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List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I **Rikke Apelfröjd**, Daniel Aronsson and Mikael Sternad, "Measurement-based evaluation of robust linear precoding for downlink CoMP," Presented at *the IEEE International Conference on Communications (ICC) 2012*, June 2012.

II **Rikke Apelfröjd** and Mikael Sternad, "Design and measurement based evaluations of coherent JT CoMP: A study of precoding, user grouping and resource allocation using predicted CSI," Submitted to *Eurasip Journal on Wireless Communications and Networking*, Submitted December 2013, Revised April 2014.

III **Rikke Apelfröjd** and Mikael Sternad, "Robust linear precoder for coordinated multipoint joint transmission under limited backhaul with imperfect CSI," Submitted to *the IEEE International Symposium on Wireless Communication Systems (ISWCS) 2014*, Submitted April 2014.

IV N. Jamaly, **Rikke Apelfröjd**, Ana Belén Martinez, Michael Grieger, Tommy Svensson, Michael Sternad and Gerhard Fettweis, "Analysis and measurement of multiple antenna systems for fading channel prediction in moving relays," Presented at *the 8th European Conference on Antennas and Propagation (EuCAP)*, April 2014.

V **Rikke Apelfröjd** "Kalman predictions for multipoint OFDM downlink channels", Technical Report, Signals and Systems, Department of Engineerging Sciences, Uppsala University, May 2014. Also presented at the Swedish Communication Technologies Workshop (Swe-CTW) in Västerås, Sweden, June 2014.

List of contributions not included in this thesis

VI Daniel Aronsson, Carmen Botella, Stefan Brueck, Cristina Ciochina, Valeria DAmico, Thomas Eriksson, Richard Fritzsche, David Gesbert, Jochen Giese, Nicolas Gresset, Hardy Halbauer, Tilak Rajesh Lakshmana, Behrooz Makki, Bruno Melis, **Rikke Abildgaard Olesen**, Mara Luz Pablo, Dinh Thuy Phan Huy, Stephan Saur, Mikael Sternad, Tommy Svensson, Randa Zakhour, Wolfgang Zirwas, "Artist 4G, D1.2 Innovative advanced signal processing algorithms for interference avoidance," December 2010. Available: https://ict-artist4g.eu/projet/deliverables (Accessed March 2014).

VII Mikael Sternad, Michael Grieger, **Rikke Apelfröjd**, Tommy Svensson, Daniel Aronsson and Ana Belén Martinez, "Using "predictor atennas" for long-range prediction of fast fading for moving relays," Presented at *IEEE Wireless Communications and Networking Conference (WCNC) 2012*, 4G Mobile Radio Access Networks Workshop, April 2012.

VIII Valeria DAmico, Bruno Melis, Hardy Halbauer, Stephan Saur, Nicolas Gresset, Mourad Khanfouci, Wolfgang Zirwas, David Gesbert, Paul de Kerret, Mikael Sternad, **Rikke Apelfröjd**, Maria Luz Pablo, Richard Fritzsche, Hajer Khanfir, Slim Ben Halima, Tommy Svensson, Tilak Rajesh Lakshmana, Jingya Li, Behrooz Makki, Thomas Eriksson, "Artist 4G, D1.4 Interference avoidance techniques and system design," July 2012.
Available: https://ict-artist4g.eu/projet/deliverables (Accessed March 2014).

IX Jingya Li, Agisilaos Papadogiannis, **Rikke Apelfröjd**, Tommy Svensson and Mikael Sternad, "Performance evaluation of coordinated multi-point transmission schemes with predicted CSI," Presented at *IEEE Personal Indoor and Mobile Radio Communications (PIMRC)*, September 2012.

X Tilak Rajesh Lakshmana, **Rikke Apelfröjd**, Tommy Svensson, and Mikael Sternad, "Particle swarm optimization based precoder in CoMP with measurement data," Presented at *5th Systems and Networks Optimization for Wireless (SNOW) Workshop*, April 2014.

XI Volker Jungnickel, Konstantinos Manolakis, Wolfgang Zirwas, Volker Braun, Moritz Lossow, Mikael Sternad, **Rikke Apelfröjd**, and Tommy Svensson, "The role of small cells, coordinated multi-point and massive MIMO in 5G," *IEEE Communications Magazine*, May 2014.

Contents

Abbreviations

3GPP	3rd Generation Partnership Project
AR	Auto Regressive
CDF	Cumulative Distribution Function
CoMP	Coordinated MultiPoint
COP	Code-Orthogonal Pilots
CQI	Channel Quality Index
CRS	Common Reference Symbols
CSI	Channel State Information
CU	Control Unit
DPC	Dirty Paper Coding
FDD	Frequency Division Duplex
GPS	Global Positioning System
JB	Joint Beamforming
JP	Joint Processing
JS	Joint Scheduling
JT	Joint Transmission
LOS	Line Of Sight
LTE	Long Term Evolution
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MMSE	Minimum Mean Squared Error
MSE	Mean Squared Error
NLOS	Non Line Of Sight
NMSE	Normalized Mean Squared Error
OFDM	Orthogonal Frequency-Division Multiplexing
RLP	Robust Linear Precoder
ROP	Resource-Orthogonal Pilots
SINR	Signal to Interference and Noise Ratio

SISO	Single-Input Single-Output
SNR	Signal to Noise Ratio
TDD	Time Division Duplex
WTR	Weakest to Total SNR Ratio

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Rikke Apelfröjd

1. Coordinated Multipoint - a brief introduction

In a traditional cellular network, each base station serves the users that are located within its own cell, see Figure 1.1. When a user moves from one cell to another, the base stations cooperate in the *hand-over* procedure, but otherwise they serve their users independently of each other. The base stations can use different resources and/or different beams to avoid *intracell interference*, i.e. that the energy leak between the different users' messages. However, as base stations generally do not cooperate, except for in the hand-over procedure, energy might leak between cells, causing *intercell interference*. This interference decreases the data throughput for the users and is especially severe for users located at the cell borders, referred to as cell edge users.

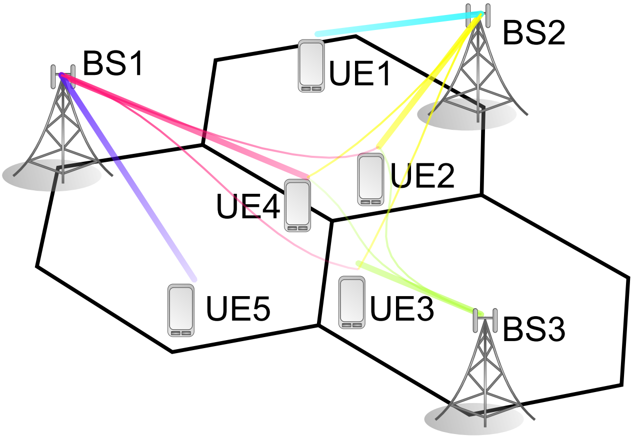

Figure 1.1. A set-up of a cellular network where each base station (BS) serves the users (UE) in its own cell only. Different colors indicate messages intended for different users. In the absence of base station cooperation, some of the energy intended for a user in one cell might leak to a user in another cell, causing interference.

In order to decrease the intercell interference, the base stations can use different frequency bands to serve their users. For example, if the total bandwidth is divided into three sub-bands, then each of the three base stations in Figure 1.1 can serve its users within its own sub-band.

This sub-band can then be reused by every third base station. With this scheme, known as frequency reuse 3, the intercell interference from the neighbouring cells is avoided. However, the solution comes at the cost of fewer resources per base station, as each base station can only use one third of the total bandwidth.

Data demanding wireless communication applications, such as e.g. social network applications for smart phones, video calls and streaming services, are becoming more common amongst the users. Solutions on how to serve the growing amount of data hungry users need to be presented. A simple way of doing so is to set up more base stations. This will ensure that each base station has good signal strength within its own cell, but it will also allow nearby base stations, which are potential interferes, to be closer. This results in an increased intercell interference.

Another tempting options is to let all base stations use the full bandwidth in serving their users. However, that will again increase the intercell interference. It is realistic to assume that both of these options will be part of the solution to serve the data hungry users.

Some questions then naturally arise; What if the base stations could cooperate, not only in the hand-over scenario, but for all users in the system? What if they could serve their users such that intercell interference can be avoided? Or, even better, what if they could even turn the interfering energy into useful signal energy.

These questions have lead up to the research topic of Coordinated MultiPoint (CoMP). Within this topic, different options of how to let the base stations cooperate are investigated.

1.1 Related work

CoMP was introduced in the beginning of the millennium as a way to increase the spectral efficiency of downlink transmission [1, 2, 3]. It has recently been identified as one of the main building blocks for the fifth generation (5G) mobile communication network [4] and first steps towards support for CoMP have been added to the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) standard in Release 11 [5].

Downlink CoMP is often divided into two categories, [6, 7, 8]. The first is Joint Transmission (JT), sometimes referred to as Joint Processing (JP), where multiple base stations attempt to transmit to one, or more, users simultaneously, see Figure 1.2. The second includes Joint Scheduling (JS) and/or Joint Beamforming (JB). In this category base stations coordinate their transmission, e.g. such that they avoid serving closely located users within the same resources and thereby lower the intercell interference. For example, in Figure 1.1, base station 1 and base station 3 may serve user 2 and user 4 on different frequencies, while they may serve user 1 and user 5 on the same frequencies. The later category provides lower gains in spectral efficiency than JT, but is more robust to errors in Channel State Information (CSI).

