a fixed average system throughput of 2.2 bps/Hz/cell, the cell edge bit rate of LTE release 8 reaches 0.25 bps/Hz, while it is 0.8 bps/Hz and 0.93 bps/Hz for the coordinated scheduling and the zero-forcing, respectively. A summary of the gains relative the LTE release 8 system configuration is given in Table B.2, where also results for the coordination cluster size of 21 cells are summarized.

Table B.2: Summary of relative gains over the baseline LTE release 8 system configuration

Coordination cluster size	CoMP approach	Cell-edge bit rate fixed at 0.75 bps/Hz	Average throughput fixed at 2.2 bps/Hz/cell
9	Coordinated scheduling	54 % gain in average throughput	220 % gain in cell-edge bit rate
	Zero-forcing	67 % gain in average throughput	272 % gain in cell-edge bit rate
21	Coordinated scheduling	51 % gain in average throughput	200 % gain in cell-edge bit rate
	Zero-forcing	108 % gain in average throughput	500 % gain in cell-edge bit rate

B.7.4 Conclusions

In this appendix we have carried out dynamic system level simulations of two different CoMP approaches. One of the approaches is a coherent approach based on zero-forcing precoding, while the second approach is non-coherent and based on coordinated scheduling. The results show that the coherent approach achieves best performance, but that the non-coherent approach also achieves significant gains over the baseline LTE release 8 system configuration. It should though be noted that the coordinated scheduling approach trade offs packet delay for user bit rate, which is not shown in these results.

Finally, it should be emphasized that the results here are based on relatively ideal assumptions and that the performance and conclusions might change as more impairments are added and when practical implementation limitations are taken into account. However, the evaluations should as least provide an indication of the technology potential of CoMP approaches.

B.8 A multi-user MIMO relaying approach

The performance of the multi-user MIMO relaying concept described in Section 3.4.1 has been evaluated. The channel matrices are assumed to consist of complex-valued, zero-mean independent identically distributed Gaussian random variables with unit variance. To these matrices attenuation due to path-loss is applied and the links from the BS and the relays to the UTs are subject to shadow fading, see [WSO08] for further details.

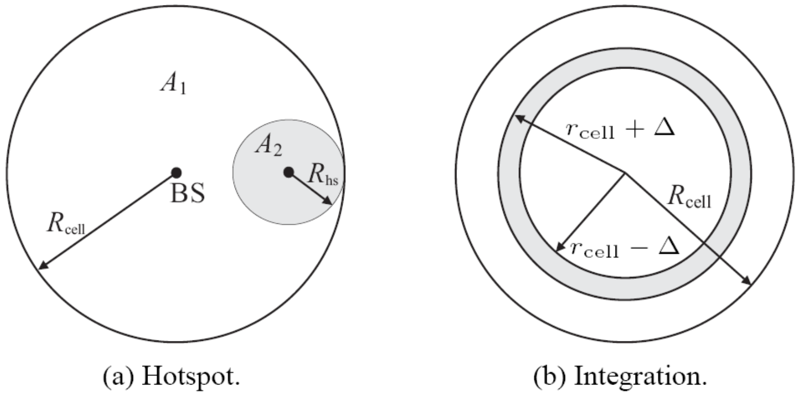


Figure B.25: Considered scenario and integration method for performance evaluation

Let us consider a hot spot scenario, where K_{A1} UTs are distributed uniformly over a cell with radius R_{cell}=500m, and assume that K_{A2} UTs are uniformly distributed in an area A_2 placed at the cell border, which has as a radius of R_{hs}=100m, as illustrated in Figure B.25a. A single relay is placed in the center of A_2. The relay as well as the UTs are assumed to have N=2 receive antennas each. The BS is assumed to use M=4 transmit antennas. For all shown simulation results 10 000 random drops of the UTs were performed. In Figure B.26 we show the ratio between the sum capacity for a system with and without relay as a function of K_{A2} for different noise levels σ_M^2 at the UTs. The noise at the relay is assumed to be the same as for the UTs. The BS transmits with unity power, while the output power of the relay is 20% of the BS power. The power of the system without relay is normalized, such that its total power is identical to the power of the relay aided system. The number of UTs in A_1 was set to K_{A1}=10.

