BASE STATION COOPERATION IN MULTIPLE INPUT MULTIPLE OUTPUT ORTHOGONAL FREQUENCY DIVISION MULTIPLE ACCESS SYSTEMS

A THESIS

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MASTER OF SCIENCE

By

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August 2009

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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M.S. in Electrical and Electronics Engineering
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August 2009

Newly emerging advancements such as multiple input multiple output (MIMO) and orthogonal frequency division multiple access (OFDMA) techniques become indispensable parts of today's wireless systems such as WiMAX (IEEE 802.16 standard) since they can increase the supportable data rates significantly. However, achieving the maximum spectral efficiency in a MIMO system requires perfect channel state information (CSI) at the transmitter side and multicarrier nature of OFDMA systems increase the necessary CSI feedback from users to base stations remarkably. To further increase the supportable data rates, using frequency reuse factor of 1 in the system is also mandatory. Unfortunately, this results in significant cochannel interference (CCI) observed especially by the users near cell edges, which can severely degrade the system spectral efficiency. To cope with this problem, base station cooperation may play an important role. In this thesis, the problem of cooperative data transmission from base stations to users in multicellular MIMO-OFDMA systems is considered. An efficient cooperative scheduling and data transmission scheme, requiring limited CSI feedback from users to base stations and also limited information exchange between the base stations, is proposed. The numerical results demonstrate that, the proposed algorithm offers considerable spectral efficiency gains compared to conventional frequency reuse and noncooperative schemes, under severe CCI conditions.

Keywords: Base Station Cooperation, Multiple Input Multiple Output (MIMO), Orthogonal Frequency Division Multiple Access (OFDMA), Limited Channel State Information (CSI) Feedback.

ÖZET

ÇOK GİRDİLİ ÇOK ÇIKTILI DİKGEN FREKANS BÖLMELİ ÇOKLU ERİŞİM SİSTEMLERİNDE TELSİZ ERİŞİM TERMİNALLERİNİN İŞBİRLİĞİ

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Yeni gelişen çok girdili çok çıktılı (MIMO) dikgen frekans bölmeli çoklu erişim (OFDMA) teknikleri desteklenebilir veri hızlarını önemli ölçüde arttırmaları nedeniyle WiMAX (IEEE802.16 standardı) gibi günümüz kablosuz iletişim teknolojilerinin vazgeçilmez bir parçası olmuşlardır. Ancak, çok girdili çok çıktılı sistemlerden tam verim alınabilmesi için vericilerde tam bir kanal durum bilgisi gerekmektedir. Bu ise, dikgen frekans bölmeli çoklu erişim sistemleri gibi çok taşıyıcılı sistemlerde kullanıcılardan telsiz erişim terminallerine önemli ölçüde bir kanal bilgisi geribeslemesi gerektirmektedir. Kullanıcı veri hızlarını daha fazla arttırabilmek için bu sistemlerde frekans yeniden kullanım faktörünün 1 olmasına da ihtiyaç vardır, fakat bu özellikle hücre sınırlarındaki kullanıcıların önemli ölçüde ortak kanal girişimine (CCI) maruz kalmalarına ve sistem spektral verimliliğinin düşmesine neden olur. Telsiz erişim terminalleri işbirliği hücreler arası girişimin azaltılmasında önemli bir rol oynabilmektedir. Bu tezde çok hücreli çok girdili çok çıktılı, dikgen frekans bölmeli çoklu erişim sistemlerinde, telsiz erişim terminallerinden kullanıcılara işbirlikli veri iletimi ve çizelgeleme yapılan, kullanıcılardan telsiz erişim terminallerine sınırlı kanal bilgisi geribeslemesi ve aynı zamanda telsiz erişim terminalleri arasında sınırlı veri paylaşımı gerektiren bir algoritma önerilmiştir. Sayısal sonuçlar bu algoritmanın, ciddi ortak kanal girişimi koşullarında, geleneksel frekans tekrar kullanım ve işbirliksiz yöntemlerden daha iyi bir başarım sağladığını göstermiştir.

Anahtar Kelimeler: Telsiz Erişim Terminallerinin İşbirliği, Çok Girdili Çok Çıktılı Sistemler, Dikgen Frekans Bölmeli Çoklu Erişim, Sınırlı Kanal Durum Bilgisi Geribeslemesi

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List of Abbreviations

BS	Base Station
cCDF	Complementary Cumulative Distribution Function
CCI	Cochannel Interference
CSI	Channel State Information
FFT	Fast Fourier Transform
ICI	Intercarrier Interference
ISI	Interstream Interference
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MSR	Maximum Sum Rate
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PFS	Proportionally Fair Scheduling
QoS	Quality of Service
SINR	Signal to Interference plus Noise Ratio
SVD	Singular Value Decomposition
WiMAX	Worldwide Interoperability for Microwave Access

Dedicated to my family who never ceases to support me in my life . . .

Chapter 1

Introduction

Wireless communication systems, such as cellular telephone or wireless networks have become very popular in recent years. With increasing demand, the amount of research about these subjects has increased as well and new technologies are developed. However, these developments have also increased the complexity of communication systems significantly. Hence, to design a communication system which has high spectral efficiency to satisfy the data rate demands and at the same time which is practical enough to implement, has become an important and attractive area of research.

1.1 Motivation

The research presented in this thesis, is intended as a proposal for the emerging IEEE 802.16*m* standard [1]. Worldwide Interoperability for Microwave Access (WiMAX) is a broadband wireless metropolitan area network with large coverage area both for fixed and mobile stations. It targets high spectral efficiencies at long ranges.

In order to satisfy these requirements most of the newly emerging advancements must be used in a WiMAX network. Hence, multiple input multiple output (MIMO), orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA) techniques are accepted as its essential parts, since they can increase the system spectral efficiency significantly. However, even in single cell multiuser scenarios, these techniques increase the system complexity remarkably. To fully exploit the advantage of MIMO channels, perfect channel state information (CSI) is needed at the transmitter, which increases the necessary feedback from users to base stations (BS) drastically, especially for a multicarrier system like OFDMA. Hence, our first aim is to develop a simple and practical transmission and scheduling scheme for MIMO-OFDMA systems.

In realistic multicellular scenarios, cochannel interference (CCI), caused by the usage of same frequency band in adjacent cells, becomes an important performance degrading factor. In conventional cellular networks, frequency reuse scheme is used to mitigate CCI. It is a simple method where by using frequency planning, the available frequency band is divided between cells such that the distance between cells using same frequency band is increased to reduce interference power. However, this method is known to be spectrally inefficient, since the whole frequency band cannot be utilized in a given cell. Because of the high data rate targets of WiMAX, usage of frequency reuse factor of 1 is required, which indicates that the whole available frequency band is used in all cells. Hence, our second aim is to develop an algorithm to mitigate the CCI without increasing the complexity and feedback load significantly.

1.2 Related Work

In this section, firstly, studies in the literature on the problem of resource allocation in OFDMA systems with or without MIMO transmission in single or multicellular scenarios will be discussed, then the current state of art about cooperative systems will be given.

CSI at the transmitter can provide significant gains in the spectral efficiency of wireless systems. It is especially important in OFDMA systems to exploit frequency and multiuser diversities. Although it is assumed that users can estimate the downlink channel, this information must be fed back to BSs in the uplink phase. In the literature, there are several works on radio resource allocation and scheduling under perfect CSI assumption at the transmitter for OFDMA systems. [2] considers adaptive multiuser subcarrier, bit and power allocation, which is shown to outperform conventional multiple access schemes such as frequency division or time division multiple access in a single cell environment. [3] considers a subcarrier allocation scheme with adaptive modulation and coding and subcarrier reuse in multicellular systems. However, full CSI assumption at the transmitter side, due to its multicarrier nature, becomes impractical to implement in OFDMA systems. Hence, some suboptimum transmission techniques requiring limited feedback are being researched [4], where the resource allocation is done with only statistical information, instead of perfect channel knowledge at BSs.

All aforementioned works consider only single antenna systems, but MIMO systems require even more CSI feedback for full efficiency. One of the attractive methods for multiantenna transmission with limited channel knowledge at the transmitter is random transmit beamforming. In the literature, this idea is first seen in [5]. For systems with multiple antennas at the transmitter side, by using pseudorandom transmit beamformer vectors, rate and dynamic range of fading can be increased to exploit multiuser diversity with opportunistic scheduling. In this way remarkable performance gains can be achieved with limited channel knowledge at the transmitter side. This article is also important for its contributions about proportionally fair scheduling (PFS), which is an important fair scheduling algorithm.

The random beamforming method is adapted to MIMO systems in [6] where random unitary transmit beamformer matrices, instead of vectors, are used at the transmitter to exploit spatial multiplexing gain. In [7] it is generalized to single cell MIMO-OFDMA systems. A remarkable proposal is the best random beamforming idea, where users try different random beamformers from a given codebook, find the optimum one and feed back its index together with the achievable data rate. In [8], layered random beamforming for MIMO-OFDMA systems is considered, where different users can be multiplexed on the spatial layers of the same MIMO channel. Finally, [9] is another interesting study which considers time domain random beamforming where only one transmit beamformer is used for all subchannels and can therefore reduce the feedback cost for best random beamforming. However, Vertical Bell Laboratories Layered Space Time (VBLAST) detection algorithm should be used at the receivers, which in turn increases the complexity.

The most important performance degrading factor in multicellular networks is the CCI, which can cause dramatic reductions in supportable data rates, especially for the users at cell edges. In traditional cellular systems, frequency reuse scheme with a frequency reuse factor other than 1 is used to mitigate CCI. Hence, neighboring cells use different frequency bands, which results in a loss in spectral efficiency. In [10], different frequency reuse patterns are compared in terms of throughput and outage probability for a WiMAX network. A noncooperative method offered to mitigate CCI is to use adaptive frequency reuse [11,12]. In this method, cell area is divided into two regions. At the inner region where the CCI level is low, subchannels are used systemwide by all BSs, while in the outer cell region where the CCI level is high, subchannels are orthogonally shared among BSs. In [13], this division is done adaptively based on signal power feedback from users to BSs for a WiMAX network.

Relays are simple structures, which are traditionally used to increase coverage in wireless networks. They are simpler and less costly than BSs. However, the links between BSs and relays are generally wireless and less reliable. Since they can be mobile, wireless networks can extend to areas where BSs and wired infrastructure cannot be built. They can easily be used in emergency situations. In [14], it is explained how relays can be used to increase coverage area in IEEE 802.16j based mobile WiMAX systems. In the recent years, relaying also appeared as a possible cooperative transmission technique in the literature. In [15], two uses of relays especially in multihop sensor networks is explained. Firstly, the concept of a mobile broadband system based on fixed relay stations and secondly cooperative usage to form antenna array to exploit spatial diversity. BSs and relays can also make cooperative transmissions to form "virtual" MIMO channels as explained in [16, 17].

BS cooperation is an another attractive proposal both to increase the coverage area and to mitigate CCI. It can use existing infrastructure, since BSs are already connected to each other with high speed wired links, which have higher capacity and reliability. This eases information sharing and cooperative data transmission. A practical advantage is that handover procedure becomes easier, since users are already communicating with all BSs. Although BSs have higher processing power, they are not mobile and costly to build and operate. In [18], there is a cooperative scheme where BSs sometimes act as a relay to achieve frequency reuse factor of 1. In [19, 20], BSs act as distributive antenna systems to make collaborative MIMO transmissions. However, all these works on BS cooperation assume full CSI at BSs, which becomes even more impractical for MIMO-OFDMA systems.

1.3 Contributions of This Thesis

To the best of our knowledge, there is no study in the literature on practical resource allocation and scheduling scheme for multicellular MIMO-OFDMA systems. Also, the algorithms proposing cooperation to mitigate CCI, assumes full CSI at BSs, which is not practical when combined with a multicarrier system like OFDMA. In this thesis, a cooperative transmission and scheduling scheme for multicellular MIMO-OFDMA systems is proposed. The important properties of this algorithm are as follows:

- It is of low complexity at both transmit and receive ends.
- It requires limited CSI feedback from users to BSs.
- It requires limited information exchange between BSs.
- It outperforms noncooperative transmission schemes such as conventional frequency reuse in terms of spectral efficiency.
- It maintains systemwide fairness effectively under severe CCI conditions.
- It offers modifications for feedback/complexity versus spectral efficiency tradeoffs.

1.4 Thesis Organization

The rest of the thesis is organized as follows. In Chapter 2, some background information on the properties of MIMO channels, OFDM, OFDMA and CCI is offered, which will be necessary in the development of the system model and the proposed algorithm. Furthermore, the multicellular signal and cellular models are presented.

In Chapter 3, the cooperative transmission and scheduling algorithm is explained in detail, i.e., how transmitter and receiver beamformers are chosen; CCI is mitigated; a suboptimum power allocation strategy without full CSI is implemented; complexity, feedback and fairness issues are handled by increasing spectral efficiency.

In Chapter 4, the proposed algorithm is compared with the existing transmission methods using numerical simulations under different channel and system conditions. Also, how modifications of the algorithm affect the feedback/complexity versus spectral efficiency tradeoffs are studied.

In Chapter 5, the thesis is concluded with a summary of results and the future research areas are discussed.

1.5 Notation

Upper case bold letters, $\mathbf{A}$, are used to denote matrices. Lower case bold letters, $\mathbf{a}$, are used to denote column vectors. A_{ij} is the element of matrix $\mathbf{A}$ on ith row and jth column. a_i denotes the ith element of column vector $\mathbf{a}$. E[.] is the statistical expectation operator. $|.|$ indicates the absolute value. $(\cdot)^T$, $(\cdot)^H$ and $(\cdot)^{-1}$ are the transpose, Hermitian transpose and inverse matrix operators respectively. $\mathbf{I}_N$ is $N \times N$ identity matrix. $\text{mod}(a, b)$ denotes modulo of a in base b. $\max\limits_i$ ($\min\limits_i$) is the maximum (minimum) operator taken over all possible i. $P(X > x)$ is the probability that given random variable X is greater than x.