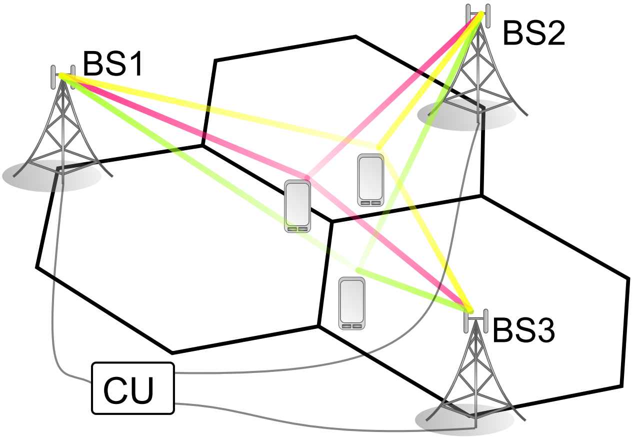

Figure 1.2. A set-up of a JT CoMP scenario where three base stations (BS) transmit jointly to three users. The base stations share information over backhaul links via a control unit (CU).

In JT CoMP, base stations share payload data and CSI over *backhaul channels*, i.e. channels that connect the base stations. These might e.g. be wireless radio channels with separate frequencies or fiberoptic cables. Based on the CSI, some or all of the base stations may then be selected to transmit payload to one user, without any pre-compensation of the message symbol intended for that user. As the message is transmitted with radio waves these may sometimes add up constructively at the users, providing a stronger receive signal than if only one of the base stations transmitted. However, when no pre-compensation of the message is used, then the signals may also add up destructively, lowering the total received power[1]. This is called *non-coherent* JT CoMP.

An alternative is that the base stations *precode* the message symbol, based on the CSI, before transmission, to ensure that the signals from the different base stations add up constructively. This scheme, which is called *coherent* JT CoMP, allows base stations to serve multiple users on the same time-and-frequency slot, or *resource*. The messages are then precoded such that, at each user, only the message intended for that user is constructively added, while the messages intended for the other users are destructively added. Coherent JT CoMP, also known as network

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[1] On average the received power will be stronger.

Multiple-Input Multiple-Output (MIMO) or multi-cell MIMO, thereby has the potential to provide very large gains in spectral efficiency (see e.g. [5, 9, 10, 11]). However, it is more sensitive to errors in the CSI than non-coherent JT CoMP [12].

CoMP can also be utilized in the uplink, i.e. when a user transmits information to the base stations. Then the base stations cooperate either through JS or through joint detection, see e.g. [13, 14]. Joint detection in the uplink is easier than downlink coherent JT in the sense that the processing can be based on fully updated CSI. However, it faces other challenges, e.g. the statistics of the intercluster interference might be more difficult to estimate, as this will tend to be more bursty than for the downlink problem.

1.1.1 Challenges for downlink coherent joint transmission

There are many challenges and hurdles to overcome before downlink CoMP can be fully deployed, especially for coherent JT. Some of these are discussed below.

The clustering problem

One of these challenges is the problem of forming the cooperation clusters. There is a trade-off in the number of base stations included in the cooperation cluster. In a cluster with a low number of base stations, the remaining uncompensated intercluster interference will be large, lowering the potential CoMP gains. In a cluster with a large number of base stations, there might be large system delays, causing severe outdating of the CSI. This, in turn lowers potential CoMP gains. Moreover, in very large clusters, base stations will be so far away from each other that this may cause severe synchronization problems.

The problem of clustering has been studied for intracluster interference limited scenarios in e.g. [10, 15, 16, 17]. According to these works, for single antenna base stations, clusters of about three base stations are sufficient in order to achieve most of the CoMP gains. After this point, CoMP gains grow slowly. For MIMO systems with 2-4 transmit antennas per base station, clusters of 7-9 base stations are required.

Such cluster sizes are fairly small, so intercluster interference levels will still be significant. Therefore external schemes to manage intercluster interference can improve the CoMP gains further. An interesting method to limit the intercluster interference is proposed in [15] and further evaluated in [18]. It uses cluster-specific antenna tilting and power control for this purpose.

Backhaul latencies and capacity constraints

Data sharing over backhaul will cause time delays between the channel estimation and the payload transmission. CoMP decisions will then be based on outdated CSI. How this affects the potential CoMP gains depends on the CoMP scheme used, i.e. JS, JB or JT, and on the network architecture, i.e. centralized, distributed or semi-distributed, see e.g. [19, 20]. It turns out that the CSI quality is especially important for coherent JT in a centralized architecture, which is also the solution that would provide the largest potential gains. It is therefore of great importance to find methods to improve the CSI, under long backhaul delay constraints, in order to make coherent JT CoMP feasible.

A second problem with data sharing over backhaul, is that it places high demands on the backhaul capacity, especially for JT. In realistic systems, these demands may not always be met. Then the information available at the Control Unit (CU), which is a logical entity that makes the CoMP decisions, will be limited. Furthermore, the possibility to share payload data between the base stations may also be limited. If the CoMP design does not handle these *backhaul constraints*, then potential CoMP gains may be lost.

A method, based on linear optimization, on how to reduce backhaul requirements for decentralized JB CoMP was suggested in [21]. Methods for reducing backhaul requirements for coherent JT CoMP have been suggested in e.g. [22, 23, 24, 25]. However, these either require joint scheduling, which introduces extra requirements on backhaul links, or they are high in computational complexity.

User grouping and resource allocation

A non-trivial problem for coherent JT CoMP is that of which users to serve jointly on each specific transmission resource. If these are selected carefully then there is a potential for large multi-user diversity gains, as was shown for multi-user MIMO in e.g. [26, 27]. However the complexity of a search through all possible user groups and all resource allocation possibilities grows combinatorially with the number of users to choose from. It is desirable to have a simple scheme that is low in complexity and preserves the multi-user diversity gains of the optimal solution.

A greedy selection scheme, as suggested in e.g. [28, 29, 30], provides close to optimal solutions at much lower complexity. For this scheme, the CU forms the groups by, for each resource, adding the users into the group one at a time, according to some criterion. Such a scheme does however require that the CU has access to the CSI of *all* potential users, which in turn places extra demands on backhaul capacity.

Precoder design

The highest gains for coherent JT CoMP are achieved with Dirty Paper Coding (DPC), see e.g. [31]. However, as this non-linear precoding scheme is high in complexity, linear precoding is an important topic of investigations. The primary objective of the precoder is often to limit the intracluster interference. In a system with perfect CSI this can be achieved by channel matrix inversion, which provides the *zero-forcing* precoder developed for MIMO, see e.g. [32].

However, there is a risk in using zero-forcing for JT CoMP, even in the presence of perfect CSI; Channel gains may be very different in amplitude, which is generally not the case for single user MIMO. The channel inversion might then cause the strongest base station's transmit power to be very low compared with the weakest base station. Although the solution is still optimal with respect to limiting intracluster interference, the noise and intercluster interference might then be large compared to the signal power, resulting in a poor data rate. An option is then to use a Mean Squared Error (MSE) criterion which includes these terms as well as the intracluster interference [33].

MSE criteria are attractive as they generally have analytical solutions. However, in practice it is often more useful to optimize over a weighted sum-rate criterion, as this is closer to the desired end performance. Such optimization pose a multi-dimensional non-convex optimisation problem. A method using stochastic optimisation to find the optimal linear precoder has been suggested in e.g. [25].

A problem with JT CoMP is, as previously mentioned, that the long delays cause inaccuracies in the CSI. If these inaccuracies are not addressed in the precoder design, then the potential CoMP gains may be lost. Robust precoder design techniques have been suggested for Multiple-Input Single-Output (MISO) systems by [34, 35], and for multiuser MIMO downlinks in [36, 37]. A robust linear precoder for JT CoMP, which is based on an MSE criterion, is suggested in [38].

Base station synchronization

Another challenge of CoMP is that of phase synchronisation between base stations [11, 39]. A potential remedy based on Global Positioning System (GPS) coordinates have been suggested in [40].

1.2 Contributions

The papers included in this thesis aim to solve some of the CoMP challenges stated above through three main contributions.

1. The problem of the outdated CSI is partly counteracted by **channel predictions**. Both conventional channel predictions through

Kalman filtering and a new concept for long range channel predictions are investigated.
2. A very low complexity method for **user grouping and resource allocation** is proposed and evaluated. This method provides very close to optimal CoMP groups and resource allocation, in the case of the sum-rate criterion. It places no extra requirements on backhaul capacity.
3. A low complexity robust linear **precoder design** is proposed. This is a robust Minimum Mean Squared Error (MMSE) design that offers a flexible tool to optimize over few parameter with respect to an arbitrary criterion, e.g. sum-rate. The robust design takes channel uncertainties due to prediction errors and quantization into account. It is also flexible with respect to including backhaul constraints.