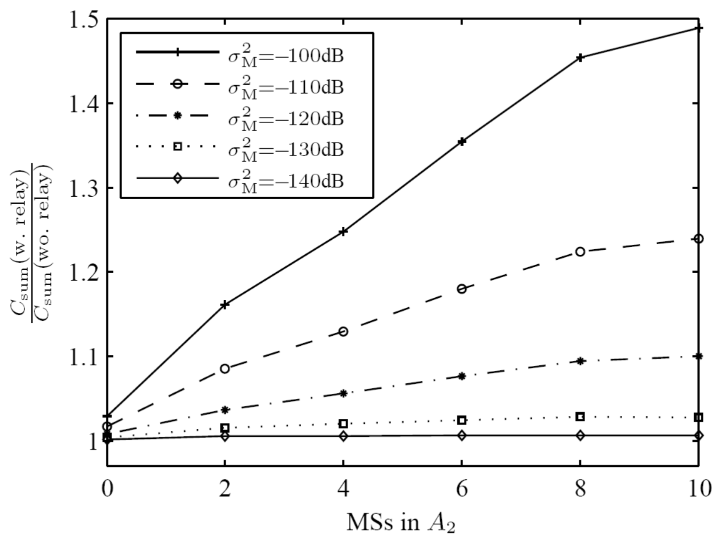


Figure B.26: Relative sum-capacity as a function of the number of UTs in A_2

As seen in Figure B.26, adding a single relay in a hot spot area with high user-density, can result in substantial sum-capacity gains for the considered system. Especially for high noise-levels a sum-capacity gain of up to 50% can be achieved. Note that the gain depends strongly on the noise-level.

But the relaying concept not only increases the sum-capacity but also results in a more desirable capacity distribution over the cell area. To illustrate this, let us define $\hat{I}(r_{cell})$ as the average mutual information for a scheduled user within distance $r \pm \Delta$ from the cell center, see Figure B.25b. In Figure B.27 the average mutual information for Δ = 10m is plotted as a function of the cell-radius. Here, the noise-level at the relay was chosen to be 1% of the noise level at the UTs , while the number of UTs was again set to be K_{A1}=K_{A2}=10. It can be observed that adding a relay increases the throughput in close vicinity to the relay, exactly where a lot of users are located. The increase in throughput in this region is mainly achieved by moving resources from the cell-center to the relay.

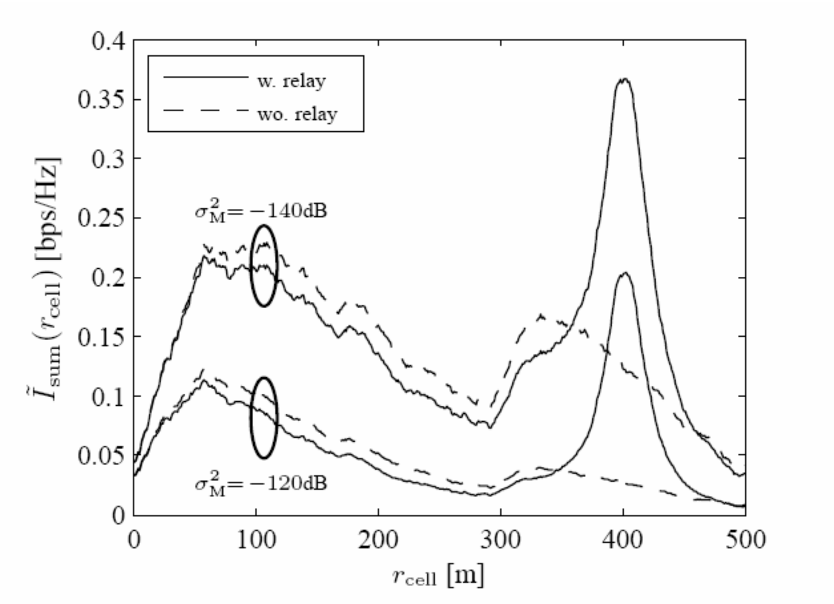


Figure B.27: Mutual information as a function of cell radius

Futher details of the relaying concept as well as further simulation results can be found in [WSO08].