Chapter 2

Background

2.1 Multiple Input Multiple Output Systems

MIMO systems have multiple antennas at both transmitters and receivers to exploit spatial diversity and spatial multiplexing. They have become indispensable parts of today's wireless communication systems, since they can provide significant diversity gains to reduce the error rate or multiplexing gains to increase the data rate, without increasing the necessary bandwidth of transmission.

The system considered is a multiuser MIMO system, which can be modeled as a MIMO broadcast channel, where multiple users can be served on a MIMO channel. However, WiMAX is based on orthogonal transmission, where in each cell only one user can be scheduled on a subcarrier. Hence, the results of optimum MIMO broadcast transmission cannot be used here. Due to orthogonality of subcarriers in OFDMA, the MIMO channels on each subcarrier can be modeled as a single user MIMO channel. In addition, the analysis here is information theoretic, without any assumption on the modulation, coding or capacity achieving strategy. The MIMO channel is used for spatial multiplexing, where multiple data steams are transmitted to increase the data rate.

Even single link MIMO systems have intrinsic interference due to the broadcast nature of wireless channels, since the signals received at the receiver antennas are sum of signals transmitted from different transmit antennas. In order to fully exploit the advantage of MIMO channels, this interference should be mitigated. This process needs complex signal processing methods. The open loop method

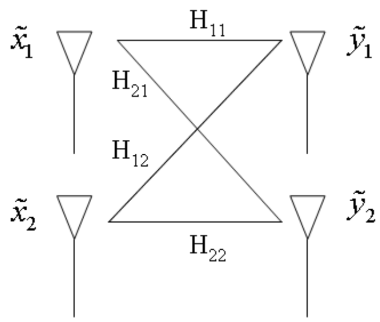


Figure 2.1: 2 x 2 MIMO channel.

uses successive interference cancelation without requiring any CSI at the transmitter, which shifts the burden of mitigating the interference to receiver side. Alternatively, interference mitigation can be done in a closed loop fashion requiring CSI at both transmitter and receiver, as it will be explained later in this section. This time the task of interference mitigation is mainly done by transmitter.

Let us now consider a simple 2×2 single user MIMO link with two antennas both at the transmitter and the receiver, where the channel is modeled as frequency flat, time-invariant channel. We would like to simultaneously transmit two independent data streams, where the information symbols in each data stream are linearly mapped to transmitted symbols, using beamformer matrices.

Denoting $\mathbf{x}$ as the information vector, where ith row corresponds to the ith stream, lets first consider an identity mapping where the 2×2 transmitted data vector, $\tilde{\mathbf{x}}$, is expressed as $\tilde{\mathbf{x}} = \mathbf{x}$, i.e., each antenna transmits one data stream. The received signal is modeled as,

$$\tilde{\mathbf{y}} = \mathbf{H}\tilde{\mathbf{x}} + \mathbf{n}. \tag{2.1}$$

where $\tilde{\mathbf{y}}$ and $\mathbf{n}$ are the 2×1 received data vector and the noise vector respectively. $\mathbf{H}$ is the 2×2 channel matrix. This signal model depicted in Figure 2.1, can be expressed as,

$$y_1 = H_{11}x_1 + H_{12}x_2 + n_1, \tag{2.2}$$

$$y_2 = H_{21}x_1 + H_{22}x_2 + n_2. \tag{2.3}$$

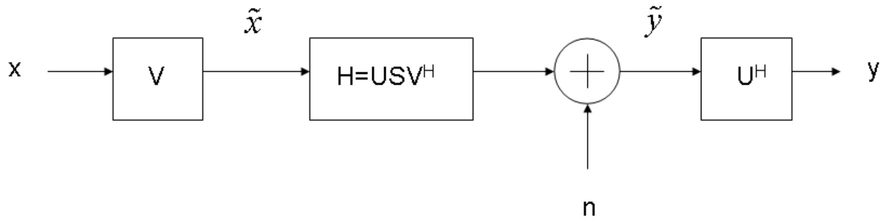


Figure 2.2: Diagonalization of 2 x 2 MIMO channel.

Definition 1. *Interstream interference (ISI) is the interference between the transmitted data streams.*

If we consider a simple receiver structure, without a receive beamformer, i.e., $\mathbf{y} = \tilde{\mathbf{y}}$, where y_i is used to detect x_i, the received signal to noise plus interference ratio (SINR) for each data stream is written as,

$$\gamma_1 = \frac{|H_{11}|^2 E[|x_1|^2]}{|H_{12}|^2 E[|x_2|^2] + E[|n_1|]^2}, \tag{2.4}$$

$$\gamma_2 = \frac{|H_{22}|^2 E[|x_2|^2]}{|H_{21}|^2 E[|x_1|^2] + E[|n_2|]^2}. \tag{2.5}$$

In this expression it is easy to see that the cross terms H_{ij} for $i \neq j$ cause the interstream interference which reduces the performance. If the channel matrix can be diagonalized, the effectiveness of MIMO channels will increase significantly. The method used to achieve this is to employ singular value decomposition (SVD) of the channel matrix by using linear processing (beamforming) at both the transmitter and the receiver, as depicted in Figure 2.2.

1. SVD of the channel matrix is found as

$$\mathbf{H} = \mathbf{U}\mathbf{S}\mathbf{V}^{\mathbf{H}}, \tag{2.6}$$

   where $\mathbf{U}$ and $\mathbf{V}^{\mathbf{H}}$ are unitary matrices and $\mathbf{S}$ is diagonal matrix composed of singular values of $\mathbf{H}$.

2. Firstly, $\mathbf{V}$ is used as transmit beamformer matrix, i.e., $\tilde{\mathbf{x}} = \mathbf{V}\mathbf{x}$ and the received signal $\tilde{\mathbf{y}}$ becomes,

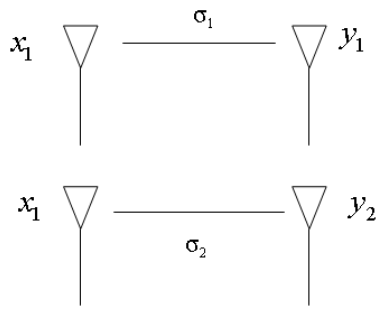


Figure 2.3: Diagonalized 2 x 2 MIMO channel.

$$\tilde{\mathbf{y}} = \mathbf{HVx} + \mathbf{n}. \tag{2.7}$$

3. At the receiver this signal is post processed with receiver beamformer matrix, $\mathbf{U}^H$, to achieve received data vector $\mathbf{y} = \mathbf{U}^H\tilde{\mathbf{y}}$. If we use SVD of channel matrix (2.6), $\mathbf{y}$ can be written as,

$$\mathbf{y} = \mathbf{U^H USV^H Vx} + \mathbf{U^H n}. \tag{2.8}$$

4. Note that $\mathbf{U}$ and $\mathbf{V}$ unitary matrices, $\mathbf{U^H U} = \mathbf{I}$, $\mathbf{V^H V} = \mathbf{I}$ and the covariance of noise vector is invariant to unitary transformation. With these observations, the decision vector can be written as,

$$\mathbf{y} = \mathbf{Sx} + \tilde{\mathbf{n}}. \tag{2.9}$$

5. If the diagonal elements of $\mathbf{S}$ are denoted by σ_1 and σ_2, the diagonalized channel model depicted in Figure 2.3, is expressed as,

$$y_1 = \sigma_1 x_1 + \tilde{n}_1, \tag{2.10}$$

$$y_2 = \sigma_2 x_2 + \tilde{n}_2. \tag{2.11}$$

6. As it can be seen from received SINRs in (2.12) and (2.13), the ISI is completely mitigated and y_i is the sufficient statistic to decode x_i. This beamforming configuration is also called eigen-beamforming configuration.

$$\gamma_1 = \frac{|\sigma_1|^2 E[|x_1|^2]}{E[|n_1|]^2}, \tag{2.12}$$

$$\gamma_2 = \frac{|\sigma_2|^2 E[|x_2|^2]}{E[|n_2|]^2}. \tag{2.13}$$

If waterfilling is used to distribute the transmit power effectively to utilize the singular values of the decomposed channel, the performance can be further increased. In fact [21] showed that Figure 2.2 represents the capacity achieving scheme when channel is known at both the transmitter and the receiver.

2.2 Orthogonal Frequency Division Multiplexing

One of the important problems of wireless systems is the intersymbol interference due to multipath, which occurs because of delayed versions of the same transmitted signal arriving at the receiver. This can cause significant performance degradation when channel delay spread is greater than symbol duration, which is the case in frequency selective broadband channels.

OFDM is a multicarrier modulation scheme easily implemented by fast fourier transform (FFT) algorithm to cope with this problem. In OFDM the frequency selective broadband channel of bandwidth B is divided into narrowband subchannels of bandwidth B_s as shown in Figure 2.4. Hence, the bandwidth of each subchannel becomes smaller than coherence bandwidth B_c and can be assumed as an approximately flat fading channel.

In addition, by using cyclic prefixes larger than channel delay spread, intersymbol interference due to multipath can be completely mitigated. In cyclic prefix method, basically a fixed length of time samples from the end of input time domain signal is added to the beginning. After this operation the linear convolution between the channel and input becomes a circular convolution. After FFT operation, the frequency equalization at the receiver becomes a division operation [22], which is very practical to implement.

In OFDM, subcarrier spacing is chosen such that all subcarriers become orthogonal as illustrated in Figure 2.5, where the frequency spectrum of OFDM

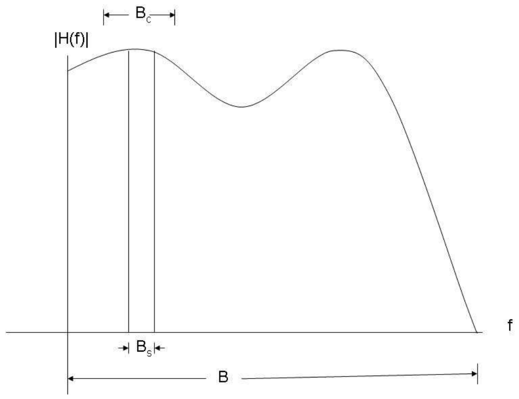


Figure 2.4: Division of frequency selective broadband channel into frequency flat narrowband subchannels.

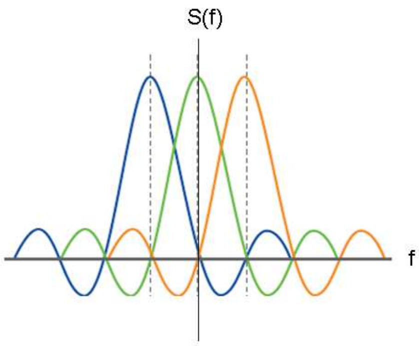


Figure 2.5: Orthogonal structure of subcarriers.

subcarriers are plotted. Under perfect frequency synchronization, this orthogonal structure will be preserved. In addition, the channel should be slowly fading or approximately constant during an OFDM symbol, which is generally valid for low mobility scenarios with insignificant Doppler spread, where it can be safely assumed that intercarrier interference (ICI) is negligible. Otherwise, ICI mitigation methods should be used to maintain the orthogonal structure.

For an OFDM symbol, the number of subcarriers is equal to FFT size, N, and due to orthogonality, each subcarrier can be analyzed as an independent MIMO channel and independent data symbols are transmitted over each subcarrier.

After the inverse fast fourier transform operation, the sampled transmitted time domain signal vector $\mathbf{s}_a$ of an OFDM symbol can be written as,

$$\mathbf{s}_a = \frac{1}{\sqrt{N}} \sum_{l=1}^{N} x^l e^{\frac{2j\pi(l-1)a}{N}}, \tag{2.14}$$

where a is time sample index, l is the subcarrier index and x^l is data symbol transmitted on subcarrier l.

2.3 Orthogonal Frequency Division Multiple Access

OFDMA is a multiple access scheme, which uses OFDM as the modulation scheme, where users can be scheduled in time (OFDM symbol) and/or frequency (subcarrier/subchannel) dimensions. When combined with opportunistic scheduling, which aims to maximize system spectral efficiency by giving the system resources to users with highest achievable data rate, OFDMA can provide significant frequency, time and multiuser diversity gains. Unfortunately, multicarrier nature of OFDMA increases the complexity of optimum resource allocation and scheduling.

In WiMAX, subcarriers are grouped into subchannels. The smallest scheduling unit is called a slot which is formed in time and frequency dimensions. These slots form a frame structure as shown in Figure 2.6.[1] Basically, a frame is divided into downlink and uplink phases, where users can transmit or receive data. The scheduling mapping is broadcasted, feedback or other media access control (MAC) layer messages are exchanged.

The slots are assigned to users using specific scheduling algorithms, which are based on MAC layer requirements, such as quality of service (QoS), delay, service type and bandwidth requests of users [23]. However, in this thesis only resource allocation based on system or user spectral efficiency is investigated. The scheduling algorithms either aim to maximize system spectral efficiency or maintain fairness between users, or both [22]. These algorithms will be explained in detail in Chapter 3.

[1] Image is taken from [22].

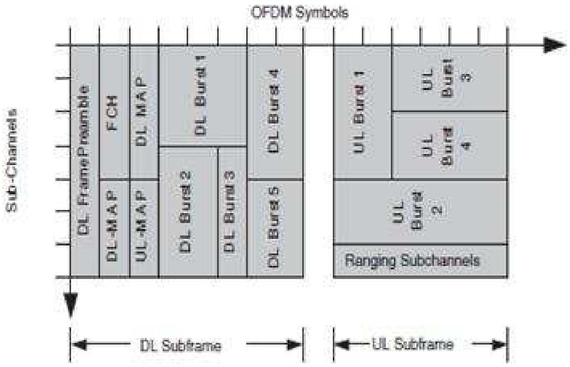


Figure 2.6: Downlink and uplink frame structure of WiMAX.

2.4 Cochannel Interference and Frequency Reuse

Definition 2. *Cochannel interference (CCI) is the interference due to the use of the same frequency channels for different users in the downlink phase.*

For the OFDMA case, CCI occurs when different BSs schedule different users on the same subcarriers in the downlink phase. If this problem is not handled properly, it can cause a significant performance loss in multicarrier systems.

It should be noted that, because of path loss, CCI is generally assumed to be significant only in adjacent sectors.