All proposed schemes apply to coherent downlink JT CoMP in Frequency Division Duplex (FDD) Orthogonal Frequency-Division Multiplexing (OFDM) systems[2]. A centralized network architecture is assumed. It is also assumed that synchronization and intercluster interference can be handled, e.g. with the above mentioned methods. The proposed algorithms are evaluated and compared to alternative schemes through simulations. The simulations are to a great extent based on channel measurements from two separate measurement campaigns. Cluster sizes are limited to three base stations for single antenna base stations, and to nine base stations in the case of multi-antenna base station.

1.2.1 Measurement campaigns

The results in the included papers are, to a large extend, based on channel sounding measurements. Some of these were collected in Kista, in Sweden, by Ericsson research in December 2008. The others were collected in Dresden, in Germany by the Technical University of Dresden, Uppsala University and Chalmers University of Technology in March 2012.

Measurements in Kista

In Papers I, II and V, most of the simulated results are based on channel measurements that were conducted by Ericsson Research in the urban environment in Kista, Stockholm, see Figure 1.3.

In this campaign, three omnidirectional base stations transmitted channel sounding pilots in a 20 MHz band, at a carrier frequency of 2.66 GHz. The pilots where measured by a vehicle which was driving

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[2] They could be used also for downlinks in Time Division Duplex (TDD) systems.

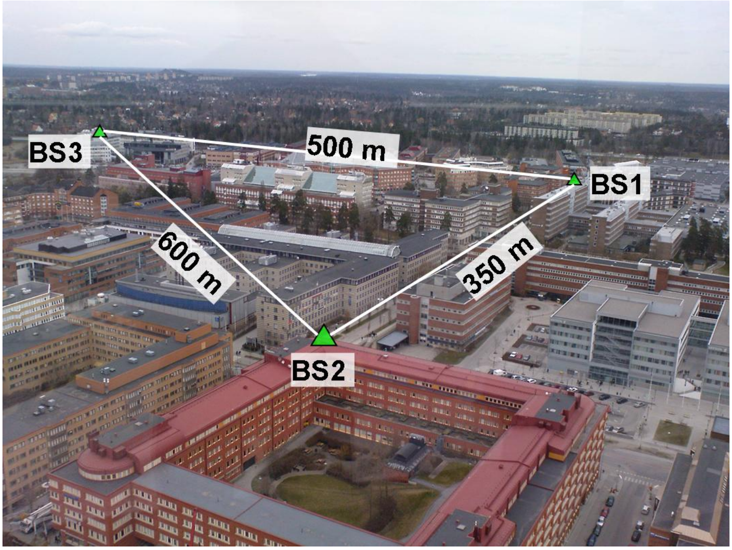

Figure 1.3. The urban environment of Kista, Stockholm, seen from above. The locations of the base stations (BS) are marked by triangles.

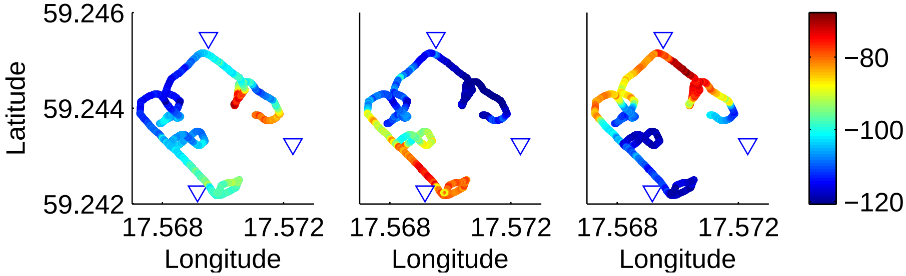

Figure 1.4. The signal powers from base station 1 (left), base station 2 (middle) and base station 3 (right). The base station locations are marked by triangles.

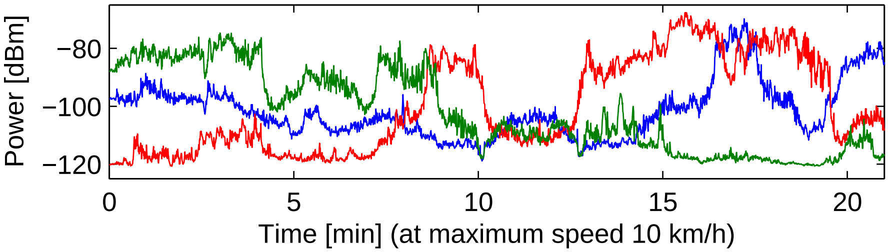

Figure 1.5. The variation of the power of the received signals that were transmitted from base station 1 (blue), base station 2 (green) and base station 3 (red). For details, see Paper V.

through the area between the base stations. The powers of the signals received from the different base stations are presented as a function of the measurement location in Figure 1.4 and as a function of time in Figure 1.5.

The quality of the measurements are very high and in the simulations included in the papers, the corresponding estimates of the OFDM channels are regarded to be the exact channels. More details on the set-up for this measurement campaign can be found in Paper I, Paper II and in [41].

Measurements in Dresden

The results of the second measurement campaign is presented in Paper IV. The measurements were collected in Dresden in a collaboration between the Technical University of Dresden, Uppsala University and Chalmers University of Technology, within the EU-project Artist4G. In this campaign the radio channels were measured by two antennas, which were mounted on top of a measurement van, see Figure 1.6.

During sequences of 0.5 s, the van was driving at 45-50 km/h along the road in Figure 1.7. The measurements were conducted in one Line Of Sight (LOS) location and one Non Line Of Sight (NLOS). For the NLOS location the base station is shadowed by the tall building on the left hand side of figure 1.7.

For each location, LOS/NLOS, measurments were collected for dipole antennas mounted on a metal rod over the van, see Figure 1.6; for monopole antenna mounted on a large metal sheet, see Figure 1.8; and for dipole antennas mounted on the same large metal sheet. More details can be found in Paper IV and in [42, 43, 44].

1.3 Organization of this thesis

The thesis is organized in the following manner. Chapter 2 includes a summary of the channel prediction methods investigated in Paper I, II, IV, V. In Chapter 3 different user grouping and resource allocation schemes for CoMP are summarised and compared with the proposed scheme in Paper II. Chapter 4 includes a summary on the linear precoder proposed in Papers I-III. In each of Chapters 2-4 the main results of the papers are highlighted. An overview of the included papers is provided in Chapter 5.

Figure 1.6. Two dipole antennas (inside the red circle) are mounted on a metal rod over the car roof. For more details, see Paper IV.

Figure 1.7. The environment for the Dresden measurement campaign.

Figure 1.8. Two monopole antennas are mounted over a metal sheet to ensure that they experience similar fading. For more details, see Paper IV.

2. Channel Predictions

The accuracy of Channel State Information (CSI) at the transmitter is very important, both to ensure coherent Joint Transmission (JT) Coordinated MultiPoint (CoMP) gains [45] and for other applications. These include adaptive modulation and coding [46] and single cell MIMO transmission [47].

A challenge with CoMP is the long system delays. These include the process time for channel estimation, the CSI feedback from the users to the base stations, the CSI sharing between the base stations over backhaul, e.g. via a Control Unit (CU), the process time for the precoder design and the sharing of the precoder weights between base stations. The sum of all these delays are often in terms of tens of milliseconds and will cause the CSI to be outdated at the time of transmission [48, 49].

The outdating of CSI can to some extend be counteracted by channel predictions [50, 51, 52, 53].

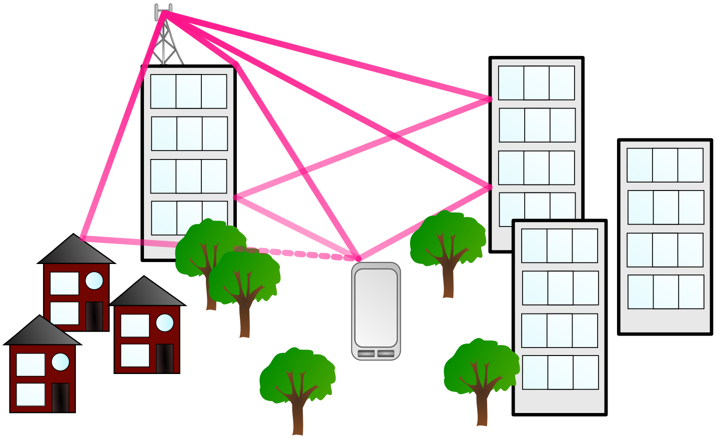

Figure 2.1. An illustration of a multipath channel.

2.1 Predictability of small scale fading

There are limitations in the predictability of fading radio channels [52, 54]. These limitations are caused by measurement noise as well as the fading statistics of the radio channels. For long range predictions, the limitations are almost solely due to the fading statistics on the channel. This section includes results on the predictability of fading channels, in the absence of measurement noise.

When radio signals are transmitted from an antenna they will spread into multiple rays, see Figure 2.1. These rays will interact with matter in different ways. They will reflect from different surfaces, such as walls and ground, refract over edges, such as roof tops or corners of buildings, and experience dampening e.g. when passing through a window or a tree. All of these phenomena will cause rays of different strength to arrive at different time delays from multiple paths, which in turn will create a complicated standing wave pattern. As the users travel through the standing wave pattern their received signal strength will vary, see Figure 2.2. It will be very weak when the user is at a node in the standing wave pattern and strong when it is at an anti-node. This is referred to as the small scale *fading* of radio channels [55].