B.9 Distributed space time coding

B.9.1 System model

Let us consider one BS, one relay and one mobile. The path loss model is assumed is decreasing with d^2. By denoting by x the fast fading coefficient between the source (BS or RN) and the destination, the signal to noise ratio received by the mobile when it is only connected to the source or the relay has the following general expression:

$$SNR_{SISO} = \frac{P}{d^2}\frac{|x|^2}{N_0}\ .$$

Let R denotes the distance between the BS and the RN, and $r=\alpha R$ is the distance between the relay and the mobile as depicted in the following figure:

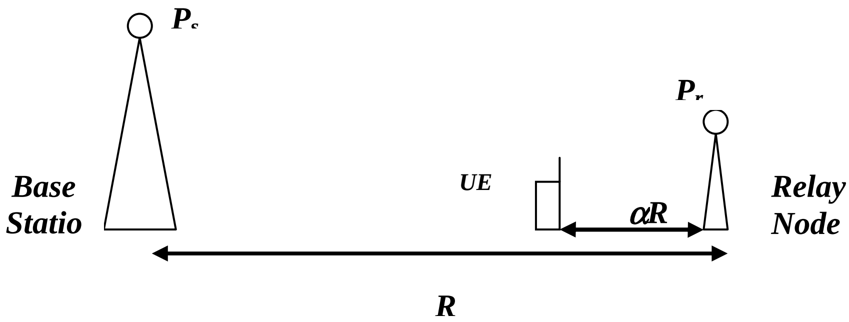


Figure B.28: System model

In the sequel we assume that the BS, relay and destination have only one antenna. The mobile, can be connected at the same time to the BS and the RN. In this case, we have a virtual MISO system with distributed antenna. This system is different from the collaborative MIMO system by the fact that there is a first phase in which the BS transmit information to the relay station.

B.9.2 Protocol descriptions

This section studies the configurations in which the use of distributed space time codes is beneficial compared to direct connection of the mobile to the BS and RN. The cooperation protocols are genie aided meaning that they consider the first transmission phase between the source and the destination but assume that the relay detects perfectly the source message. This presents the upper bound of the performance. In a next step the Amplify and Forward will be considered.

Genie aided Alamouti protocol

It is well known that the optimal space-time code for 2x1 MISO systems is the Alamouti code and this code has the advantage to be orthogonal making the decoding very simple. In literature, this code has been previously proposed to be used in a distributed way. This protocol contains a first phase in which the source transmits to the relay as shown in Figure B.29.

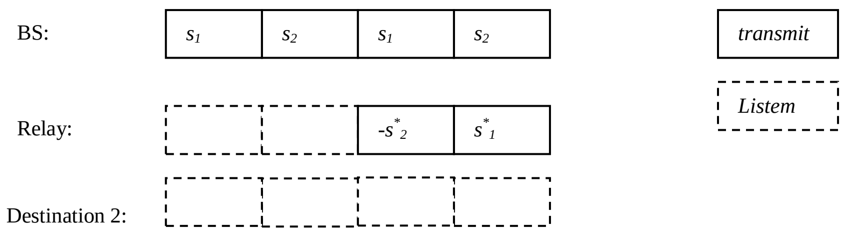


Figure B.29: Genie aided Alamouti protocol

The signal to noise ratio of such transmitting scheme is:

$$SNR_{g-aided} = \frac{\left[(P+P_2)|h_{sd}|^2 + P_2|h_{rd}|^2\right]}{N_0}$$

with $h_{sd} = \frac{x_{sd}}{(1-\alpha)R}$ and $h_{rd} = \frac{x_{rd}}{\alpha R}$ and P is the maximum transmitted power of both BS and Relay. P_2 is the same power assumed to be used by the source Relay and the source in the second phase of the cooperation. The maximum achievable throughput for this protocol is