Definition 3. *Frequency reuse factor is the inverse of the ratio of frequency channels allocated to a cell/sector/BS to the total available frequency channels in the system.*

The conventional method of mitigating CCI is frequency reuse, where frequency reuse factor greater than 1 is used, as illustrated in Figure 2.7. In the OFDMA case, the available subcarriers are shared by BSs in an orthogonal fashion. Since, all available subcarriers cannot be used by all BSs at the same time, this method is known to be spectrally inefficient. In Chapter 3, a more efficient method to mitigate CCI for a system with frequency reuse factor of 1 will be presented.

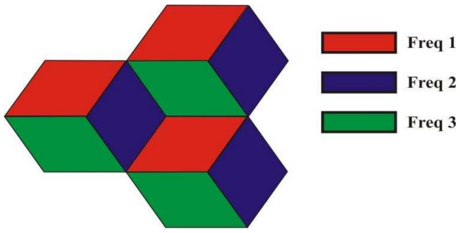


Figure 2.7: Cellular model with frequency reuse factor of 3.

2.5 Multicellular System Model

2.5.1 Signal Model

The system to be considered is the downlink of a multicellular MIMO-OFDMA network. There are a total of K users, each with N_r receive antennas, and B base stations, each with N_t transmit antennas. The OFDMA system has a total of N subcarriers where L of them are used for data transmission. It is assumed that orthogonal OFDMA structure is preserved within a cell, i.e., only one user is scheduled on each subcarrier in a cell and it is assumed that there is no ICI between the subcarriers. For simplicity, the index for OFDM symbols is omitted.

Let k_b^l be the index of the user scheduled by BS b on subcarrier l. It is assumed that each scheduled user has Q independent data streams to be transmitted on a subcarrier. Q is generally chosen as $\min(N_r, N_t)$ due to information theoretic limits on spatial multiplexing. The elements of the $Q \times 1$ data vector $\mathbf{x}_{k_b^l}^l$, which is destined from BS b to user k_b^l on subcarrier l, are modeled as independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian (c.s.c.g.) random variables with zero mean and unit variance.

At the BSs this data vector is firstly multiplied by a $Q \times Q$ diagonal power allocation matrix $\mathbf{P}_b^l$, whose elements, $\sqrt{P_{b,q}^l}$, denote the power allocated to sub-stream q on subcarrier l by BS b. $P_{b,q}^l$'s are subject to the power constraint,

$$\sum_{b=1}^{B}\sum_{l=1}^{L}\sum_{q=1}^{Q} P_{b,q}^l = P_T, \tag{2.15}$$

where P_T is the total transmission power of the system. The power-allocated data vector is then multiplied by a $N_t \times Q$ transmit beamformer matrix $\mathbf{F}_b^l$, which is used on subcarrier l by BS b. Hence, the signal vector sent from BS b becomes $\tilde{\mathbf{x}}_b^l = \mathbf{F}_b^l \mathbf{P}_b^l \mathbf{x}_{k_b^l}^l$.

If we assume that the signals from the BSs arrive at user k synchronously, the signal received by user k is the sum of signals received from all BSs. After FFT operation and cyclic prefix removal, the received signal vector by user k on subcarrier l can be written as,

$$\tilde{\mathbf{y}}_k^l = \sum_{b=1}^{B} \mathbf{H}_{k,b}^l \tilde{\mathbf{x}}_b^l + \mathbf{n}_k^l, \tag{2.16}$$

where $\mathbf{n}_k^l$ is the $N_r \times 1$ noise vector whose elements are modeled as i.i.d. zero mean c.s.c.g. random variables with variance σ_n^2 and $\mathbf{H}_{k,b}^l$ is the $N_r \times N_t$ channel matrix between user k and BS b, whose elements are modeled as i.i.d. zero mean c.s.c.g. random variables with zero mean and variance $10^{0.1X}/(d_{k,b})^n$. Here,

1. $d_{k,b}$ is the distance between BS b and user k; n is the path loss exponent, used for modeling path loss. We choose this path loss model for simplicity. One can use more complicated path loss models such as the two-way model, Hata model etc. [24]

2. X is a zero mean Gaussian random variable with standard deviation σ_s, used for modeling lognormal shadowing.

In order to have a simple receiver structure, it is assumed that users do not cooperate with each other and do not use complex signal processing methods to mitigate CCI and ISI, and treat these two sources of interference as additional Gaussian noise. To achieve this, user k postprocesses the received signal vector on subcarrier l by a $Q \times N_r$ receiver beamformer matrix, $\mathbf{G}_k^l$, to form $Q \times 1$ vector $\mathbf{y}_k^l = \mathbf{G}_k^l \tilde{\mathbf{y}}_k^l$, which is formulated in (2.17). Afterwards, each element of the data vector $\mathbf{x}_k^l$ can be detected individually using the corresponding element of $\mathbf{y}_k^l$. The whole system model is depicted in Figure 2.8.

$$\mathbf{y}_k^l = \mathbf{G}_k^l \sum_{b=1}^{B} \mathbf{H}_{k,b}^l \mathbf{F}_b^l \mathbf{P}_b^l \mathbf{x}_{k_b^l}^l + \mathbf{G}_k^l \mathbf{n}_k^l. \tag{2.17}$$

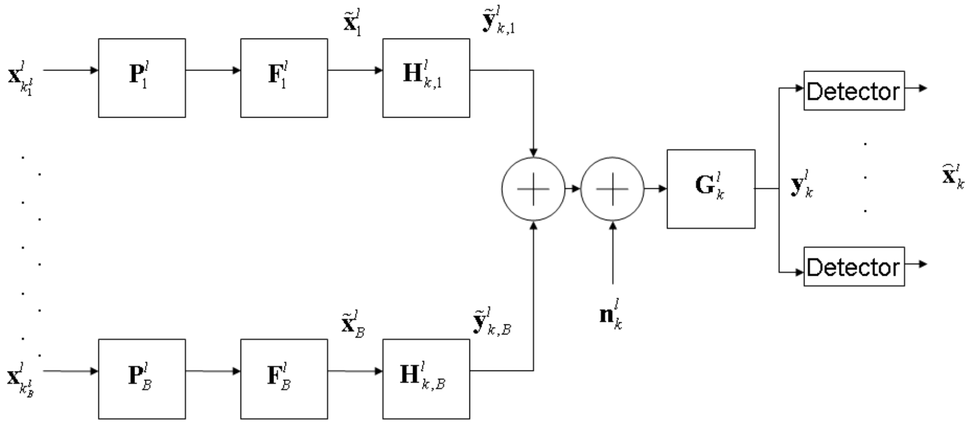


Figure 2.8: System model.

2.5.2 Cellular Model

The system to be considered assumes hexagonal cellular structure with radius r and uses frequency reuse factor of 1. It is assumed that, all BSs use directional antennas and each cell is separated into three 120 degree sectors. CCI is assumed to be limited to the area generated by the intersection of these sectors of three neighboring cells, where BSs can make transmissions as a collaborative MIMO system. It is assumed that users are uniformly distributed in this area and evenly distributed in the sectors of three cells as shown in Figure 2.9.[2] Each user considers the nearest BS, as its own BS.

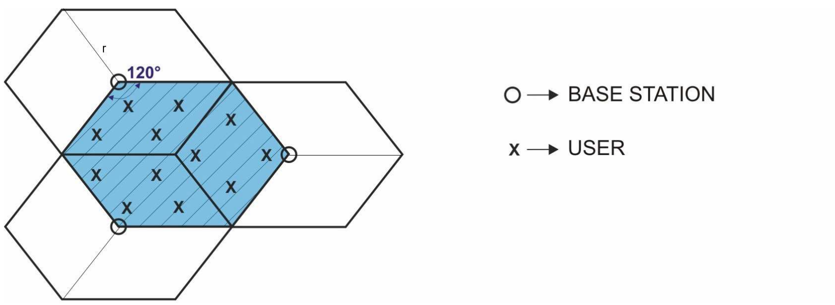


Figure 2.9: Cooperative cellular model with frequency reuse factor of 1.

[2]Note that the terms "cell" and "sector" are used interchangeably in the rest of the thesis, since we are interested in the shaded area depicted in Figure 2.9.

Chapter 3

Cooperative Transmission and Scheduling Algorithm

While designing the algorithm the first aim is to make it implementable in real world systems. Although, the methods explained in Chapter 2 increase the spectral efficiency of wireless communication systems, at the same time they increase the complexity of the system. The issues that should be considered for the performance versus complexity tradeoff problem are listed below:

1. Due to the multicarrier nature of OFDMA, full CSI assumption at BSs will be impractical since it will need a great amount of feedback from users to BSs in the uplink phase. Hence, an efficient MIMO transmission without full channel knowledge should be considered.

2. The second problem arising from the multicarrier nature of OFDMA is that the scheduling complexity and feedback load increases if users are scheduled on a subcarrier basis.

3. The usage of frequency reuse factor of 1 will cause significant CCI especially to the cell edge users. Hence, it can increase the spectral efficiency provided that the CCI is properly dealt with.

4. A proper power allocation scheme without full channel knowledge at the transmitter should be considered.

3.1 Transmission Strategies

In the proposed algorithm, first and second of the following three transmission strategies are considered. The third one is for the sake of comparison with the frequency reuse scheme and is not used in the proposed algorithm.

1. **Noncooperative Transmission Strategy (TS 1):** On a given subchannel, users are served only by the BSs in their cells. In this case three users can be served at the same time on a subchannel. Hence, there is no loss in spectral efficiency when CCI level is low.

2. **Cooperative Transmission Strategy (TS 2):** On a given subchannel, users are jointly served by all BSs. In this case, only one user can be served on a subchannel, without any CCI.

3. **Orthogonal Transmission Strategy (TS 3):** On a given subchannel, users are served only by the BSs in their cells. However, the other two BSs do not make any transmission on this subchannel. Hence, again only one user can use this subchannel with no CCI.

After defining the transmission strategies, the signal model in (2.17) can be rewritten as

$$\mathbf{y}_k^l = \mathbf{G}_k^l \sum_{\substack{b=1 \\ b:k_b^l=k}}^{B} \mathbf{H}_{k,b}^l \mathbf{F}_b^l \mathbf{P}_b^l \mathbf{x}_{k_b^l}^l + \mathbf{G}_k^l \sum_{\substack{b=1 \\ b:k_b^l \neq k}}^{B} \mathbf{H}_{k,b}^l \mathbf{F}_b^l \mathbf{P}_b^l \mathbf{x}_{k_b^l}^l + \mathbf{G}_k^l \mathbf{n}_k^l. \tag{3.1}$$

In this summation the first term corresponds to the signal received from own BSs, the second term is the received signal from interfering BSs and the last term is noise. With this signal model, the received SINR of user k on qth stream of subcarrier l for all mentioned transmission schemes can be written as,

$$\gamma_{k,q}^l = \frac{|\sum\limits_{\substack{b=1 \\ b:k_b^l=k}}^{B} (\mathbf{A}_{k,b}^l)_{qq}|^2}{\sum\limits_{\substack{j=1 \\ j\neq q}}^{Q} |\sum\limits_{\substack{b=1 \\ b:k_b^l=k}}^{B} (\mathbf{A}_{k,b}^l)_{qj}|^2 + \sum\limits_{j=1}^{Q} \sum\limits_{\substack{b=1 \\ b:k_b^l\neq k}}^{B} |(\mathbf{A}_{k,b}^l)_{qj}|^2 + \sigma_n^2 \sum\limits_{j=1}^{Q} |(\mathbf{G}_k^l)_{qj}|^2}, \tag{3.2}$$

where $\mathbf{A}_{k,b}^l = \mathbf{G}_k^l \mathbf{H}_{k,b}^l \mathbf{F}_b^l \mathbf{P}_b^l$. In this SINR expression the numerator term is the desired signal power. The first term of the denominator is ISI, the second is CCI which is present only when noncooperative transmission strategy is selected and the last term is noise power. Our main design objective is to optimize the system spectral efficiency expressed as,

$$C = \sum_{k=1}^{K} \sum_{l \in \mathcal{L}^k} \sum_{q=1}^{Q} \log_2(1 + \gamma_{k,q}^l), \tag{3.3}$$

where $\mathcal{L}^k$ is the set of indices of subcarriers on which user k is scheduled. In order to optimize system spectral efficiency, the transmit beamformer matrix, $\mathbf{F}_b^l$, power allocation matrix, $\mathbf{P}_b^l$, and receive beamformer matrix, $\mathbf{G}_k^l$, must be jointly chosen such that the received SINRs, $\gamma_{k,q}^l$'s, are maximized. Since we require limited information feedback from the users, the transmit beamformer and power allocation matrices should be chosen with limited channel knowledge.

3.2 Transmit Beamforming

Random transmit beamforming seems to be an attractive method for MIMO transmission with limited channel knowledge. By exploiting multiuser diversity and opportunistic scheduling, near optimum performances close to eigen-beamforming configuration can be achieved, especially under cooperative transmission, where there is no CCI.

Firstly, a random beamformer codebook $\mathbf{W}_b$ with length N_c is generated at BS b, where each element is a $N_t \times Q$ unitary matrix and the wth element is denoted as $\mathbf{W}_b(w)$. For each OFDM symbol the same codebook is used and for successive subcarriers, the elements of the beamformer codebook are also selected in successive manner. Then, the beamformer matrices in (2.17) becomes,

$$\mathbf{F}_b^l = \tilde{\mathbf{V}}_b^l, \tag{3.4}$$

where $\tilde{\mathbf{V}}_b^l = \mathbf{W}_b(\text{mod}(l, N_c))$.

With this transmit beamforming method, the MIMO channel on subcarrier l is in general not diagonalized and ISI can not be completely mitigated.

The effective channel matrix seen by user k on subcarrier l is defined as $\bar{\mathbf{H}}_k^l = [\mathbf{H}_{k,1}^l \mathbf{H}_{k,2}^l \dots \mathbf{H}_{k,B}^l]$ and similarly the **effective beamformer matrix** as $\bar{\mathbf{V}}_k^l = [(\tilde{\mathbf{V}}_1^l)^T (\tilde{\mathbf{V}}_2^l)^T \dots (\tilde{\mathbf{V}}_B^l)^T]^T$, $\forall\, b : k_b^l = k$.