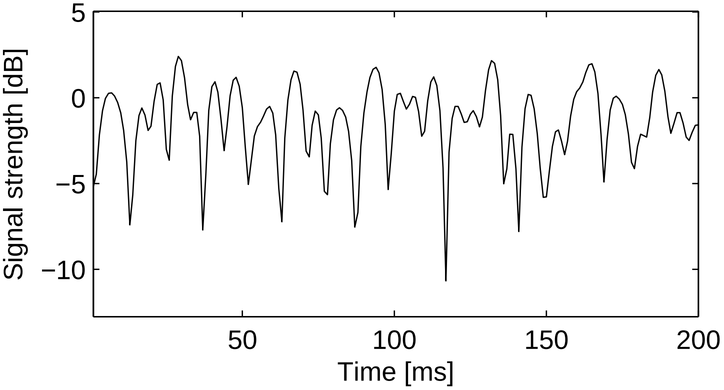

Figure 2.2. Example of the signal strength for a user travelling through a standing wave pattern caused by a multipath channel.

If the standing wave pattern is composed of a sum of perfect sinusoids, then, in the absence of measurement noise, the channel is infinitely predictable. However, in reality the standing wave pattern is often composed of a sum of damped sinusoids. Mathematically, these can be represented by Auto Regressive (AR) models. Paper V includes a detailed description on how to estimate these models for multipoint MIMO channels, based on some past measurements of the channel.

In frequency domain, such AR models can be represented by the Doppler spectrum, see e.g. [52]. Each sinusoid that contributes to the standing wave pattern will appear as a spike in the spectrum. If the sinusoid is very damped, then the spike will be smeared and if it is a pure sinusoid it will be a Dirac delta function. A strong Line Of Sight (LOS) component, or a dominating Non Line Of Sight (NLOS) component, will translate as a strong spike in the spectrum. In the presence of many equally strong NLOS components arriving from multiple directions (in all three spatial dimensions) the spectrum will tend to be more flat.[1]

Paper V provides a tutorial on how to calculate the theoretical limitations of the predictability of channels whose fading are described by an AR model. The results of such calculations are provided in Figure 2.3 for two different examples. For the first example (the solid line), the poles of the AR model are placed close to the unit circle, yielding a very spiky spectrum. For the second example (the dashed line), the poles are placed further into the unit circle, yielding a more flat spectrum, for details see Paper V. Most channel fading environments fall in between of these two examples in terms of predictability. The prediction performance, expressed as Normalized Mean Squared Error (NMSE), is shown as a function of the spatial prediction horizon, d_λ, in terms of carrier wavelength. Although a fading environment with a spiky spectrum allows for better prediction performance, predictions for more than 0.5 wavelengths are not very good.

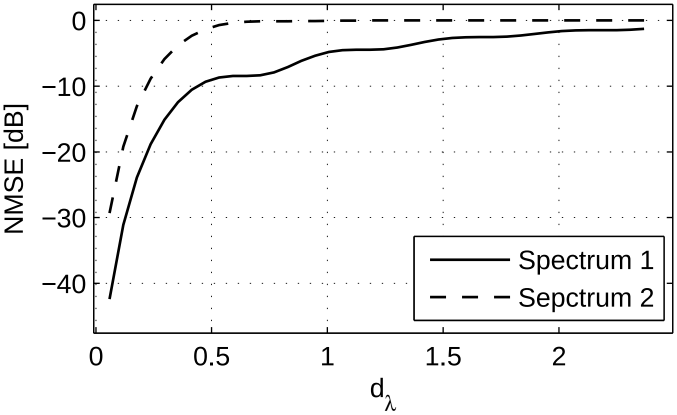

Figure 2.3. The theoretical upper limit on the NMSE of channel predictions as a function of the prediction horizon in space relative to the carrier wavelength. The fading statistics is here represented by two different fourth order AR models. The solid curve represents a fading environment with a 'spiky' spectrum and the dashed curve fading environment with a 'flat' spectrum. For more details, see Paper V.

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[1] If equally strong NLOS components arrive from multiple directions in a two dimensional plane then the Doppler spectrum will converge to the spectrum of the commonly used Jakes model with an increasing number of components, see [55].

The spatial prediction horizon can be translated into a temporal prediction horizon, τ, using the carrier frequency, f_c, the speed of light, c, and the user velocity, v, as

$$\tau = \frac{d_\lambda \cdot c}{v \cdot f_c}. \tag{2.1}$$

For example, a spatial prediction horizon of $d_\lambda = 0.5$ carrier wavelengths will, at a carrier frequency of 2.65 GHz, correspond to temporal prediction horizons of 30 ms and 3 ms for user velocities of 5 km/h and 50 km/h respectively. As system delays under 30 ms are achievable for CoMP systems, channel predictors have the potential to provide sufficiently accurate CSI for pedestrian users. However, to ensure sufficiently accurate CSI for vehicular users at high carrier frequencies, system delays either need to be significantly shortened, or other techniques to acquire CSI are needed.

2.2 Linear predictors

If the fading statistics is known, then linear filters, such as the Wiener filter and the Kalman filter, can provide optimal predictions, with respect to a Minimum Mean Squared Error (MMSE) criterion [56]. The average prediction error is then zero and the prediction error becomes uncorrelated with the prediction.

2.2.1 Kalman filter

The Kalman filter was first introduced by Rudolf Kalman in [57]. It is derived from the Weiner filter and is based on state space models of the fading statistics. The Kalman filter has the advantage that not only does it provide the optimal predictions, it also provides the covariances of these. Such covariance information is used in the robust linear CoMP precoder design presented in Paper I and Paper II. Furthermore, the Kalman filter is recursive and only requires the latest channel measurement to update the filter. It is hence low in memory requirements.

The Kalman filter is used as an enabler in Paper I and Paper II. It is also the main focus of Paper V. In all of these, prediction are investigated for different parameter settings. The main results are highlighted below.

Main results

The two main factors that decide whether or not channel predictions are sufficient to ensure CoMP gains are the intercluster interference and the system delays, which dictate the required prediction horizon.

Results of Paper II show that Kalman filters provide sufficient predictions to ensure CoMP gains at prediction horizons up to $d_\lambda \approx 0.3$ wavelengths. If system delays are kept short, e.g. 5 ms, then Kalman filters can ensure good CSI even at vehicular velocities, e.g. up to 120 km/h at a carrier frequency of 500 MHz.

The importance of limiting intercluster interference is illustrated in Figure 2.4 where the Cumulative Distribution Functions (CDF) of the NMSE of the predictions are shown for two different noise floors (separated by 20 dB), at a prediction horizon of $d_\lambda \approx 0.12$. The low noise floor causes a gain in prediction performance of 4 dB at the 50% percentile. At the 90% percentile the NMSE decrease from -3 dB, which is as good as useless, to -8 dB, which was shown to be the limit for adaptive modulation and coding gains in [46].

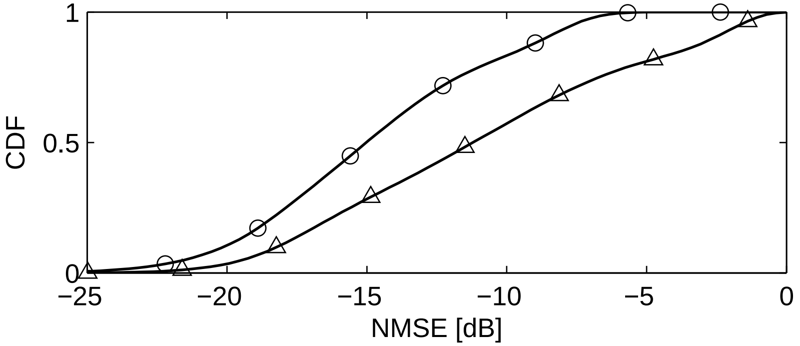

Figure 2.4. CDF of NMSE for a low noise floor (circles), and a high noise floor (triangles) at a spatial prediction horizon of 0.12 wavelengths. For details, see Paper II or Paper V.

The gain of using predictions instead of outdated CSI is especially high for the strongest and second strongest base stations. As these are the main participants in the linear JT, this is of high importance.

In order to measure the channels, the transmitter frequently sends pilots. These are symbols that are known both at the transmitter and at the receiver. Through the pilots, channel measurements can be abstracted. The transmission power used for pilots cannot be used for payload data, so the transmission of pilots causes some overhead in the system. The transmitter might use Code-Orthogonal Pilots (COP) or Resource-Orthogonal Pilots (ROP), see Paper I and Paper V for details[2]. With COP the prediction performance decrease significantly for the weakest base station when the ratio of the channel power received from the weakest base station over the channel power from the strongest base station is small. This problem does not occure when using ROP.

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[2] In Paper I, code-orthogonal pilots are called quasi-orthogonal pilots.