$$R_{g\text{-aided}}=E[1/2.\log(1+SNR_{g\text{-aided}})]$$

Genie aided Golden code protocol

One can show easily that the coding matrix is unitary and therefore the system capacity can be written as:

$$C = E\left[\frac{1}{4}\log(\det(I + \frac{P}{N_0}H^*H))\right]$$

where $H = \begin{bmatrix} H_1 & 0 \\ 0 & H_1 \end{bmatrix}$ and $H_1 = \begin{bmatrix} \sqrt{P}h_{sd} & 0 \\ \sqrt{P_2}h_{rd} & \sqrt{P_2}h_{sd} \end{bmatrix}$.

Amplify and forward protocol

The RN amplifies and forwards the received signal from the fisrt phase. By this way, they amplify their own noise. Let's denote by A the amplification factor. By considering that P is the maximum transmitting power at the RN, the factor A satisfies:

$$A = \frac{1}{\sqrt{P|h_{sr}|^2 + N_r}},$$

Using the same approaches to provide the maximum throughput for genie aided protocols, one can obtain the ones of the AF cases respecting the amplification factor constraint.

B.10 Low-complexity SDMA resource allocation ProSched

In this appendix the main principles of the low complexity multi-user scheduling algorithm ProSched for SDMA are described, with extensions to coordination schemes in multi-cell and relay enhanced cell (REC) environments. Furthermore, simulation results of interference avoidance in a REC with SDMA are provided. For an introduction see Section 2.3.3.

B.10.1 Basic scheduling

The ProSched approach inherently allows the consideration of both the performance loss due to spatial correlation between users' channels and optimal SDMA group size. It consists of two parts:

- We use a scheduling metric which reflects the performance of one user's effective channel after any MIMO transmit precoding in the presence of a set of other users that are to be served simultaneously via space division multiple access (SDMA). The metric is an estimate of the Shannon rate with Zero Forcing precoding which can be considered an upper bound for other linear precoders. It has the following advantageous properties:
  - The ZF capacity of one user can be written with the help of an orthogonal projection into the intersection of the nullspaces of all other users' channels in the same SDMA group. The projection would normally have to be recomputed for every user in every possible SDMA combination. Instead, ProSched approximates the intersection by a product of projection matrices into the nullspaces of the single users. These matrices remain constant throughout the scheduling run, which dramatically reduces complexity. This means that the precoding matrices do not have to be computed while testing combinations. For details see also [WIN2D341].
  - Capacity as a metric reflects the impairment of spatial correlation and the effect of the average power assigned to a user, which again reflects the SDMA group size. It can be calculated based on channel matrix knowledge as well as on second order statistics channel knowledge.
  - A capacity based metric can be combined with proportional fairness in the sense of [Ho01] and with methods taking into account fairness and QoS in the form of user rate requirements such as in [SWO04].
- A tree-based best candidate search algorithm is carried out to reduce the number of combinations to be tested. It delivers beneficial user terminal combinations for all possible group sizes and allows in a second step a decision on the best group size based on the scheduling metric. Joint scheduling of all chunks is possible as well as tracking of the solution in time.

B.10.2 ProSched for multiple transmitting stations with coordination

The multi-BS extension presented in [FDH06] consists of two modifications. The first one is to extend the per-user scheduling metric by an estimate of the total received intra-cell interference power at each terminal. This estimate is obtained using the already available orthogonal projection matrices and requires only matrix multiplications and no additional matrix decompositions.