Recalling Section 2.1, if the first Q rows of right singular matrix of $\bar{\mathbf{H}}_k^l$ is denoted as $\hat{\mathbf{V}}_k^l$, ISI is mitigated if and only if $(\hat{\mathbf{V}}_k^l)^H \bar{\mathbf{V}}_k^l = \mathbf{I}$. As this result gets closer to $\mathbf{I}$, the performance gets closer to eigen-beamforming configuration and with increasing number of users the probability that any one user may be in eigen-beamforming configuration will increase.

At each OFDM symbol the order of elements of the codebook is randomly changed. Hence, a different random beamformer is used on the same subcarrier on different OFDM symbols, and regardless of the velocity, each user effectively experiences a fast fading channel with increased time diversity. In addition, usage of different random beamformers on each subcarrier increases the frequency diversity, even if there is a correlation between subcarriers or subchannels.

The properties of these $\tilde{\mathbf{V}}_b^l$ matrices are as follows:

1. They are unitary matrices.
2. They are selected independent of the scheduled users.
3. They are formed pseudorandomly with predefined seeds assumed to be known by all users.
4. They are chosen without any channel information.

3.3 Receive Beamforming

Assuming that users can perfectly estimate the instantaneous channel gains from all BSs and they can predetermine the transmit beamformer and power allocation matrices used by BSs on a given subcarrier, in order to maximize its received SINR user k can calculate the well-known minimum mean square error (MMSE) receiver beamformer for subcarrier l as,

$$\mathbf{G}_k^l = \sum_{\substack{b=1 \\ b:k_b^l=k}}^{B} (\mathbf{D}_{k,b}^l)^H \left[\sigma_n^2 \mathbf{I}_Q + \sum_{\substack{b=1 \\ b:k_b^l=k}}^{B} \mathbf{D}_{k,b}^l (\sum_{\substack{b=1 \\ b:k_b^l=k}}^{B} \mathbf{D}_{k,b}^l)^H + \sum_{\substack{b=1 \\ b:k_b^l \neq k}}^{B} \mathbf{D}_{k,b}^l (\mathbf{D}_{k,b}^l)^H \right]^{-1}, \quad (3.5)$$

where $\mathbf{D}_{k,b}^l = \mathbf{H}_{k,b}^l \mathbf{F}_b^l \mathbf{P}_b^l$. It should be noted that, in this formulation the first term in the inverse operator is the noise covariance matrix, the second term is the desired signal covariance matrix and the last term is the CCI covariance matrix, absent in the cooperative transmission strategy, TS 2.

When the receiver beamformer matrix is the MMSE beamformer, the received SINR given in (3.2) can be written in a simplified form as shown in [25, 26] as,

$$\gamma_{k,q}^l = \frac{1}{(\mathbf{M}_k^l)_{qq}} - 1, \quad (3.6)$$

where $\mathbf{M}_k^l$ is the mean square error matrix calculated as,

$$\mathbf{M}_k^l = \mathbf{I} - (\sum_{b=1}^{B} \mathbf{D}_{k,b}^l)^H (\mathbf{G}_k^l)^H. \quad (3.7)$$

The transmit beamformer matrices are already known by the users, since they are generated pseudorandomly using predetermined seeds known by the users, and are selected independent of the scheduled users and the channel conditions.

Optimum power allocation requires significant feedback and information passing as discussed in Section 3.6. Therefore, we will be interested in power allocation strategies that can be predetermined by users based on limited information to keep the feedback and backhaul loads low.

Furthermore, in the case of noncooperative transmission, for the power allocation to be predetermined by the users this allocation should be independent of the users scheduled on the same subcarrier and served by other BSs. This way under the noncooperative transmission strategy, interference seen by one user in a cell will be independent of the scheduled users in other cells.

3.4 Subchannelization

In order to reduce scheduling complexity and feedback load, the available subcarriers are grouped into subchannels. This process is done according to partial usage of subchannels (PUSC) permutation as explained in [1]. Basically, L subcarriers are used for data transmission from a total of N subcarriers, after separating the rest as guard band or plot subcarriers. After a series of pseudorandom permutations, these L data subcarriers are grouped into S subchannels. These subchannels can be divided into 3 different segments, which can be assigned to 3 sectors for the conventional frequency reuse scheme. Some important properties of PUSC in WiMAX are,

1. Subcarriers of a given subchannel are distributed over the whole frequency band, which increases frequency diversity in a subchannel. However, since the permutations may distribute correlated subcarriers among subchannels, there may be a correlation between subchannels.

2. Users are scheduled on a subchannel basis but over two consecutive OFDM symbols, which decreases the scheduling complexity and feedback load since the data rate feedback must be done once two OFDM symbol. However, this may cause performance loss for high mobility scenarios, where two consecutive time slots become highly uncorrelated.

3.5 Scheduling

The scheduling algorithm is formulated in order to maximize the system spectral efficiency. Hence, the optimization problem here is to maximize the instantaneous total sum rate of all the users under the total power constraint P_T. Orthogonal structure of OFDM is preserved in each cell. Hence, total sum rate $C(t)$ is equal to the sum of achieved rates on each subchannel $C^s(t)$, where t is time slot or OFDM symbol index.

$$C(t) = \sum_{s=1}^{S} C^s(t). \tag{3.8}$$

Here, the optimization problem is equivalent to maximizing $C^s(t)$ for each subchannel s. Since each BS serves only one user on each subchannel, the maximization can be done using opportunistic scheduling of the users over the subchannels.

However, calculation of $C^s(t)$ depends on the transmission strategy to be used on subchannel s. Under noncooperative transmission strategy TS 1, maximization of $C^s(t)$ is achieved when each BS schedule the user in its own cell with the highest achievable data rate on subchannel s. Under cooperative transmission strategy TS 2, subchannel s should be allocated to the user over all the users in the system with the highest achievable rate under TS 2 on subchannel s.

In proposed algorithm, firstly each user must calculate the received SINRs given in (3.6) $\gamma^l_{k,q}(t,i)$, where t indicates the time slot index and i represents the transmission strategy, TS i, $i \in \{1,2\}$. Then, the achievable data rate of user k on subchannel s for time slot t and TS i is simply,

$$R^s_k(t,i) = \sum_{l \in \mathcal{L}^s} \sum_{q=1}^{Q} \log_2(1 + \gamma^l_{k,q}(t,i)), \tag{3.9}$$

where $\mathcal{L}^s$ is the set of indices of subcarriers within subchannel s, with size L_s. Here, the achievable data rate on a subchannel is sum of data rates of the subcarriers of that subchannel, because of the orthogonal structure of OFDM.

Then, each user feeds back the two data rates $R^s_k(t,i)$ under the two transmission strategies to the BS in its cell for each subchannel s. Each BS b firstly calculates the maximum of the achievable data rates under the two transmission strategies for all subchannels s over all users in its own cell as,

$$\bar{R}^s_b(t,i) = \max_{k \in \mathcal{K}(b)} R^s_k(t,i), \tag{3.10}$$

where $\mathcal{K}(b)$ is the set of indices of users in the cell served by BS b. BSs exchange this information over the backhaul with each other. In this case total of $2S$ data rates are sent by each BS over the backhaul. This procedure is depicted in Figure 3.1. The aim is to use the wired links at the backhaul of BSs instead of transmitting rate information to BSs over the wireless link, to reduce feedback load and increase reliability.

Afterwards, the sum rate on subchannel s is jointly calculated by all BSs as,

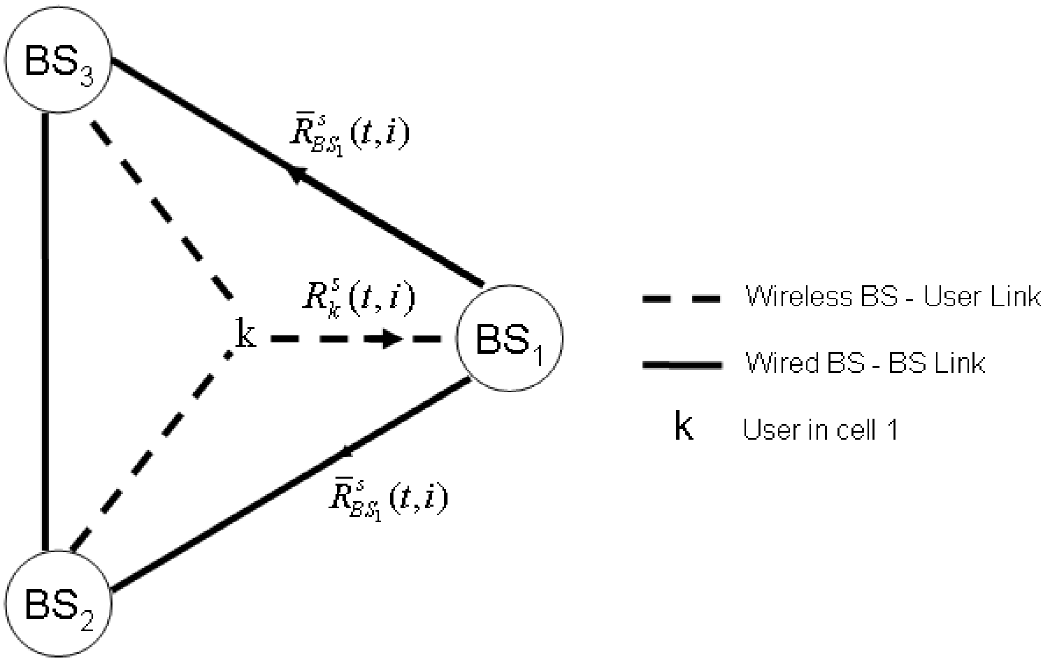


Figure 3.1: Illustration of data rate feedback and information exchange between base stations.

$$C^s(t) = \max_i C^s(t,i), \tag{3.11}$$

where

$$C^s(t,1) = \sum_{b=1}^{B} \bar{R}^s_b(t,1), \tag{3.12}$$

$$C^s(t,2) = \max_b \bar{R}^s_b(t,2). \tag{3.13}$$

Recall that, the rate in (3.12) corresponds to best total rate on subchannel s at time slot t under noncooperative transmission strategy TS 1, where each BS transmits to a different user. The rate in (3.13) is the best total rate on subchannel s at time slot t under cooperative transmission TS 2, where all BSs transmit to the same user. Hence, the algorithm chooses noncooperative transmission, if there is no gain in terms of the sum rate from cooperation for subchannel s. This way, the scheduled user(s) and the transmission strategy to be used on each subchannel is jointly determined by all BSs using (3.11).

Let $\bar{k}_b^s(t,i)$ denote the index of the user maximizing (3.10) under TS i, $\bar{b}^s(t)$ denote the index of the BS maximizing (3.13) and $\bar{i}^s(t)$ denote the index of transmission strategy TS i maximizing (3.11).

As a result, on subchannel s, if

1. $\bar{i}^s(t) = 1$, noncooperative transmission is done simultaneously to users $\{\bar{k}_1^s(t,1), \bar{k}_2^s(t,1), \ldots, \bar{k}_B^s(t,1)\}$.
2. $\bar{i}^s(t) = 2$, all BSs cooperatively transmit to the user with index $\bar{k}^s_{\bar{b}^s(t)}(t,2)$. In this case, BS $\bar{b}^s(t)$ has to share the data vectors, $\mathbf{x}^l_{\bar{k}^s_{\bar{b}^s(t)}}(t,2)$, for $l \in \mathcal{L}^s$ with all BSs over the backbone.

Finally, scheduling and the corresponding transmission strategy information can then be broadcasted to all users in the system by their corresponding BS.

3.6 Power Control

So far in our discussion of the proposed algorithm, we assumed a power allocation scheme that can be predetermined by the users in order to compute the corresponding receiver beamformer matrices and their resulting SINR feedback before the scheduling task is performed by the BSs.

The simplest power allocation scheme under the above requirement that one can come up with is the uniform power allocation scheme where the total power is equally distributed to all subcarriers, base stations and data streams. In this case, power allocation matrices are expressed as,

$$\mathbf{P}_b^l = \frac{P_T}{BLQ}\mathbf{I}_Q \quad \forall\, b, l \tag{3.14}$$

However, as we will demonstrate in Section 4.3.4, the performance of the proposed algorithm can be significantly improved if power allocation is done more intelligently without increasing the feedback load that much.

The optimum power allocation maximizing the system spectral efficiency is identified by solving the following optimization problem,

$$\begin{aligned} &\max_{\{\mathbf{P}_b^l, k_b^l\}} \sum_{k=1}^{K} \sum_{l \in \mathcal{L}^k} \sum_{q=1}^{Q} \log_2 \left(1 + \gamma_{k,q}^l\right) \\ &\text{subject to} \quad \sum_{b=1}^{B} \sum_{l=1}^{L} \sum_{q=1}^{Q} (\mathbf{P}_b^l)_{qq} = P_T. \end{aligned} \tag{3.15}$$

Note that this optimization problem involves power allocation, scheduling (subcarrier allocation, i.e., determination of k_b^l's) and choosing receiver beamforming matrices. Since $\gamma_{k,q}^l$ depends on the transmission strategy, the channel matrix of k to all BSs, the receiver beamformer matrix of user k and the power allocation of all BSs on subcarrier l, it is a complex optimization problem that cannot be solved distributively with limited channel knowledge at BS. Therefore, we will resort to suboptimal power allocation techniques.

As mentioned earlier, since the limited channel information fed back by the users are the achievable data rates under transmission strategies TS 1 and TS 2 for each subchannel, which in turn depends on the power allocation scheme used, it would be feasible to consider a power allocation strategy that can be predetermined by the users in advance with limited information. Therefore, one can consider uniform power allocation among subcarriers and data streams to keep the complexity and feedback load of the users low. In this case,

$$\mathbf{P}_b^l = P_b \mathbf{I}_Q \quad \forall\, l, \tag{3.16}$$

where $\sum_{b=1}^{B} P_b = P_T/(QL)$.