Based on this, it is suggested that ROP are used for transmitters located at different base stations. However, for transmitters located at the same base station, COP should be used to avoid that pilots must be separated too much in time and frequency to limit the overhead due to pilots.

2.3 Long horizon predictions

Some times prediction horizons of several wavelengths are required. For example, buses and trains might provide hot spots, i.e. spots where many data-hungry users are gathered. It would then be desirable to have a relay node on the vehicle that can utilize sophisticated transmission schemes, such as coherent JT CoMP. As buses and trams normally travel at high velocities they will require long spatial prediction horizons.

Since the fundamental limit of the predictability of fading radio channels is usually less than a wavelength, conventional predictors cannot provide sufficiently accurate CSI.

A potential remedy might be to have a database of coordinate specific CSI, e.g. located at the base stations [58]. The users can then feed back an estimate of their locations, e.g. based on Global Positioning System (GPS) information, to the base stations. As this method is not really predicting the fading in the conventional sense, it is not bound by the limitations discussed in Section 2.1. However, such a model will require collection of a large amount of data. This data might in turn need to be updated continuously, due to e.g. seasonal changes in the environment. It is also unclear how such a scheme might be affected by e.g. bypassing vehicles that alter the standing wave pattern.

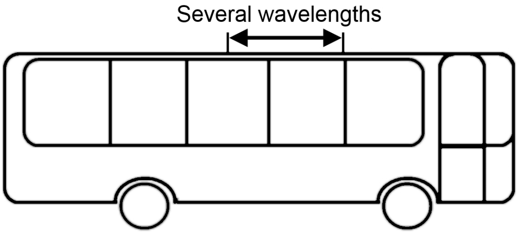

Figure 2.5. A predictor antenna can be place in front of a receive antenna, in the direction of travel, to scout the environment.

2.3.1 Predictor antennas

An alternative remedy is to place a predictor antenna in front of the main receive antenna, see Figure 2.5. This ”predictor antenna” might be the first antenna of a linear antenna array or a separate antenna. The predictor antenna can then be used as a scout that estimates the channel at a specific location[3]. When the receive antenna arrives at the same location it will experience approximately the same channel. Therefore, the channel estimated by the predictor antenna can be used as a channel prediction for the receive antenna. This concept was first introduced in [42] and is further developed in Paper IV. It is also the topic of two master theses, one at Uppsala University [43] and one at the Technical University of Dresden (TUD) [44].

Assume that the antennas are separated by a distance d, then this correspond to the maximum spatial prediction horizon. Assuming that the measurement of the predictor antenna will be used as the predicted CSI for the main receive antenna, the antenna correlation can be translated into NMSE through

$$\text{NMSE} = 1 - \mid a \mid^2, \tag{2.2}$$

where $\mid a \mid$ is the maximum absolute value of the correlation between the measured channels over time, which is obtained at the delay that corresponds to the spatial separation of the antennas, see [42].

The prediction antenna concept could potentially be combined with predictions from Kalman filters or with a location-based CSI as proposed in [58].

Main results

The concept is validated by a measurement campaigns in Dresden, Germany, see Section 1.2.1. In this the correlation between the two antennas' measurements were measured for one LOS and one NLOS setting with different types of antennas and different mountings. The results are presented partly in Paper III and partly in [42][4].

The two main factors that affected the correlation are the antenna type and the nearby fading environment caused by the car roof. The correlation greatly increases when the antennas where mounted on a large metal sheet, see Figure 1.8, instead of directly on the car roof, see Figure 1.6. Moreover, the correlation increases when using monopole antennas instead of dipole antennas.

Further performance enhancement is achieved by antenna coupling compensation. In Figure 2.6 the results of Paper IV are translated into potential prediction NMSE through (2.2) for different antenna separations when monopole antennas are mounted on a metal sheet with antenna coupling compensation[5]. The results are very promising. Even

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[3] As is the case for the location-based CSI suggested in [58], this is not prediction in the conventional meaning and therefore it is not bound by the limitations discussed in Section 2.1.

[4] In [42], results from an an earlier measurement campaign were used.

[5] In Paper IV the results are shown in terms of the maximum correlation $\mid a \mid$ in (2.2).

for very long prediction horizons there seems to be no degradation in performance. These results indicate that this concept has the potential to extend the usable prediction horizon in space (and thereby in time) by at least one order of magnitude, as compared to the use of old channel samples only.

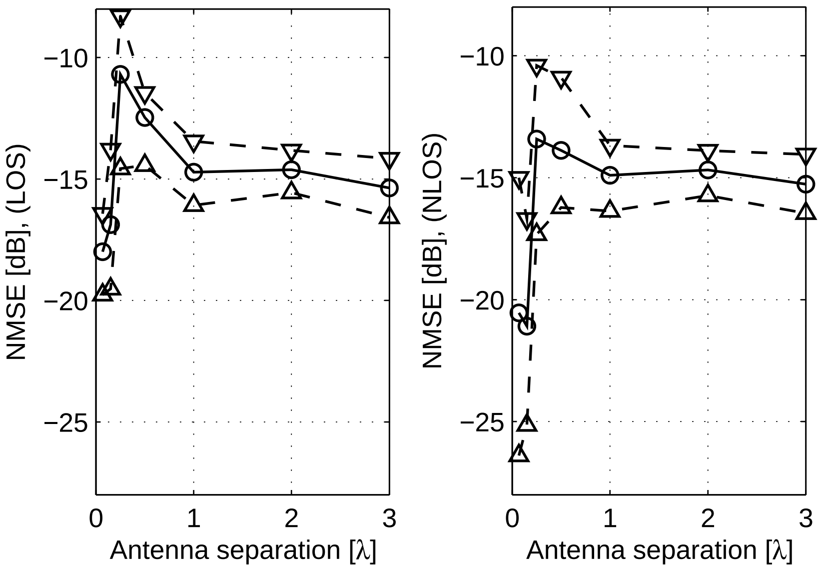

Figure 2.6. The potential NMSE for predictions through a predictor antenna calculated through (2.2), based on the measured antenna correlations obtained in Paper IV. The average (circles), 5% percentile (upward-pointing triangles) and 95% (downward pointing triangles) are shown for LOS (left) and NLOS (right). The antenna seperations are provided in terms of carrier wavelenght. For more details, see Paper IV and [42].

3. User Grouping

Two important problems to solve to achieve coherent JT CoMP gains are that of which users to group together and that of which resources to allocate to the different user groups.

Multi-user diversity was first introduced in [59]. Since then, the potential for multi-user scheduling gain has been thoroughly invested for single cell Single-Input Single-Output (SISO) transmission and for single cell Multiple-Input Multiple-Output (MIMO) transmission, see e.g. [26, 27]. These gains are significant and it would therefore be unfortunate if the user grouping scheme destroys some of the potential for scheduling gains.

One such user grouping scheme is when user groups are formed based on spatial compatibility, without considering the independent fading of the users, as in e.g. [22, 60]. In a second step the user groups are then allocated resources. There is a large risk with this scheme; the users generally have uncorrelated fading, so one or more of the users in the group may have a poor channel for the particular resource allocated to the group. Therefore, the scheduling and user grouping problems should not be solved independently of each other.

One option is then to search through all the possible combinations of potential user groups and resource allocations. This would require search through

$$\left(\sum_{m=0}^{M_{g,max}} \binom{M}{m} \right)^{K} \tag{3.1}$$

combinations. Here, M is the number of users in the cluster, K is the number of potential resources to use and $M_{g,max}$ is the maximum number of users per group. This is often set by the maximum of the total number of transmit antennas in the coordination cluster or by the total number of users in the system.

Note, that the complexity of (3.1) assumes that the option to serve no users within any given resource must be investigated with respect to the desired optimization criterion. This would be the case if the criterion e.g. is to minimize the transmit power under a utility constraint. Under the assumption of a fully loaded system with a sum-rate criterion, the sum in (3.1) need only to include $1 < m < M_{g,max}$.

It is easy to see that a search through all combinations is infeasible in realistic problems. For example, in a small CoMP cluster with three base stations, each with two transmit antennas (with a maximum of six users per group) and only ten users to be grouped and allocated over ten resource slots, the expression in (3.1) turns into $1.9 \cdot 10^{29}$ possible combinations.

3.1 Greedy user grouping and scheduling

In order to decrease the number of combinations, a greedy user grouping and scheduling algorithm can be used. This has been suggested for downlink single cell MIMO transmission in e.g. [28, 29] and for uplink CoMP in [30].

The users are then allocated one by one, to each resource at a time. First, the scheduler chooses the first user in the group based on a given criterion. Second, the scheduler searches through the remaining users and adds the user that, together with the first user, improves the optimization criterion most. The scheduler now repeats this for the remaining users until the addition of more users no longer improves the optimization criterion, or until the maximum number of users per group has been allocated.

This yields a search through a maximum of

$$K\left(\sum_{m=0}^{M_{g,max}-1}(M-m)\right), \tag{3.2}$$

combinations. For the example above, this is 450 combinations, which is substantially smaller than for the full search (3.1).