The second part of the multi-BS extension is a virtual user concept (see also [WIN2D341]). The tree based search algorithm is no longer executed on user numbers, but on numbers representing all allowable combinations of users and transmitters (denoted, in the example below as user#@basestation#). In this way, the underlying algorithm stays the same except for the interference term that is to be taken into account when virtual users belonging to the same transmitter are grouped. The approach allows for hard and soft handover scheduling with the difference that in the case of hard handover, a virtual user is deleted from the tree once it has been assigned to a candidate group. In the case of soft handover, multiple transmitters may serve the same user with the help of another dimension such as orthogonal codes, which has to be taken into account in the metric by a division. Examples for soft and hard handover are given in Figure B.30 for the case of two BS and 3 users. The identified candidate groups are displayed in yellow. In the last step of the algorithm a selection between them is made. To that extent, soft and hard handover are system designer's choices whereas extension of the algorithm can be thought of to provide an automated choice.

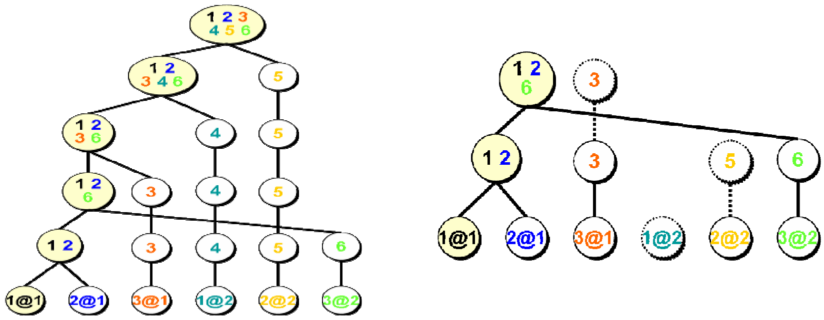


Figure B.30: Example scheduling runs for soft and hard handover

B.10.3 Extension to relay enhanced cells with coordination

Based on the version for multiple base stations, the spatially beneficial transmitter/receiver combinations can also be estimated in a REC. When the RNs are half duplex, they can be treated as user terminals in the time slots when the RNs receive. And when they transmit, they become additional base stations for the algorithm. Full duplex relay nodes could be supported in a similar fashion.

A key element of the extension is a model of a buffer at the RNs: RNs can only transmit as much as they have received before. Each RN's buffer is implemented as one number rather than storing a vector for each user. The buffer is kept in bits/sec/Hz because no exact time reference is needed for this study, since relative performance is shown rather than absolute values.

To generate the buffer levels for each UT needed in the scheduling metric we proceed as follows: when a RN is scheduled for reception, its currently achievable rate is added to its buffer. When a RN is scheduled for transmission, it is assumed that the buffer for transmission to each UT has been loaded optimally based on the achievable rates of the attached users in the current time slot (since we target maximum sum rate rather than user specific quality of service constraints). In real systems, this knowledge is of course not available a priori and represents a simplification which is justified because the channel changes only gradually. In other words, the situation in the time slot in which the buffers would have been filled can be assumed to be similar to the situation when transmission takes place. To generate the user specific buffer levels out of the single value buffer of a RN, the RN buffer figure is distributed via a standard water pouring algorithm on the UTs. To do so, the UTs' achievable rates when served from a certain transmitter represent the squared coefficients of the channels to be loaded and the RN buffer number is the power to be distributed. To summarize, the benefit of ProSched is that during any testing of user assignments, the precoding solutions at each base station do not have to be re-computed but can be estimated with the help of fixed orthogonal projection matrices. The same applies to the interference which is different for each possible user assignment – it can also be estimated without knowing the final precoding solution. Additionally, ProSched may work with rank one approximations of the users' long term channels, reducing the required overhead dramatically.

B.10.4 Preliminary simulations of interference avoidance in REC with SDMA

In this section a proof of concept investigation is discussed in which the proposed approach of low-complexity centralized scheduling with interference coordination is compared to a reference approach without interference coordination. The scenario under consideration is a Metropolitan area deployment based on the guidelines given in [WIN2D6137]. It differs from previous recommendations mainly by the following points:

- For interference avoidance, the operation of the RNs in at least two groups using different resources is recommended.
- RNs are also placed in the vertical streets, thus increasing the occurrence probability of line of sight (LOS) conditions in the channel.
- RNs now have omnidirectional antennas.