Hence, the complex optimization problem in (3.15) reduces to

$$\begin{aligned} &\max_{\{P_b, k_b^l\}} \sum_{k=1}^{K} \sum_{l \in \mathcal{L}^k} \sum_{q=1}^{Q} \log_2 \left(1 + \gamma_{k,q}^l\right) \\ &\text{subject to} \quad \sum_{b=1}^{B} P_b = P_T/(QL). \end{aligned} \tag{3.17}$$

In the case of non cooperative transmission strategy, for the users to be able to predetermine the power allocation between base stations, the allocation needs to be BS specific and independent of the scheduled users in other cells. Therefore, it is reasonable to assume uniform power allocation, $P_b = \frac{P_T}{BLQ} \quad \forall\, b$, for the noncooperative transmission strategy. This way fairness among the cells is maintained, since each BS only transmits to users in its own cell.

In the case of cooperative transmission strategy, the SINR expression is simplified as there is no CCI term. Therefore, users can compute the optimum power allocation between BSs. However, the SINR depends on channel matrices from all BSs to the user considered which contain both large scale fading (path loss and lognormal shadowing) and small scale fading. As a result, optimum power allocation might be different for different subcarriers. While these channels are assumed to be perfectly known at the users, BSs have limited CSI, i.e., only the knowledge of the achievable data rates on subchannels which are fed back by the users is present. Therefore, they can not perform the optimum power allocation between themselves without additional feedback from the users, i.e., $3L$ real numbers should be fed back.

However, one can assume that BSs can determine the distance between them and a user. As a result, they can predict the path loss. Ignoring lognormal shadowing and small scale fading, a suboptimal power allocation method based on path loss can be utilized. The proposed suboptimal power allocation for user k under the cooperative transmission strategy is,

$$
\begin{aligned}
&\max_{\{P_b\}} \sum_{b=1}^{B} \log_2\left(1+\frac{P_b}{(d_{k,b})^n}\right) \\
&\text{subject to} \quad \sum_{b=1}^{B} P_b = P_T/(QL).
\end{aligned}
\tag{3.18}
$$

Note that this power allocation is user specific, since it depends on the location of the user with respect to all BS and can be solved with the well-known waterfilling method [27]. In this way, for each subchannel and user to be scheduled under TS 2, BSs share the total power in the subchannel in a such a way that closer BSs transmit with higher power.

It should be noted that the proposed power allocation in (3.18) is not optimal in any way, i.e., it is not maximizing the achievable data rate under TS 2. However, it is simple to implement without requiring any additional feedback from the users, since it only depends on user locations and does not require any other

CSI on each subcarrier. Numerical results presented in Section 4.3.4 demonstrate that although not optimal in any way, the proposed power allocation scheme results in performance gains with negligible increase in complexity and feedback load.

This power allocation scheme also demonstrates the relationship between cooperative and orthogonal transmission strategies. If we consider a scenario where a user is too far way from the BSs in other cells, all the available power will be allocated to the BS in user's own cell, which will correspond to the orthogonal transmission strategy. However, for the scenarios where the user is closer to the cell edge, the proposed power allocation scheme will allocate the power between BSs to provide spatial diversity again, as it will be demonstrated in Chapter 4.

Finally, the power allocation scheme considered here is based on a total power constraint which is not practical. Per BS or per transmit antenna constraints are more practical as each transmit antenna typically has its own RF chain and is limited by the linearity region of its power amplifiers. However, per BS or antenna constraints are known to require complex optimization tools and increased feedback load [28]. In the proposed scheme, for users served under TS 2, there is expected to be a power imbalance between the BSs, only for the subchannels used in cooperative mode. In the long run, the transmit power of all BSs is expected to be balanced on average.

3.7 Modifications to the Algorithm

3.7.1 Transmit Beamformer Optimization

In addition to the advantages of random transmit beamforming explained in Section 3.2, it can also be used with best random beamformer selection method. The basic idea is that users calculate their achievable rates for all possible random beamformer matrices in the codebook and feed back the data rate along with the index of the random beamformer.

This method can only be used with cooperative transmission strategy. If it is used for noncooperative transmission, then transmit beamformers will not be independent of scheduled user and users can not compute their SINRs without additional knowledge about what is going on in other cells.

A codebook of length N_c needs $\log_2(N_c)$ bits for indexing. If the best beamformer is found for each subcarrier and each BS, then the feedback load increases by $LB \log_2(N_c)$ bits. To reduce the feedback load it is more suitable to find a random beamformer for each subchannel and use the following method:

To find the optimum effective beamformer matrix, users firstly calculate (3.9), recalling the codebooks are denoted as $\mathbf{W}_b(w)$, $\forall\, w \in [1, N_c]$, to find $R_k^s(t, 2, w)$. Then they find,

$$R_k^s(t, 2) = \max_w R_k^s(t, 2, w). \tag{3.19}$$

Afterwards, users feed back this data rate along with the corresponding $\bar{N}_k^s$, which is the single index of the random beamformer matrices in all $\mathbf{W}_b$'s that maximizes (3.19). If cooperative transmission strategy, TS 2, is chosen for subchannel s after scheduling, then the transmit beamformers at each BS should be chosen as,

$$\mathbf{F}_b^l = \mathbf{W}_b(\bar{N}^s_{\bar{k}^s_{\bar{b}^s(t)}(t,2)}) \quad \forall\, l \in \mathcal{L}^s. \tag{3.20}$$

Note that the joint optimization of the transmit beamforming matrices for all BSs is not employed to keep the feedback load and computational complexity low. Although this method will increase the performance, along with the increased feedback, users must also calculate N_c times more data rates per subchannel. Hence, there is a performance versus complexity and feedback load tradeoff to be considered.

3.7.2 Feedback Reduction

Although the algorithm needs limited feedback, there seems to be a possibility that the feedback load can be further reduced at the expense of some performance loss, due to the following observations:

1. If all BSs can find a user with good instantaneous channel, i.e., typically close to itself, noncooperative transmission is preferred.

2. For the cell edge users far away from their own BSs, cooperative transmission is preferred, since noncooperative achievable rates are very low for these users due to observed CCI levels.

These two observations and aforementioned studies about adaptive frequency reuse can bring motivation to partition the cell into two regions. A low CCI region closer to BSs (region 1) and a high CCI region near cell edges (region 2).

It is obvious that, it is not optimum to make this partitioning based only on distances due to shadowing effect. However, in a suboptimal fashion this partitioning can be done based on the power control method explained in Section 3.6. It is observed that, under cooperative transmission strategy TS 2, for the users close to their own BSs the power control method allocates nearly all power to their own BSs and very small power to other BSs. Typically, their cooperative rate is lower than the sum rate archived under noncooperative transmission over all cells. These users are assumed to be in low CCI region. The users, for whom the power allocation involves two or three BSs, are assumed to be in high CCI region.

Considering the first observation, firstly it seems reasonable to make region 1 users just calculate and feed back data rates for noncooperative transmission. However, due to cooperative nature of the system this can cause the following problem. If there is no user in region 1 of other cells, the noncooperative sum rate will decrease significantly. Hence, a region 1 user may never be scheduled because of this pairing problem. So, it seems more suitable for region 1 users to consider both noncooperative and cooperative transmission.

Because of the second observation, it is reasonable that region 2 users can just calculate and feed back the data rates for cooperative transmission. Hence, with this feedback reduction scheme the feedback load and computational cost can be halved for cell edge users.

3.8 Fairness

Until now, the scheduling scheme we discussed aims to maximize the total achievable sum rate of the users. It is known that maximum sum rate (MSR) scheduling results in an unfair rate allocation, because this algorithm always chooses the best user with the highest achievable data rate. Hence, a user with a very good instantaneous channel, i.e., typically a user very close to its own BS, may dominate the channel, while a cell edge user may never be served at all.

If fairness between users is desired, i.e., all users are to achieve more or less equal average data rates at the long run, proportionally fair scheduling (PFS) can be implemented, by modifying the algorithm such that the data rate to be fed back by the users for a subchannel, $\tilde{R}_k^s(t,i)$, is the instantaneous achievable data rate on that subchannel weighted with the inverse of the time averaged data rate achieved so far.

$$\tilde{R}_k^s(t,i) = \frac{R_k^s(t,i)}{T_k(t)}, \tag{3.21}$$

where time averaged data rate $T_k(t)$ of user k is calculated with the exponentially weighted low pass filter

$$T_k(t+1) = (1 - \frac{1}{t_c})T_k(t) + \frac{1}{t_c}\sum_{s\in\mathcal{S}^k} R_k^s(t,\bar{i}^s(t)). \tag{3.22}$$

where t_c is the window length, $\mathcal{S}^k$ is the set of subchannels where user k is scheduled and $R_k^s(t,\bar{i}^s(t))$ is the total achieved rate of user k on subchannel s at slot t with the chosen transmission strategy. Since users' instantaneous data rates are not normalized with the time averaged data rates averaged over the given subchannel, scheduling will be fair even in short term [8].

It is obvious that PFS is more suitable to use in practical systems; since users generally have minimum data rate requirements. One of the aims of this algorithm is to provide acceptable data rates to users who suffer from CCI the most, i.e., cell edge users. Only under PFS, every user will have a chance to be scheduled, hence gains from cooperation is expected to be more under this scheduler. Furthermore, while providing cell edge users with acceptable data rates to ensure fairness, the algorithm also targets to use system resources such as transmit power and time slots efficiently, in order not to decrease system spectral efficiency significantly.

3.9 Practical Considerations

In this section, practical issues about the underlying assumptions made in the development of the algorithm are discussed.

3.9.1 Distance Measurements

Accurate measurement of distances between BSs and users is important for the algorithm, since we assume that distance information is present both at BSs and users for the proposed power allocation strategy to work properly. This may be accomplished by using GPS devices both at BSs and mobile stations, with periodic coordinate information exchange. However, as mobility increases this measurement and information exchange should be done more often.

3.9.2 Synchronization

Synchronization is an important problem for a cooperative system, since distances from BSs to a user may vary greatly. However, if BSs are synchronized based on a common timing source and downlink frames sent by BSs arrive at the users within the cyclic prefix interval [22], then there should be no synchronization problem.

For a hexagonal cellular system with radius, $r = 1000$ m, the largest distance, i.e., distance between 2 BSs is approximately 1732 m. Hence, the largest delay happens to be approximately 5.8 μs which is smaller than cyclic prefix time 11.43 μs [30]. Hence, there should not be a timing synchronization problem.

3.9.3 Intercarrier Interference

Intercarrier interference (ICI) is an important performance degrading factor in multicarrier systems. Even with perfect frequency synchronization, under high mobility scenarios it can cause significant performance loss. Since, the numerical results presented in Chapter 4 are for low mobility scenarios, it may be expected that the performance loss is insignificant. To study the effect of ICI on the performance of the proposed algorithm, we provide the following analysis.

When ICI is present, the system model given in (2.17) becomes,

$$\mathbf{y}_k^l = \mathbf{G}_k^l \sum_{b=1}^{B} (\tilde{\mathbf{H}}_{k,b})_{ll} \mathbf{F}_b^l \mathbf{P}_b^l \mathbf{x}_{k_b^l}^l + \mathbf{G}_k^l \sum_{b=1}^{B} \sum_{\substack{y=1 \\ y \neq l}}^{L} (\tilde{\mathbf{H}}_{k,b})_{ly} \mathbf{F}_b^y \mathbf{P}_b^y \mathbf{x}_{k_b^y}^y + \mathbf{G}_k^l \mathbf{n}_k^l. \tag{3.23}$$

Since the orthogonal structure is not preserved, data vector received on subcarrier l is not independent of transmissions on other subcarriers which is modeled by the second summation in (3.23). Dropping the indices b and k to simplify the discussion, new channel matrix is calculated as given in [29],

$$\tilde{\mathbf{H}}_{ly} = \frac{1}{N} \sum_{a=1}^{N} \sum_{z=1}^{Z} \bar{\mathbf{H}}_{az} e^{\frac{2j\pi(a-1)(y-l)}{N}} e^{-\frac{2j\pi y(z-1)}{N}}, \tag{3.24}$$

where $\bar{\mathbf{H}}_{az}$ is time selective sampled time domain channel, a is the time sample index, z is the index of the delay tap in tapped delay line and Z is the length of the tapped delay line modeling the frequency selective channel. Here the actual received SINR is similar to (3.2) with the following differences:

1. $\mathbf{A}_{k,b}^l = \mathbf{G}_k^l (\tilde{\mathbf{H}}_{k,b})_{ll} \mathbf{F}_b^l \mathbf{P}_b^l$.
2. An ICI term $(P_{\text{ici}})_{k,q}^l$ must be added to denominator, which can be written as,

$$(P_{\text{ici}})_{k,q}^l = \sum_{j=1}^{Q} \sum_{\substack{y=1 \\ y \neq l}}^{L} (\mathbf{Z}_{k,b}^y)_{qj}, \tag{3.25}$$

where

(a) If TS 1 is used on subcarrier y, then $(\mathbf{Z}_{k,b}^y)_{qj} = \sum_{b=1}^{B} |(\mathbf{G}_k^l (\tilde{\mathbf{H}}_{k,b})_{ly} \mathbf{F}_b^y \mathbf{P}_b^y)_{qj}|^2$.

(b) If TS 2 is used on subcarrier y, then $(\mathbf{Z}_{k,b}^y)_{qj} = |\sum_{b=1}^{B} (\mathbf{G}_k^l (\tilde{\mathbf{H}}_{k,b})_{ly} \mathbf{F}_b^y \mathbf{P}_b^y)_{qj}|^2$.

Since ICI depends on the transmission strategy it cannot be calculated without prior knowledge of transmission strategy used on other subcarriers. Hence, users cannot calculate its covariance matrix. Also, (3.6) can no longer be used to calculate the SINR anymore, since MMSE beamformer is not optimum due to ignorance of ICI. As a result, the data rates fed back by users are no longer achievable since they are computed ignoring the ICI.

Chapter 4

Numerical Results

In this chapter, the performance of the proposed BS cooperation algorithm is studied via computer simulations. The performance of different transmission schemes are compared to investigate the tradeoffs involved.