The complexity of this greedy scheduler is however not limited to (3.2). In order to find the best user group with respect to an optimization criterion, the signal power and interference power for each user must be estimated for all considered user groups. Then, for each combination of users, the scheduler must compute the CoMP (or MIMO) precoding matrix. This requires at least inversion of the channel matrix, which, for a full rank channel matrix, has the complexity of n^3 where n is the rank of the channel matrix. Therefore, to appreciate the full complexity, the expression in (3.2) must be multiplied with the complexity of calculating the precoding matrix (and through that the signal power and interference power at the users). The same goes for the full search in (3.1). Nevertheless, even though the complexity will be non-negligible with a greedy user grouping and resource allocation algorithm, it will still be manageable for reasonably sized channel matrices.

The main problem with using a greedy scheduling and user grouping scheme for CoMP is that, with many potential users to choose from, it places high capacity demands on the backhaul link. The greedy algorithm requires full Channel State Information (CSI) for *all* the considered users, see Paper II for details. This CSI needs to be shared over the backhaul links. Then, for a CoMP system with N base stations and M users, with p MIMO paths between each user and each base station, $N \cdot M \cdot p$ complex channel components per resource need to be transmitted over backhaul.

3.2 Cellular user grouping

In Paper I a random user grouping and scheduling scheme was used to investigate the potential of coherent JT CoMP for a set-up with three single antenna base stations serving three single antenna users per resource. From these results it is evident that, although the average rate increases with coherent JT CoMP compared with single cell transmission, many of the included user groups actually suffer a loss, see Figure 3.1. Further studies show that the groups that suffered from a CoMP loss have a common property; all users within the group have a poor channel to a common base station.

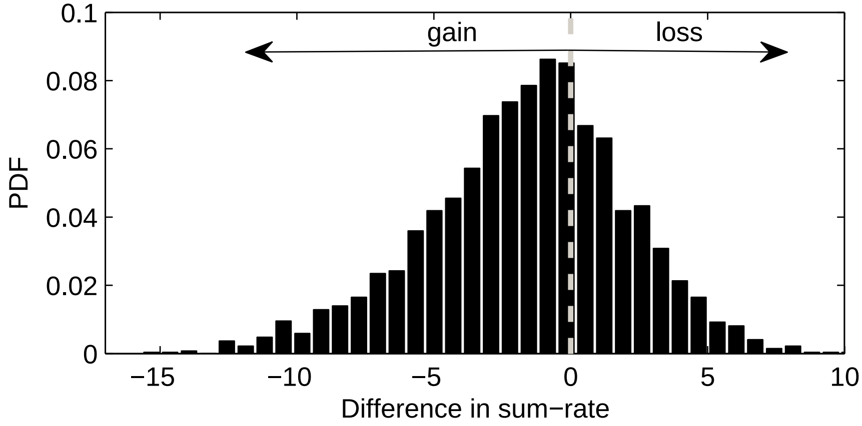

Figure 3.1. Distribution of the difference in sum-rate between single cell transmission and coherent JT CoMP, from Paper I. Bins in to the left of zero indicates CoMP gains and bins to the right of zero indicate CoMP loss. For more details see Paper I.

These results lead to the conclusion that, for coherent JT CoMP, the number of base stations with strong channels to at least one user within a group must be larger than or equal to the number of users in the group. One way of achieving this is to ensure that users in the group have different *master base stations*[1]. For single antenna base stations this means that no user scheduled on a resource is allowed to have the same master base station as any other users scheduled on that resource. For multi-antenna base station, a number of users, no larger than the number of transmit antennas at the base station, might be allowed to be scheduled on the same resource, even though they share the same master base station.

Assuming that the most important requirements on different users is that they need to have different master base stations, a user grouping scheme based on local scheduling choices at each base station is proposed in Paper II. In this scheme, each base station schedules all users within its own cell only. The scheduling may be based on some coarse Channel Quality Index (CQI) of these users, e.g. a roughly quantized, resource specific, estimate of the power of the channel gain. Once the scheduling decisions are made, the full CSI is transmitted over backhaul links for the M_g users that are actually scheduled to be served on a given resource. The requirements on backhaul capacity is then lowered to $N \cdot M_g \cdot p$. In a system with many users to choose from, i.e. with $M \gg M_g$, this induces a large relaxation of backhaul requirements. Moreover, feedback requirements are also lowered as the users must only feed back their full CSI for the resources they are scheduled to be served on.

Let M_j be the number of users located in cell j. The proposed *cellular user grouping* scheme then only requires a comparative search of

$$K \cdot M_j, \tag{3.3}$$

options per base station. For the example above, this yields an average of 33.3 options per base station, or a maximum of 100 options, if all users are in the same cell.

Furthermore, depending on the scheduling algorithm, for each option, a comparison of two scalar CQI values might suffice, as opposed to requiring matrix inversion, which is the case for the greedy user grouping and scheduling scheme.

A further advantage of the cellular user grouping scheme is that it may, but does not have to, utilize already existing scheduling algorithms. For example, if the objective is to maximize the sum-rate, then the base station might schedule the user with the best CQI for any given resource. If fairness amongst users are considered, then a *proportional fair* scheduler, which allocates the resource to the user that have the highest ratio of its CQI for the given resource over the its average CQI

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[1] The master base station of a user is here defined as the base station that, on average over all resources considered and over all MIMO channels, have the strongest channel gain to that user.

for all resources, see [61], can be chosen[2]. Another option is to use the *score-based* scheduler introduced in [63].

For example, consider the CoMP cluster in Figure 3.2. Assume that with single cell MIMO transmission, each base station can serve as many users as it has transmit antennas, here given by two[3]. Base station 1 will then schedule users 1-5, base station 2 will schedule users 6-7 and base station 3 will schedule users 8-11 according to some scheduling algorithm. Assume that the outcome of this scheduling algorithm is in accordance with Table 3.1. Then, users 1, 2, 6, 7, 8 and 9 form the CoMP group on resource 1, users 1, 4, 6, 7, 8 and 11 form the CoMP group on resource 2 and users 3, 5, 6, 7, 10 and 11 form the CoMP group on resource 3.

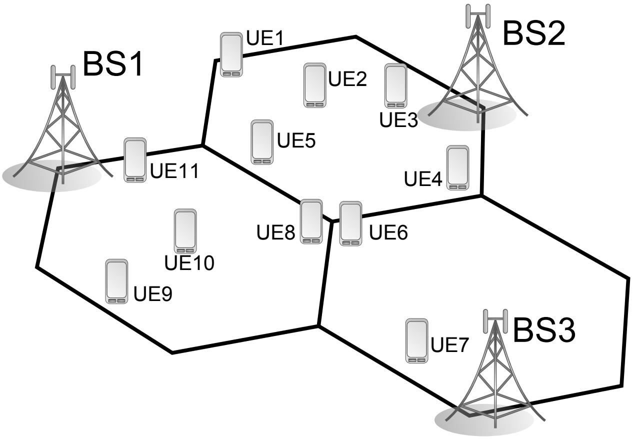

Figure 3.2. An example of how users (UE) might be distributed within a three cell CoMP cluster with directional base stations (BS), each with two transmit antennas.

Table 3.1. *An example of how the base stations (BS) in Figure 3.2 might schedule their users (UE) over three different resources.*

Resource	BS1	BS2	BS3
1	UE1, UE2	UE6, UE7	UE8, UE9
2	UE1, UE4	UE6, UE7	UE8, UE11
3	UE3, UE5	UE6, UE7	UE10, UE11

---

[2] For the greedy user grouping and scheduling scheme, a proportional fair allocation can be achieved by using a weighted sum-rate optimization criterion, see [62].

[3] Generally this number should be set lower for optimal performance.

Main results

Although the user grouping scheme outlined above does not consider the spatial compatibility of users, other than to the extent that they have different master base stations, the results of Paper II show that it is very well suited for CoMP.

The multi-user diversity gain is illustrated in Figure 3.3, where the average sum-rate is shown as a function of the number of users in the system, when all decisions are with respect to maximizing the sum-rate. The proposed cellular user grouping scheme preforms very close to the optimal solution (and to the greedy user grouping and scheduler scheme).