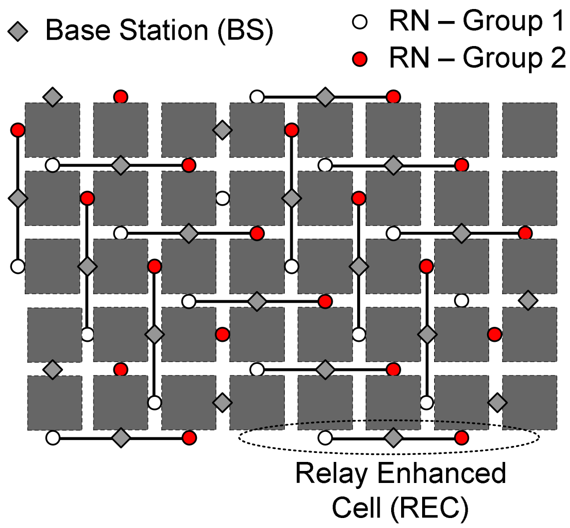


Figure B.31: Sketch of microcellular cell layout with relay nodes which was implemented except for the transmitters on the edges

Performance figures are given per square meter to allow some independence of the deployment section size. For the same reason, the total number of users in the system is not fixed, but is obtained from a user density per square meter which was set to $10^{-5}/m^2$. Compared to the previous investigations in [WIN2D341] [FKK+07], all rates are now bounded to *4.8 bits* per channel use, to take into account the fact that the system performance is modulation and coding limited (part of a so-called Shannon fitting procedure).

The basic system design is close to that of [WIN2D351]: Relays do not transmit and receive at the same time, resulting in the TDD frame structure also given in that reference. Only two hops are considered. Simulation parameters are kept close to those of [WIN2D6137], except for the restrictions due to the reference method (see below) and for a change in base station antenna element elevation gain, which is set to *8 dBi* instead of *14 dBi*, corresponding approximately to an assumed beam width of 60 degrees in elevation. Indoor users are not present in this simulation.

B.10.4.1 Description of the reference method used for comparison

To be independent of the choice of space-time processing technique in the reference method, it is based on the theoretically achievable maximum sum rate under sum power constraint when channel knowledge is available at the transmitter (aka Dirty Paper Code Bound). The approach is an updated version of the one used in [WIN2D341] and published in [FKK+07], see below. The DPC bound rates are computed using the frequency flat, iterative uplink algorithm of [JRV05]. As a consequence, the study is limited to one subcarrier and the possibility of using OFDMA (which is given in the basic design of [WIN2D351]) cannot be investigated. This is due to the fact that in the literature no such algorithm was available when this research was started to treat also the space frequency power loading problem at the same time. A simplified frame structure is used such that one instance of the DPC algorithm is run per drop of the channel. The Doppler effect is not analysed.

When a system with SDMA and relaying is considered, a scheduler is needed to assign the users to the transmitters. A genie-like scheduler is used and the RNs have a data buffer. The simulation steps for the reference performance are as follows:

1. Compute the DPC bound rates for all users when served by each one of the BSs and RNs separately, assuming independent single cell systems with one transmitter only. In the odd time slots RNs do not transmit but are also users (receivers). In the even time slots, the RNs act as BSs.
2. Genie-like scheduler knowing all achievable rates: Decide on the assignment of users to RNs and BSs based on the achievable DPC rates from step 1 (no interference considered in this step, suboptimal).
3. Recompute DPC covariance matrices for the newly assigned groups (second run of DPC algorithm required).
4. Perform uplink-downlink conversion of the newly computed covariance matrices as in [VJG03].

5. Compute downlink rates for the entire system WITH interference (all transmitters) using the downlink DPC covariance matrices from step 4 and taking into account a buffer level at the RNs: The role of the RNs depends on the time slot number. When the RNs receive, they fill up their buffer. When they transmit, the achievable rates of the UTs assigned to RNs is limited by a user specific buffer level of the serving RN (see the ProSched for REC description for how the buffer is implemented).