4.1 Comparison of Transmission Schemes

Different transmission schemes that are compared in this section are summarized below.

1. **Noncooperative Scheme (Noncoop):** In this scheme, only noncooperative transmission strategy is considered. Each user must calculate one data rate per subchannel and then this data rate must be fed back to user's own BS. BSs do not exchange any information, data transmission and scheduling is done independently and individually. The frequency reuse factor is 1.

2. **Frequency Reuse Scheme (Fr):** The conventional frequency reuse scheme is also a noncooperative system, where subchannels are shared orthogonally and deterministically between the three BSs. Since only one BS broadcasts on a given subchannel, $P_b = \frac{3P_T}{LQ}$ to have the same P_T. In this scheme, only orthogonal transmission strategy is considered. Each user must calculate one data rate per subchannel allocated to its own BS, and then this data rate must be fed back. BSs do not exchange any information,

data transmission and scheduling is done independently and individually. The frequency reuse factor is 3.

3. **Adaptive Frequency Reuse Scheme (AdFr):** The adaptive frequency reuse scheme is a noncooperative system, where half of the subchannels are shared orthogonally and deterministically between three BSs, and the remaining half can be used by all BSs. In this scheme, both noncooperative and cooperative transmission strategies are used. The power allocations are chosen as $P_b = \frac{3P_T}{LQ}$ and $P_b = \frac{P_T}{LQ}$ for orthogonal and noncooperative subchannels respectively to have the same P_T. Each user must calculate one data rate per subchannel for both orthogonal and noncooperative subchannels allocated to its own BS, and then this data rate must be fed back. BSs do not exchange any information, data transmission and scheduling is done independently and individually. The frequency reuse factor is 3 / 2.

4. **Cooperative Scheme (Coop):** As explained in detail in Chapter 3, both cooperative and noncooperative transmissions strategies are considered in this proposed scheme. Each user must calculate two data rates per subchannel and then these data rates must be fed back to user's own BS. For each subchannel, BSs should exchange the information about these two data rates, data transmission and scheduling is done jointly. The frequency reuse factor is 1.

5. **Cooperative Scheme with Best Random Beamformer Selection (CoopBest):** As explained in detail in Section 3.7.1, this modification increases the performance, by increasing the computations done by users such that each user must now calculate N_c times more data rate to find the optimum beamformer. Also, an extra $\log_2(N_c)$ bits per subchannel for the index of the best effective transmit beamformer matrix must be fed back and exchanged between BSs. The frequency reuse factor is 1.

6. **Cooperative Scheme with Reduced Feedback (CoopRed):** As explained in detail in Section 3.7.2, in this modified cooperation algorithm users in the inner cell region must calculate two data rates per subchannel, while cell edge users must calculate only one data rate per subchannel. These data rates must be fed back to their own BSs. The amount of information that should be exchanged between BSs does not change. The frequency reuse factor is 1.

Here, it can be assumed that each data rate is quantized with R_q bits. Also, it should be noted that rate computations, feedback and information exchange

Table 4.1: Comparison of transmission schemes in terms of feedback and backhaul loads and computational complexity.

TSC	Feedback ($bits/T_s$)	Backhaul ($bits/T_s$)	Comp (T_s^{-1})
Noncoop	$SR_q/2$	0	$S/2$
Coop	SR_q	SR_q	S
Fr	$SR_q/6$	0	$S/6$
AdFr	$SR_q/3$	0	$S/3$
CoopBest	$S(R_q + \log_2(N_c))$	$S(R_q + \log_2(N_c))$	SN_c
CoopRed	SR_q (reg. 1), $SR_q/2$ (reg. 2)	SR_q	S (reg. 1), $S/2$ (reg. 2)

between BSs must occur at every scheduling slot, that is 2 time slots (T_s) in PUSC permutation. In Table 4.1, the transmission schemes above are compared in terms of:

1. Total number of bits to be fed back by a user per time slot (Feedback).
2. Total number of bits that a BS has to exchange with other BSs per time slot (Backhaul).
3. Total number of data rates that should be computed by a user per time slot (Comp).

4.2 Simulation Parameters

In the simulations for studying the performance of the algorithm, a WiMAX system with PUSC permutation is considered. The parameters used in the simulations are given in Table 4.2. Compared data rates are computed for $M = 100$ random user location scenarios, where users are uniformly distributed in the area of interest with the constraint that there are equal number users in each sector. For each user location scenario rates are averaged over 100 different channel realizations and random beamformer codebooks. The time averaged user rates are computed over $T = 100$ time slots for both PFS and MSR scheduling.

Definition 4. *Worst case received SNR per receive antenna and data stream (P_w) is the received SNR by the user furthest away from its own base station for a single link, ignoring the effects of small scale fading, shadowing and CCI, considering only path loss and uniform power allocation.*

The worst case received SNR per receiver antenna and data stream is formulated as,

$$P_w(\text{dB}) = 10\log_{10}(P) - 10n\log_{10}(r). \tag{4.1}$$

Recalling Section 3.6, $P_b = P$ when uniform power allocation over BSs, subcarriers and data streams is assumed, i.e., $P = \frac{P_T}{BLQ}$.

Note that P_w is used for the purpose of providing a meaningful comparison of transmit SNRs, independent of cell size and path loss effects and does not indicate the actual SNR of worst user. As P_w increases, transmission power and therefore CCI levels relative to noise also increase.

For example, typical transmission power (P_{tx}) of a WiMAX BS is at most +43 dBm (20 W),[3] which happens to be same as total transmit power (P_T), because number of sectors for a cell and number of cooperating BSs are both 3. Dividing this number by number of sectors per cell, subcarriers (L) and data streams (Q) gives the transmit power per data stream $P_t = 6.64$ dBm, since

$$P_t(\text{dBm}) = P_{\text{tx}}(\text{dBm}) - 10\log_{10}(3) - 10\log_{10}(L) - 10\log_{10}(Q). \tag{4.2}$$

Then the received signal power per antenna and stream by the worst case user is -106.15 dBm, since

$$P_r(\text{dBm}) = P_t(\text{dBm}) - 10n\log_{10}(r). \tag{4.3}$$

In WiMAX subcarrier spacing is 10.94 kHz [30]. Hence, we can calculate per stream noise power (P_n) with the corresponding system bandwidth at room temperature (300 K) with Boltzmann's formula as,

$$P_n = B_k T_s B_n, \tag{4.4}$$

where T_s is noise temperature (K), B_n is noise bandwidth (Hz) and Boltzmann constant $B_k = 1.381 * 10^{-23}$ (Joules/K). With these values, for the FFT size

[3]http://www.wimaxcom.net/2008/11/wimax-transmit-power.html

Table 4.2: Parameters used in simulations.

Number of transmit antennas (N_t)	2
Number of receive antennas (N_r)	2
Number of data streams (Q)	2
FFT size (N)	1024
Number of data subcarriers (L)	720
Number of subchannels (S)	30
Number of data subcarriers on a subchannel (L_s)	24
Number of cells (B)	3
Cell radius (r)	1000 m
Path loss exponent (n)	3.76
Standard deviation of lognormal shadowing (σ_s)	8 dB
Channel model	ITU Ped-B [30]
Mobile speeds (v)	3 km/hr
Random beamformer codebook length (N_c)	1024
PFS window length (t_c)	2

of 1024 one gets $P_n(\text{dBm}) = -133.44$ dBm. We can then compute worst case received SNR as,

$$P_w(\text{dB}) = P_r(\text{dBm}) - P_n(\text{dBm}). \tag{4.5}$$

Hence, typically the worst case received SNR is expected to be at most P_w(dB) = 27.3 dB. So, in numerical simulations, we used P_w values between 0 dB and 30 dB.

4.3 Simulation Results

In order to demonstrate the gains from cooperation, the proposed algorithm is compared with other noncooperative schemes. In this section, results of our numerical studies will be summarized.

4.3.1 Comparison of Transmission Strategies

In this section, firstly, transmission strategies explained in Section 3.1 are compared in terms their received SINRs, which can give some interesting insight since the achievable data rates are proportional to received SINRs.

The average received SINR of user k, with the assumption that the user is allocated all the available subchannels, for transmission strategy i and for location scenario m is defined as,

$$\gamma_k(i,m) = \frac{1}{TLQ}\sum_{t=1}^{T}\sum_{l=1}^{L}\sum_{q=1}^{Q}\gamma_{k,q}^{l}(t,i). \tag{4.6}$$

The minimum of achieved average SINR of each transmission strategy for each location scenario is defined as,

$$\tilde{\gamma}(i,m) = \min_k \gamma_k(i,m). \tag{4.7}$$

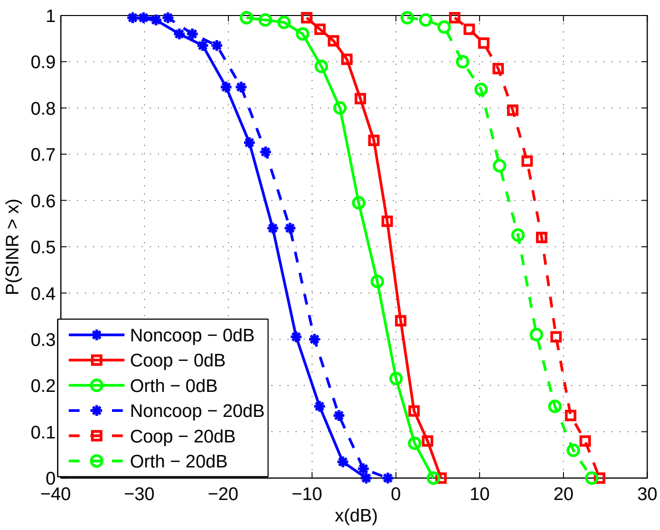


Figure 4.1: cCDF of minimum received average SINR for cooperative, noncooperative and orthogonal transmission strategies.

Complementary cumulative distribution function (cCDF) is the probability that a given random variable is greater than a determined value. In Figure 4.1, the cCDFs of minimum average SINRs of $K = 30$ users are compared for $P_w = 10$ and $P_w = 20$ dB for noncooperative (Noncoop), cooperative (Coop) and orthogonal (Orth) transmission strategies explained in Section 3.1. It is reasonable to assume that these minimum SINRs most probably belong to a cell edge user, who suffers from CCI the most. Firstly, it is clear to see that the SINRs received by noncooperative transmission strategy cannot be improved significantly by increasing transmit power. Therefore, without mitigating the CCI, cell edge users cannot be provided with acceptable SINR levels. Secondly, cooperative transmission strategy always provides cell edge users with better SINR than orthogonal transmission, by providing significant spatial diversity gain. Hence, it can be said that cooperative transmission strategy also increases the coverage area.

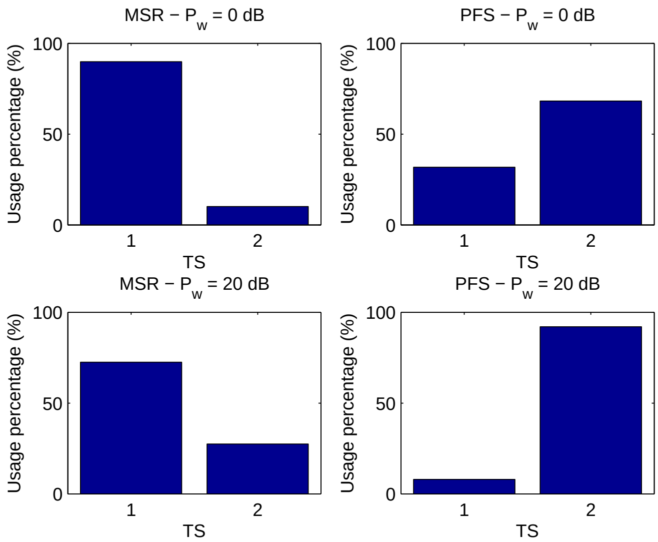


Figure 4.2: Comparison of percentage of the usage of cooperative and noncooperative transmission strategies.

Secondly, the statistics of transmission strategies used in the proposed algorithm are compared. The percentages are calculated by finding the number of times a transmission strategy is chosen over all subchannels in the scheduling process over all location scenarios. In Figure 4.2, percentage of the usage of noncooperative transmission strategy (TS 1) and cooperative transmission strategy (TS 2) are compared for $K = 30$ users, $P_w = 0$ and $P_w = 20$ dB under PFS and MSR scheduling. The results clearly indicate that, noncooperative transmission strategy is chosen more often when CCI level is low, i.e., under low transmit SNR, and when fairness is not taken into account, i.e., under MSR scheduling. Cooperative transmission strategy is used more often under the opposite conditions, when CCI level is high and under PFS where fairness is the main concern. Hence, cooperative transmission is beneficial in mitigating the CCI and providing cell edge users with acceptable data rates.

One can think of another transmission strategy, where two nearest BSs can make cooperative transmission to a user, while the furthest BSs may make noncooperative transmission in its own cell. Both users will be affected by the CCI caused by each other in this strategy. However, considering this transmission strategy in the proposed algorithm has two major problems:

1. It doubles the computational cost and feedback load. Each user must calculate an extra data rate for the case where two nearest BSs transmit to itself, while the third BS is transmitting to a user in the other cell. The second extra data rate is a noncooperative rate when the user is served by the BS in its own cell, but this time the other interfering signals are cooperative unlike the case in the noncooperative transmission strategy. These two extra data rates must also be fed back to the users' own BSs. In addition, an extra data rate per subchannel for this scheme must be exchanged between BSs at the backhaul.

2. Power allocation between cooperative BSs may not be possible this time, since the interfering signals in the second rate calculation cannot be known by the user in the other cell. Unless the power allocation is uniform over BSs, the MMSE beamformers cannot be calculated beforehand by the users.

In the beginning, this transmission strategy with uniform power allocation is also considered, but the results show that its usage percentage is nearly zero and it has almost insignificant effect on the performance. Hence, due to its extra feedback, backhaul and computational costs, it is not considered further.