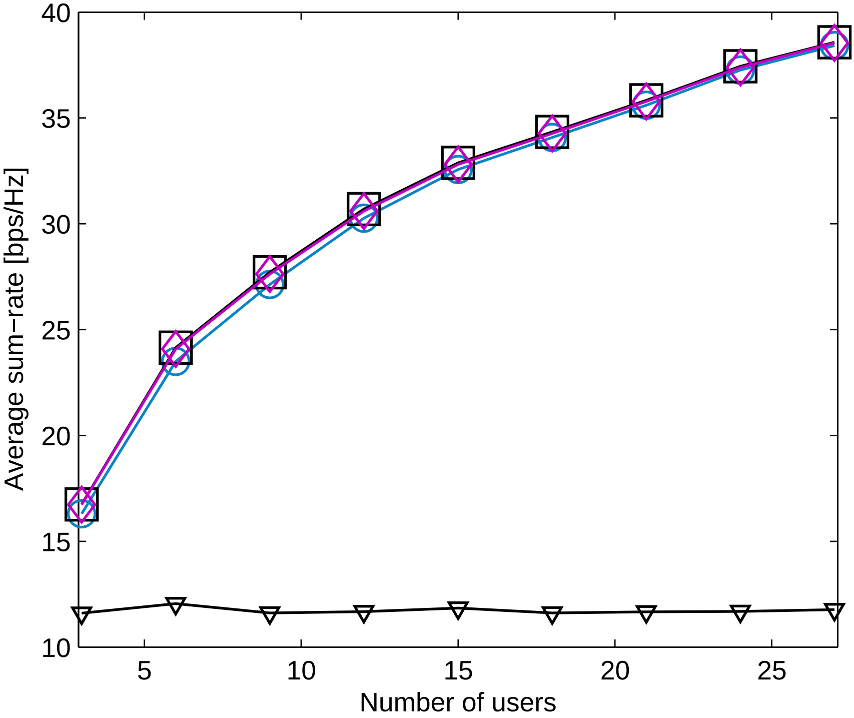

Figure 3.3. The average sum-rate when user groups and scheduling is performed through a full search over all combinations (black squares), by a greedy user grouping and scheduler (purple dimonds) and when the user group is formed through a cellular scheduling (blue circles). The lower line (with triangles) indicate the average sum-rate when users are grouped and scheduled randomly. The multi-user diversity gain is the distance to this line. All scheduling and/or user grouping decisions are here based on a maximum sum-rate criterion. Three single cell base stations with single antennas are here considered. For more details, see Paper II.

4. Robust Linear Precoding

Linear coherent Joint Transmission (JT) has shown potential to provide large gains in spectral efficiency at full load, see e.g. [7, 9, 49]. These gains are especially important for cell edge users [64].

Channel inaccuracies, due to prediction errors and quantization errors, will be present in the precoder design, see Chapter 2. These inaccuracies will cause a loss in CoMP gains [45]. In order to preserve as much of the CoMP gains as possible, the precoder can be designed with statistics of these uncertainties in consideration.

The Robust Linear Precoder (RLP) first introduced in Paper I and further developed in Papers II and III considers the first and second order statics of the channel uncertainties in the design process. It is derived from an automatic control feedforward solution developed in [65].

It is designed to optimize a Mean Squared Error (MSE) criterion that is averaged with respect to the channel uncertainty. In this aspect it is similar to the precoder schemes suggested by [34, 35, 36, 37].

For a basic set-up, were the RLP is designed to minimize the intracluster interference with no regards to the intercluster interference or noise, the solution can be compared to that of the zero-forcing precoder. The difference is that the zero-forcing precoder does not consider the channel uncertainty. In Paper I the RLP is shown to outperform the zero-forcing precoder by 26% in average sum-rate, even for this basic set-up, for the prediction errors induced by 10 km/h mobility and 5.1 ms prediction horizons at 2.66 GHz.

4.1 Design aspects for the robust linear precoder

The proposed robust precoder can be adjusted to optimize a different criterion than to minimize intracluster interference.

Both for multi-user MIMO and for coherent JT CoMP, the channel gains to *different users* may be *very* different. Then, it is important to be able to place different weights on different users, such that the precoder design does not only prioritize the users that have the strongest channels.

In contrast to MIMO transmission, for coherent JT transmission, channels *from different transmit antennas* will also have *very* different channel gains. In the channel inversion this might result in a precoder that requires very large transmit power at some base stations. The precoder must then be rescaled in order to ensure some power constraint, e.g. a per antenna power constraint. Although this does not change the optimal precoder with respect to minimizing the intracluster interference, it does lower the Signal to Noise Ratio (SNR), potentially lowering the Signal to Interference and Noise Ratio (SINR). In other words: minimizing intracluster interference is not in general optimal with respect to the SINR, and will also not be optimal with respect to a (weighted) sum-rate. To balance the solution with respect to the SINR, there needs to be a tool for influencing the transmit powers from different transmit antennas.

For the proposed precoder, the MSE criterion used includes two penalty matrices. These can be used as flexible tools to optimize with respect to an arbitrary criterion. The first of these penalty matrices can be used to place different weights on different users in order to achieve some fairness criterion. The second penalty matrix can be used to place penalties on the transmit powers at different base stations in order to balance the SINR.

4.1.1 Adjusting the base station transmit powers to maximize sum-rate

One particular, commonly used, optimization criterion is an approximation of an unweighted sum-rate criterion. Then, no user weighting is needed. In order to balance the SINR with respect to the sum-rate criterion, different scalar penalties can be placed on the transmit powers of antennas located at different base stations. These scalar parameters can be found by a sequence of one dimensional searches. The detailed procedure on how to do this, including an example, is provided in e.g. Appendix A of Paper III.

This method is suboptimal with respect to a sum-rate criterion. However, in a comparative study in [66] it was shown to perform close to the results obtained by the stochastic optimisation algorithm of [25] for a simple set-up with two users and two base stations. In the same study, it also performed better than the robust precoder suggested by [38].

Main results

In Paper I it is shown that this iterative approach (explained e.g. in Appendix A of Paper III) increases the average sum-rate by 43% compared with zero-forcing, and by 13% compared with the robust linear precoder with the basic set-up, i.e. that which is designed to minimize the intracluster interference.

Results of Paper II show that, when the precoder is iteratively adjusted to optimize the sum-rate then significant CoMP gains can be secured compared to single cell transmission with frequency reuse 1, especially if it is used in combination with the cellular user grouping scheme described in Chapter 3.

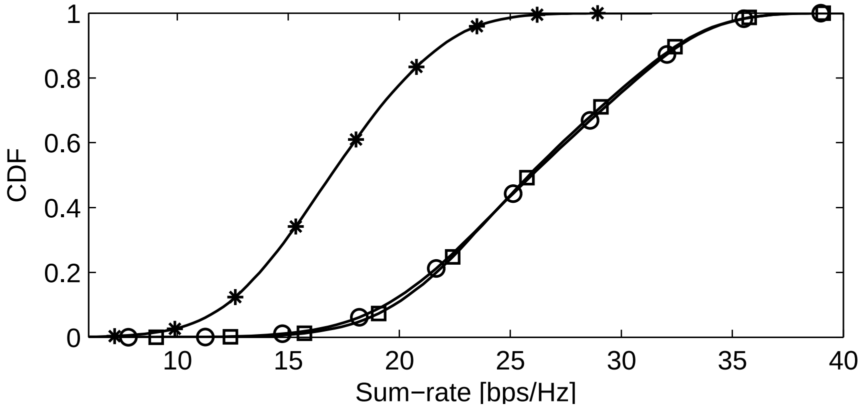

Figure 4.1. The CDF of the sum-rate for single cell transmission (stars) and coherent JT CoMP with a zero-forcing precoder (circles) and the robust linear precoder with optimization with respect to sum-rate (squares). Cellular user grouping through score based scheduling is used. For more details, see Paper II.

Interestingly, in these investigations, with three single antenna base stations, the use of the cellular user grouping scheme enables the zero-forcing precoder to perform equal to the RLP, see Figure 4.1. This is because the proposed user grouping scheme provides better conditioned channel matrices. Then, the inaccuracies of the CSI affect the sum-rate less, and rescaling to attain power constraints becomes less important.

4.2 Precoder design with backhaul constraints

For downlink coherent JT, CSI needs to be fed back from users to their master base stations. These then need to share both the CSI, and the payload data amongst each other over a backhaul network. A Control Unit (CU), which is a logical entity that may be located at one or more of the base stations within the cooperation cluster, then calculates the precoder. Finally, the elements of the precoder are, if necessary, transmitted to the base stations over backhaul, see Figure 4.2.

These large requirements on feedback and backhaul links are one of the large obstacles for the introduction of coherent JT CoMP. Some of the requirements on feedback capacity can be lowered by using cellular user grouping. The full CSI then only needs to be fed back for the

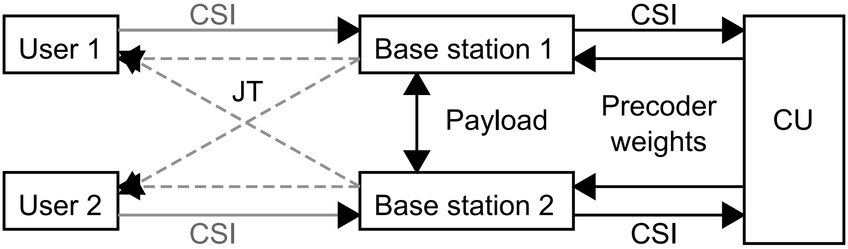

Figure 4.2. A schematic figure of data transmission of feedback over wireless uplinks (gray arrows) and backhaul links (black arrows). Dashed arrows implies coherent joint downlink transmission of the payload data.

users that are allocated to be served, as a lower bit-rate CQI feedback can be used for scheduling, see Chapter 3. This also lowers backhaul requirements as CSI only needs to be transmitted over backhaul for the users that are allocated to be served.

However, the requirements on backhaul are still large and might not always be manageable by the system. Structural constraints, delay constraints, capacity constraints or a combination of these might limit the information that can be transmitted over backhaul. These limitations must be handled by the precoder. This is achieved by setting some elements in the precoder matrix to zero. Such zeros can be forced into the precoder matrix in different ways.