B.10.4.2 Discussion

The ProSched algorithm exists in variations with different complexity. The version simulated here uses rank one reduced bases of the users' subspaces to compute their nullspace projection matrices, which was originally meant for complexity reduction. In this setting, however, it allows to reduce considerably the overhead data to be transmitted to the central intelligence. This kind of overhead was not estimated, but is certainly present in both the reference method and the more practical method.

The precoding scheme used together with ProSched is SMMSE with dominant eigenmode transmission [WIN2D341], which is the reference scheme proposed in [WIN2D6137]. We also show the performance of the proposed reference method taking into account the resource sharing between two groups of RNs as proposed in [WIN2D351] and implemented in time direction.

It can be seen in Figure B.32 that the proposed low complex scheduler performing joint interference avoidance together with low complex precoders increases the probability of achieving high rates in a wide range of the graph but suffers a slight drawback in peak throughput, likely due to the suboptimality of the precoder. Note that precoding is done separately for each transmitter but that the presented coordinated scheduler takes into account the predicted interference which depends on the selection of the users. The interference generated is different for each possible user assignment requiring different precoding matrices at each transmitter. However, the ProSched interference prediction scheduling requires no additional computation of any precoding matrices during the testing of combinations. The reference performance is based on the maximum rates that each transmitter can theoretically achieve when serving its assigned users as well as a genie scheduler which does not perform interference avoidance. To that extend the gain that is visible stems from interference avoidance.

Note that an even higher gain can be expected in a highly populated scenario (the number of users simulated was limited due to complexity) due to higher selection diversity. Furthermore, in an OFDM system, more degrees of freedom are available for interference avoidance. Furthermore it was observed that non-intelligent interference avoidance in the form of time-sharing (i.e., forming two RN groups in time) may reduce the achievable rates (dashed curve). This conclusion may also change when the number of users in the system is increased.

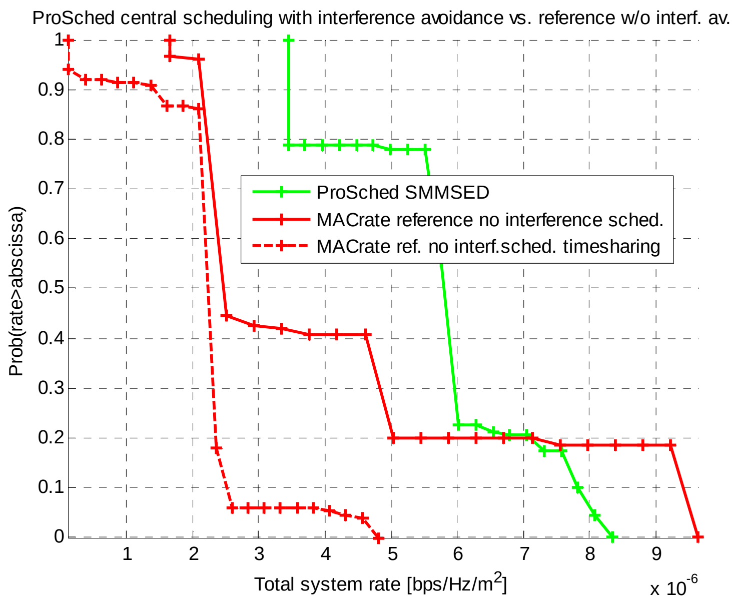


Figure B.32: ProSched central scheduling with interference avoidance

This figure shows the probability of exceeding a certain total system throughput for ProSched with interference avoidance using SMMSE dominant eigenmode transmission versus a reference based on the theoretically achievable maximum sum rate and a centralized genie scheduler without interference avoidance. The total surface was 2027200 m2. It can be seen that the proposed scheduler suffers a slight drawback in peak throughput (due to the suboptimality of the precoder), but increases the stability in a wide range of the graph. The absolute figures are, however, of limited value: the overhead present for both methods will reduce them significantly, but less for the ProSched method as said above. And both schemes will suffer from outdated and erroneous channel state information in the same way, since they are based on linear precoding.