4.3.2 Maximum Sum Rate Scheduling

In this section, performances of different transmission schemes are compared under MSR scheduling. However, firstly we should clarify how user and sum data rates are calculated. After scheduling the achieved data rate of user k on time slot t for location scenario m and transmission scheme Tr is calculated as,

$$R_{\mathrm{Tr},k}(t,m) = \sum_{s\in\mathcal{S}^k} R^s_{\mathrm{Tr},k}(t,m), \tag{4.8}$$

where $\mathcal{S}^k$ is the set of subchannels where user k is scheduled. $R^s_{\mathrm{Tr},k}(t,m)$ for transmission schemes other than the proposed one is calculated along the same lines as $R^s_k(t,i)$ in (3.9) for the chosen transmission strategy i on subchannel s, and for each transmission scheme and location scenario. Then, the average achieved data rate of user k for location scenario m and transmission scheme Tr becomes,

$$R_{\mathrm{Tr},k}(m) = \frac{1}{T}\sum_{t=1}^{T} R_{\mathrm{Tr},k}(t,m). \tag{4.9}$$

Next, average system sum rate for a given location scenario m is calculated with the following formula,

$$C_{\mathrm{Tr}}(m) = \sum_{k=1}^{K} R_{\mathrm{Tr},k}(m). \tag{4.10}$$

Lastly, the average sum rate (system spectral efficiency) becomes,

$$C_{\mathrm{Tr}} = \frac{1}{M}\sum_{m=1}^{M} R_{\mathrm{Tr},k}(m). \tag{4.11}$$

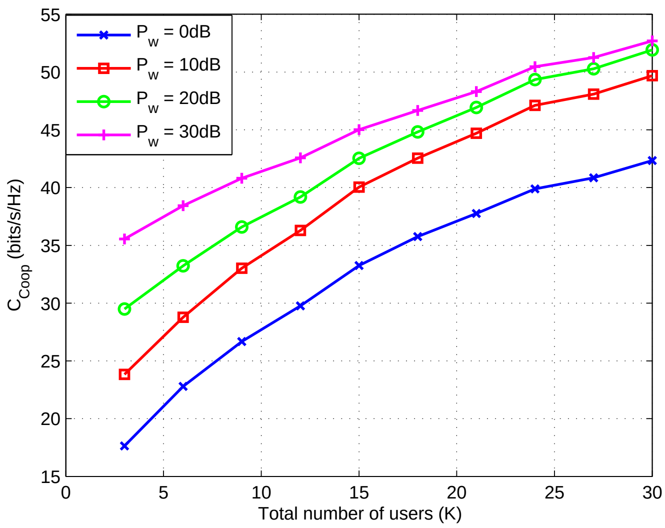


Figure 4.3: System sum rate for cooperative transmission scheme under MSR scheduling.

In Figure 4.3, the average sum rate achieved by the cooperative scheme is plotted for different number of total users, K, and worst case received SNR, P_w. It can be seen that the proposed scheme can provide a spectral efficiency of over 50 bits/s/Hz for high transmit SNR and large number of users. The effect of multiuser diversity can easily be seen as the sum rate increases with increasing number of users. Also, due to mitigation of CCI, sum rate can increase as transmit SNR increases.

To evaluate gains from cooperation, firstly the relative gain over noncooperative scheme is defined as,

$$\text{Relative gain} = \frac{C_{\text{Coop}} - C_{\text{Noncoop}}}{C_{\text{Noncoop}}}. \tag{4.12}$$

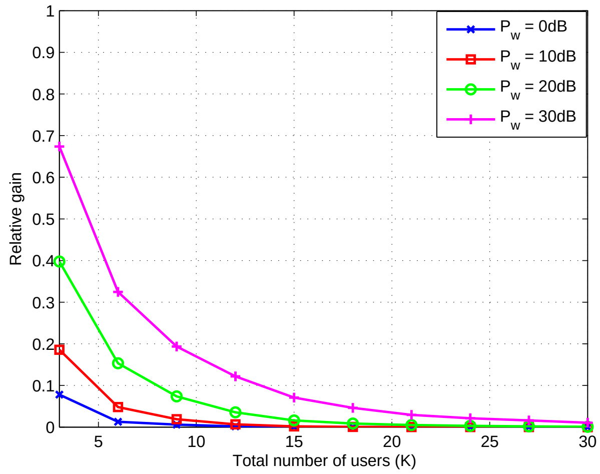


Figure 4.4: Relative gain in sum rate over noncooperative scheme under MSR scheduling.

In Figure 4.4, the relative cooperation gain over noncooperative scheme is plotted against varying K and P_w. It should be noted that, since cooperative scheme involves noncooperative scheme, it should always a have better performance as long as there is a gain from cooperation. It can be seen that, this gain diminishes at low transmit SNR where CCI level is low and when number of users are large, in which case each BS can find a user with a good instantaneous channel in its own cell, resulting in a larger sum rate.

In Figure 4.5, the relative gain in the sum rate of cooperative and adaptive frequency reuse schemes over the conventional frequency reuse scheme is analyzed for varying K, $P_w = 0$ and $P_w = 20$ dB. The relative gains are defined similar to (4.12), where C_{Noncoop} is replaced by C_{Fr}, and C_{AdFr} is used in addition to C_{Coop} to compute the relative gain of adaptive frequency reuse. It is observed that the proposed algorithm can provide up to 120% gain over the conventional frequency reuse scheme at low transmit SNR and for a large number of users.

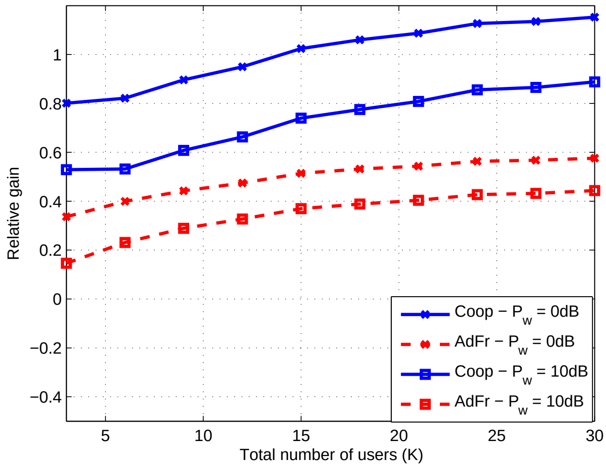


Figure 4.5: Relative gain in sum rate over the frequency reuse scheme under MSR scheduling.

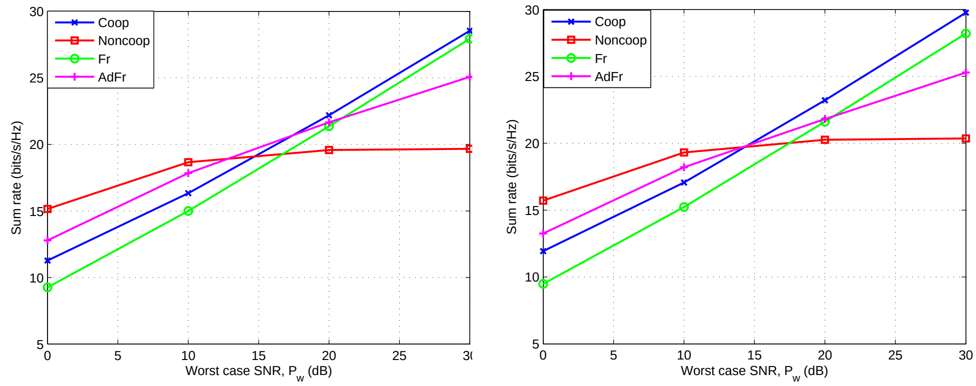
However, this time relative gains are greater for large number of users, which demonstrates that cooperative scheme can exploit the multiuser diversity more effectively, since all subchannels are used systemwide. Relative gains are also greater for low transmit SNR, since spectral inefficiency of frequency reuse is more pronounced at low transmit SNRs, where CCI is insignificant. Furthermore, the relative gains of the cooperative scheme is remarkably higher than those archived by the adaptive frequency reuse scheme.

We saw that the noncooperative transmission strategy is used more often at low transmit SNRs. Since the cooperative scheme has more subchannels to be used for noncooperative transmission strategy, it is expected that it has a better performance than both conventional frequency reuse and adaptive frequency reuse schemes.

4.3.3 Proportionally Fair Scheduling

In this section, performances of different transmission schemes are compared under PFS. Here, average sum rates are calculated in the same way as (4.11) and average user data rate is formulated as,

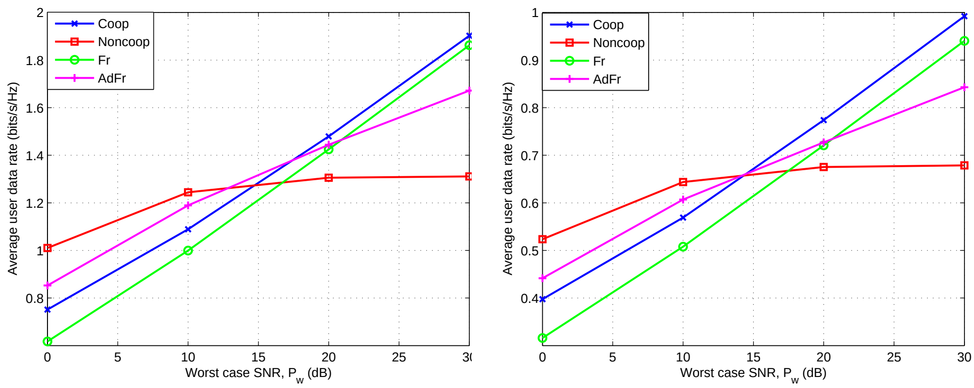
$$\tilde{R}_{\mathrm{Tr}} = \frac{1}{K} C_{\mathrm{Tr}}, \tag{4.13}$$



(a) Total number of users $(K) = 15$. (b) Total number of users $(K) = 30$.

Figure 4.6: Average sum rate under PFS.

where C_{Tr} is defined in (4.11). In Figure 4.6, total sum rate is plotted for increasing transmit SNR for $K = 15$ and $K = 30$. Firstly, it is clear to see that sum rates for PFS are less than MSR scheduling, because of the fairness issue. Also, multiuser diversity is not that effective in PFS, since there is always a possibility that some users experience worse channels over time, but need to be scheduled for fairness.



(a) Total number of users $(K) = 15$. (b) Total number of users $(K) = 30$.

Figure 4.7: Average user data rate under PFS.

In Figure 4.7, average user data rates are plotted for increasing transmit SNR for $K = 15$ and $K = 30$. It can be seen that, as the number of users increases the average user data rate decreases. This is due to the fact that the same system resources should be distributed between more users.

The first interesting point about these plots is the trend in the noncooperative schemes considered. It can be seen that for low transmit SNR regimes, the performance is higher for the scheme which has more subchannels used with noncooperative transmission strategy, i.e., the noncooperative scheme. However, as transmit SNR and CCI levels increase, the transmission scheme with less subchannels is used for noncooperative transmission, i.e., frequency reuse scheme has a better performance. This trend can easily be explained with the fact that noncooperative transmission strategy is used more often under low transmit SNRs. Also, achieved rates can not be improved for the noncooperative scheme even if transmit SNR increases. This is a good indication of how CCI may limit the achievable data rates.

Secondly, the cooperative scheme always outperforms the frequency reuse scheme. At low transmit SNR, cooperative scheme has the advantage that it has more subchannels that can be used for the noncooperative transmission strategy as stated before. At high transmit SNR where cooperative transmission strategy is used more often, this time cooperative scheme has the advantage of spatial diversity gain. Cooperative scheme outperforms noncooperative and adaptive frequency reuse schemes when CCI levels are higher, because it has more subchannels that can be used for cooperative transmission and can provide spatial diversity gain. However, at low transmit SNR these two noncooperative schemes can have a better performance in terms of sum rate.

However, it should be noted that for all mentioned noncooperative schemes, fairness is maintained within a cell since each BS transmits to the users only its own cell and scheduling is performed independently. However, in the cooperative scheme scheduling is done systemwide. Hence, fairness is maintained systemwide. This is the reason why for low CCI levels noncooperative and adaptive frequency reuse schemes can have a better performance. However, the minimum achievable data rates are also important for practical systems, since users generally have QoS requirements. These minimum achievable data rates also indicate a lower bound for achievable rates of the system. In order to compare the minimum achievable date rates of different transmission schemes, cCDF of minimum data rates is calculated. The minimum data rate over users for location scenario m is given as,

$$\tilde{R}_{\mathrm{Tr}}(m) = \min_k R_{\mathrm{Tr},k}(m). \tag{4.14}$$

In Figure 4.8 the cCDFs of minimum achievable data rates for cooperative, noncooperative and adaptive frequency reuse schemes are compared for $K = 30$ users, $P_w = 0$ and $P_w = 10$ dB. It can be seen that, minimum data rates are always higher for the proposed cooperative scheme. Hence, it can be said that

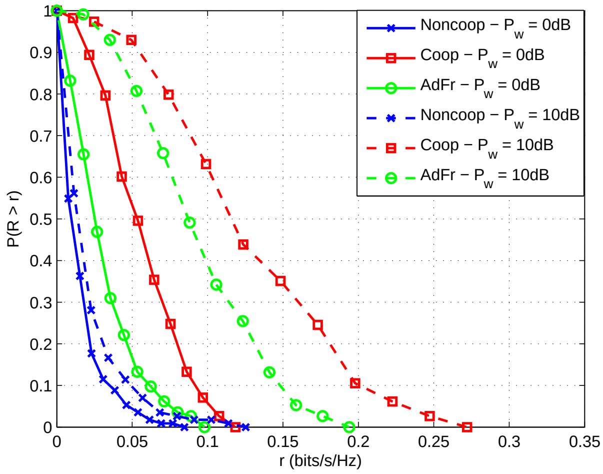


Figure 4.8: cCDFs of minimum achievable data rates of cooperative, noncooperative and adaptive frequency reuse schemes under PFS.

cooperative scheme can maintain systemwide fairness and satisfy users minimum data rates requirements much more effectively.