One option to force zeros into the precoder is to simply calculate the precoder, based on some criterion, and then set the required elements to zero, see e.g. [22]. However, the resulting precoder is then no longer optimal with respect to the criterion it was optimized for. Another option is to only feed back the channels that are going to be utilized in the transmission and then group users such that the channel matrix is block diagonal. Then, through channel inversion, the resulting precoder will automatically have zeros in the required elements [23]. However, such a solution requires joint scheduling and may therefore potentially add large demands on backhaul capacity in the user grouping step. Moreover, the suggested methods in [22, 23] do not consider the inaccuracy of the CSI in the precoding design.

A strength of the here proposed precoder is that the MSE criterion can be extended to include the backhaul constraints. This can be done by penalty terms in the robust MSE criterion. This modification only requires a low number of extra calculations and is therefore of much lower complexity than methods that use multi-dimensional searches to optimize the non-zero elements of the precoder, see e.g. [24, 25].

In [67] a different method for forming sparse precoders to fulfil backhaul constraints is suggested. This precoder, which is based on an MSE criterion that includes intracluster interference only, is also low in complexity. However, as the matrix dimensions does not add up in the published design equations of this paper and its simulations are based on very few user positions (25), it is hard to draw any conclusions from the paper. Moreover, this method does not have the flexibility to optimize over arbitrary criteria, nor does it consider CSI errors in the design.

Main results

Results in Paper III show that, under a maximum sum-rate criterion, there is a gain in the average user rate of up to 13% when using the proposed precoder with the extended MSE criterion, compared with inserting zeros as a last step. However, as CoMP is especially important for cell edge users, it is of great interest to limit the effect of backhaul constraint for them. The proposed precoder does exactly that. For example, in a scenario where each user is served by its four strongest base stations, in a cluster with nine base stations, then 13% of the users had a gain of more than 50%. These users, which are plotted in Figure 4.3, are mainly cell edge users.

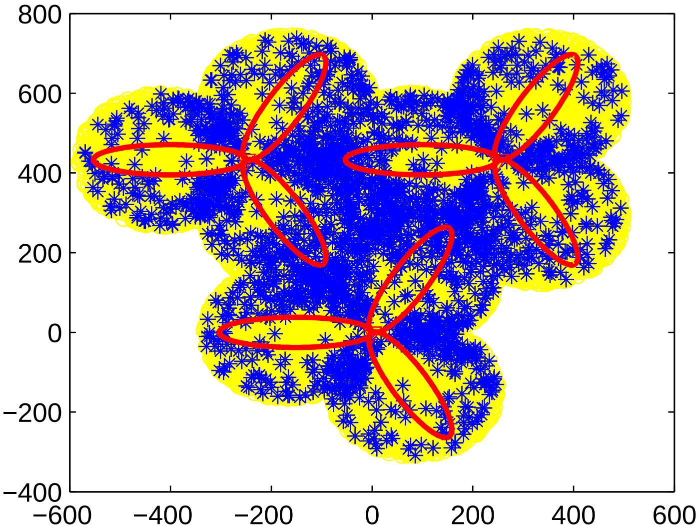

Figure 4.3. The users that benefit by more than 50% from using the precoder design proposed in Paper III, are shown as blue stars. The base station antenna directions are provided by the red ellipses and all other users are marked as yellow circles. For more details, see Paper III.

5. Summary of Papers

This chapter includes short summaries of each of the five contributions included. The author's contributions is commented.

5.1 Paper I: Measurement-based evaluation of robust linear precoding for downlink CoMP

In this paper the Robust Linear Precoder (RLP), discussed in Chapter 4, is first introduced. The Kalman filter is used to provide optimal channel predictions. The precoder is compared with zero-forcing precoding to study the effect of considering the CSI quality in the precoding design. The effect of iteratively maximizing a sum-rate criterion through the process mentioned in Section 4.1.1 is also studied.

Evaluations are based on channel measurements. These are used to simulate received signals with different noise levels. The precoder evaluation is based on predicted CSI provided by Kalman predictors that use Code-Orthogonal Pilots (COP) (referred to as *quasi-orthogonal* Common Reference Symbols (CRS) in the paper).

Results show that the for COP, the prediction performance depend on the Signal to Noise Ratio (SNR) of the received signals and also, on the ratio of the SNR of the pilots transmitted from the weakest base station over the SNR of the total received signal (referred to as Weakest to Total SNR Ratio (WTR) in the paper).

Moreover, results show that the robustness of the RLP, i.e. the fact that it takes the CSI uncertainty into account in the precoder design, provides an increase in sum-rate, as does the introduction of iteratively optimizing with respect to a sum-rate criterion. An interesting result in this paper is that, for many user groups, coherent JT CoMP lowers the sum-rate as compared to single cell transmission with reuse 1. Closer studies indicate that this occurs when users with weak channels to the same base station are grouped on the same resource.

The author has done the majority of the work.

5.2 Paper II: Design and measurement based evaluations of coherent JT CoMP - a study of precoding, user grouping and resource allocation using predicted CSI

This paper investigates if CoMP gains are realistic in real systems. The evaluations are based on measured channels, with Kalman prediction and RLP. The noise levels used in this paper are 10 dB lower than those used in Paper I.

Based on the results of Paper I and Paper V, the Kalman predictions of this paper are based on Resource-Orthogonal Pilots (ROP), which provides a lower prediction error than the use of COP. The Kalman predictions provide CSI that is sufficiently accurate to achieve significant CoMP high gains, even for long temporal prediction horizons (of 24 ms) at pedestrian velocities and at 2.66 GHz. For shorter prediction horizons (of 5 ms) and at 500 MHz, they even provide good CSI at vehicular velocities.

As the results of Paper I show that user grouping is important for CoMP gains (compared with single cell transmission) this paper investigates different user grouping strategies. In particular, a strategy based on local scheduling, over the different resources, is suggested. It is both compared with the optimal user groups, found through a very high dimensional search of all possible combinations, and with a greedy user grouping scheme suggested in literature. The here proposed user grouping scheme performs, in terms of sum-rate, close to the optimal scheme and to the greedy scheme, at a much lower complexity.

Interestingly, the results also shows that, for a small CoMP cluster (including three single antenna base stations) when users are grouped through the suggested user grouping scheme, then the zero-forcing precoder achieves similar CoMP gains as the RLP.

The author has done the majority of the work.

5.3 Paper III: Robust linear precoder for coordinated multipoint joint transmission under limited backhaul with imperfect CSI

In this paper the RLP of Papers I and II is extended to handle constraints on backhaul capacity. The aim is to ensure that the losses in CoMP gains, due to less backhaul capacity, are decreased by avoiding to design the precoder under the faulty assumptions that all channels can be used. The suggested solution is to include the backhaul constraints in the minimization criterion, via penalty terms.

Results show that if the backhaul constraints are handled as suggested, then the loss in CoMP gains is lower than if the constraints on backhaul capacity are not considered in the precoding design. The difference in loss is especially high for cell edge users, which are the users that need CoMP most and therefore have the most to loose from backhaul constraints.

The author has done the majority of the work.

5.4 Paper IV:Analysis and measurement of multiple antenna systems for fading channel prediction in moving relays

This paper focuses on how to predict channels for long system delays and/or high user mobility. Under these assumptions the spatial prediction horizon is long compared to the carrier wavelength and conventional predictions, based on the fading statistic of the environment, will fail.

The scheme presented here is based on the novel concept of placing an extra antenna in front of one or more primary receive antennas in the direction of travel on the to of a vehicle, suggested in [42]. This "predictor" antenna will then estimate the fading channel. When the receive antennas arrive to that same position, they will have similar channels. The channel estimate of the "predictor" antenna can then be used as channel predictions for the receive antennas. In order to increase performance, the effects of antenna coupling is removed in this paper.

The concept is evaluated based on channel measurements by two receive antennas mounted on a car roof in an urban environment. To increase performance, compared with that reported in [42], the impact of the close scatterers, on the roof of the measurement vehicle, is minimized by first mounting the antennas on a large metal sheet.

Results indicate that this concept can provide acceptable CSI at spatial prediction horizons of several wavelengths.

The author has had a central role in the planing and conducting of the measurements, and in the correlation results prior to the antenna coupling compensation.

5.5 Paper V: Kalman predictions for multipoint channels

This technical report provides a detailed description on how to use the Kalman filter for predicting small scale fading of channels. It extends the framework of the Ph.D. thesis [52] by Daniel Aronsson to include channels from multiple base station sites.

Design choices, such as where to locate the filters, how to estimate the channel models and which pilot pattern to use, are discussed.

The report also includes results on the predictability of small scale fading models. It illustrates how the predictability of a channel is fundamentally limited by the fading statistics, represented by the Doppler spectrum.

The measurement based prediction results of Paper II and of [66] are highlighted and studied in detail. Some additional NMSE prediction statistics results that where not included in Paper II are included in this report to highlight different aspects of the prediction performance. Based on these performance results, system design issues, such as pilot patterns, intercluster interference and system delays, are discussed in the conclusion section.

The report also includes an appendix on how to generate block-fading channel models that have (instantaneous) error statistics that correspond to the one obtained in a given physical setting when Kalman predictors are applied. This method is used in [12].

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