4.3.4 Power Control

In this section, the performance of the cooperative scheme with three different power allocation strategies is compared: Firstly, with the proposed power allocation strategy (P_a 1) explained in Section 3.6. Secondly, with uniform power allocation (P_a 2) between BSs. Finally, an adaptive allocation (P_a 3), where on each subchannel, the allocation (P_a 1 or P_a 2) with better cooperative rate is used. In other words, if we denote the achievable data rate of user k on subchannel s for power allocation strategy P_a j as $R_k^s(t,2,j)$ then (3.9) becomes

$$R_k^s(t,2) = \max_{j\in\{1,2\}} (R_k^s(t,2,j)). \tag{4.15}$$

In Figure 4.9, achieved sum rates are plotted for varying K and two different worst case SNR values, $P_w = 0$ and $P_w = 20$ dB, under MSR scheduling. It can be seen that, the proposed power control can increase the performance with respect to uniform power allocation up to 2 bits/s/Hz which diminishes with increasing number of users and decreasing transmit SNR. Here, the adaptive method has same the performance with proposed power allocation method, which shows that most of the time the proposed power allocation method (P_a 1) maximizes (4.15).

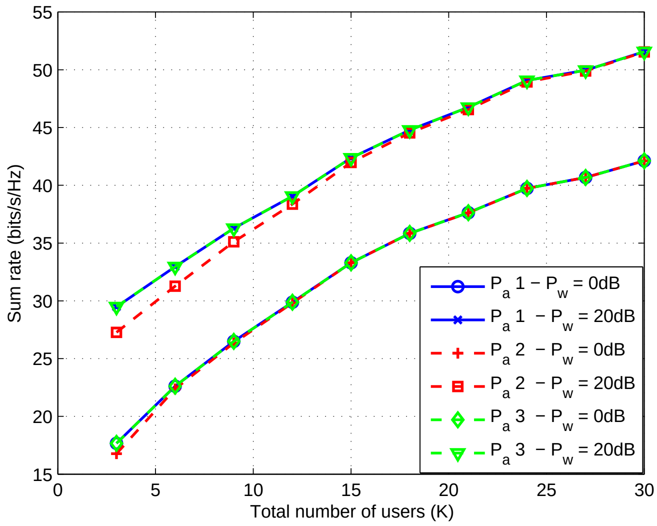


Figure 4.9: Comparison of sum rates of the cooperative scheme with different power control methods under MSR scheduling.

In Figure 4.10, sum rates are plotted for $K = 30$ and varying P_w, under PFS. At high transmit SNRs, the proposed power control method, P_a 1, can increase the performance by about 2 bits/s/Hz. However, at small transmit SNRs it has a slightly worse performance. This can be expected, since there is no guarantee that the power allocation is optimum for all users, due to the fact that shadowing and small scale fading is ignored in power control. However, generally P_a 1 still seems to have a better performance and can be used instead of uniform power allocation. Under PFS, the proposed adaptive power allocation method has a slightly better performance than the proposed power allocation strategy. This adaptive power control may be considered as another modification for the algorithm, however with an increase in feedback load. For each subchannel, users can calculate two data rates for cooperative transmission with both power allocations, P_a 1 and P_a 2, and can feed back an extra indication bit showing whichever power control has the better performance.

4.3.5 Transmit Beamformer Optimization

To evaluate the effect of the best random beamformer selection, the proposed modified algorithm is tested with different codebook sizes, i.e., $N_c = 8$ and $N_c = 16$. Also, as an upper bound, cooperative transmission with eigen-beamforming

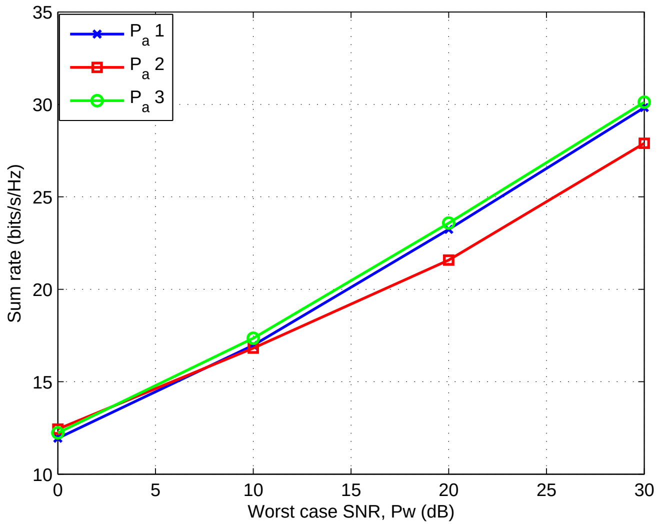
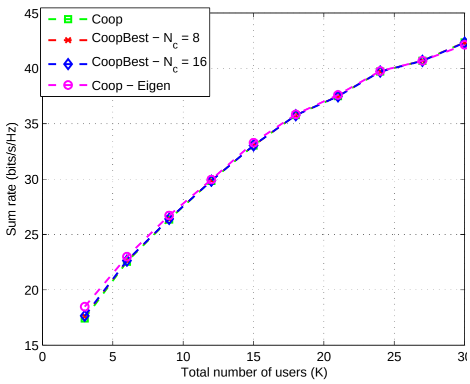
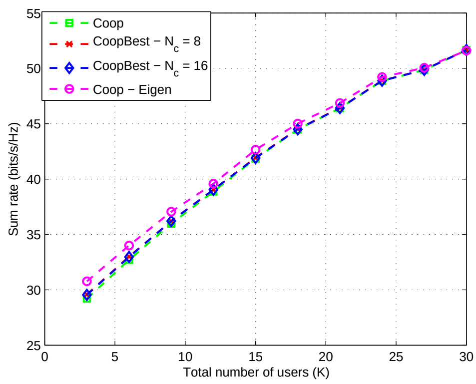


Figure 4.10: Comparison of sum rates of the cooperative scheme with different power control methods under PFS.

configuration explained in Section 2.1 is considered, which may be achieved when N_c goes to infinity.



(a) Worst case SNR, $P_w = 0$ dB.



(b) Worst case SNR, $P_w = 20$ dB.

Figure 4.11: Comparison of sum rates of the proposed cooperative scheme and the modified scheme with best random beamformer selection under MSR scheduling.

In Figure 4.11, sum rates under MSR scheduling is compared for $P_w = 0$ and $P_w = 20$ dB. Since best random beamforming is used with cooperative transmission, as we expect the sum rate gain is not significant under MSR scheduling and low transmit SNRs. Even eigen-beamforming is not able to improve the sum rates significantly.

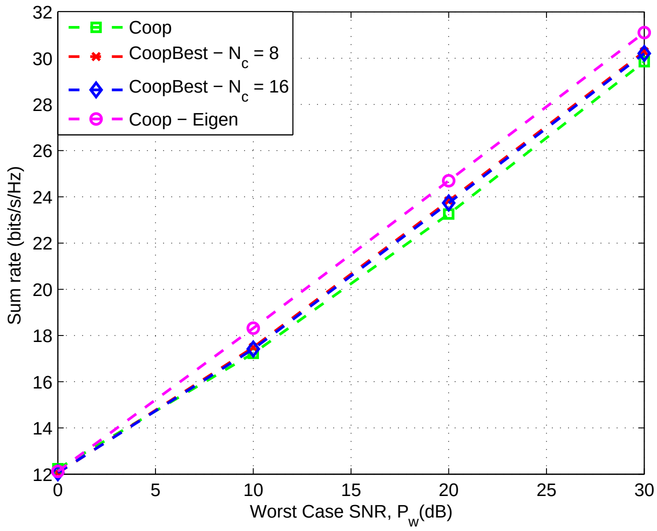


Figure 4.12: Comparison of sum rates of the proposed cooperative scheme and the modified scheme with best random beamformer selection under PFS.

In Figure 4.12, sum rates under PFS scheduling is compared for varying P_w when $K = 30$. Although the sum rate gains are higher compared to MSR scheduling, they still seem to be negligible. Only at eigen-beamforming configuration an approximate gain of 3 dB, while achieving the same spectral efficiency, is observed.

These results indicate that the best random beamforming modification to the proposed scheme is not very practical, since the gains are not significant compared to the increased feedback and backhaul loads, and the computational complexity. Secondly, the results also indicate that random beamforming method has a performance closer to optimum eigen-beamforming configuration especially for large number of users and low transmit SNR levels.

4.3.6 Feedback Reduction

The effect of the feedback reduction obtained by modifying the proposed algorithm in Section 3.7.2, is evaluated in this section.

Firstly, achieved sum rates under the same conditions is plotted for varying K and two different worst case SNR values $P_w = 0$ and $P_w = 20$ dB, in Figure 4.13. It can be seen that regardless of the total number of users, there seems to be a loss

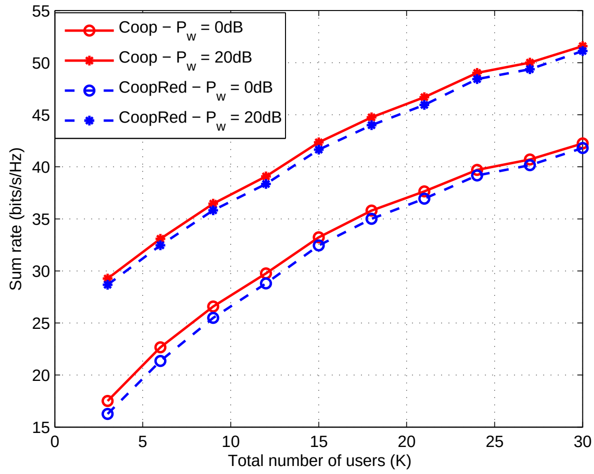


Figure 4.13: Comparison of sum rates of the proposed cooperative scheme and the modified scheme with reduced feedback under MSR scheduling.

of less than 1 bit/s/Hz. However, the loss is a little greater for $P_w = 0$ dB, since noncooperative transmission is used more often than cooperative transmission strategy under low transmit SNR.

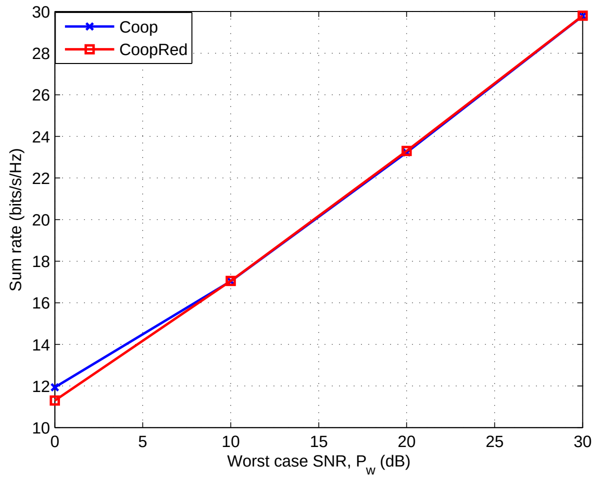


Figure 4.14: Comparison of sum rates of the proposed cooperative scheme and the modified scheme with reduced feedback under PFS.

In Figure 4.14 sum rates under PFS scheduling is compared for varying P_w with $K = 30$. It can be seen that there is a small performance loss due to feedback reduction, only at low transmit SNR levels. The reason for this trend is that as CCI increases, only cooperative transmission is used for the cell edge users, hence the feedback of noncooperative rates for the cell edge users becomes completely redundant in the proposed algorithm.

4.3.7 Intercarrier Interference Analysis

Here a simple analysis is offered for investigating the effect of ICI. For simplicity, only a single user $\bar{k}$ and a single subcarrier $\bar{l}$ is considered. The achievable data rate on this subcarrier with transmission strategy i without ICI is defined as $R_{\bar{k}}^{\bar{l}}(i)$. Similarly the achievable data rate with ICI is defined as $\tilde{R}_{\bar{k}}^{\bar{l}}(i)$. Then the relative rate loss on subcarrier $\bar{l}$ due to ICI is defined as,

$$\text{Relative loss} = \frac{R_{\bar{k}}^{\bar{l}}(i) - \tilde{R}_{\bar{k}}^{\bar{l}}(i)}{R_{\bar{k}}^{\bar{l}}(i)}. \tag{4.16}$$

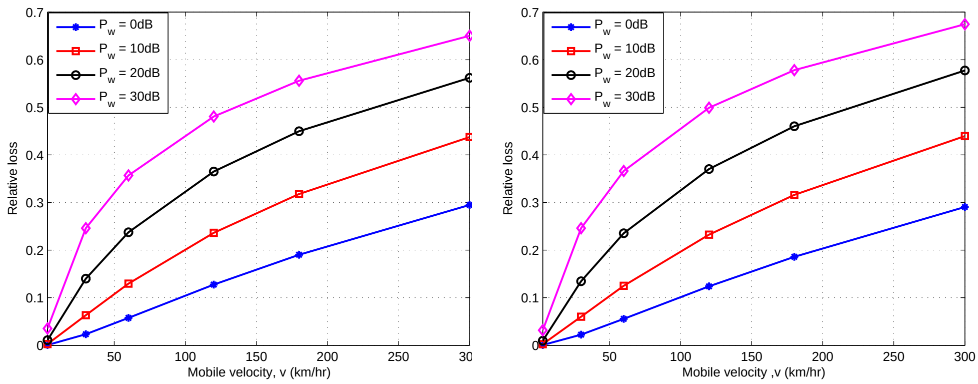
We argue that this might be a good approximation for the worst case performance loss of the proposed algorithm due to ICI on the basis of the following assumptions and observations:

1. ICI observed on subcarrier $\bar{l}$ of user $\bar{k}$ is expected to be more when other subcarriers with significant interference levels are also used by the same user $\bar{k}$. This is due to the fact that power allocation for that subcarrier is more likely to be more suitable for user $\bar{k}$ than any other user k, ignoring effects of shadowing and small scale fading.

2. Assuming all subcarriers are used by the same user $\bar{k}$, the performance loss on the subcarrier $\bar{l}$ is expected to be approximately equal to that for other subcarriers, ignoring the effects of small scale fading.

3. It is not straightforward to determine whether cooperative or noncooperative transmission strategy used on the subcarriers causing ICI will create the most performance loss. Hence, the worse case transmission strategy is chosen for other subcarriers in the calculation of $\tilde{R}_{\bar{k}}^{\bar{l}}(i)$.

Although this analysis does not exactly demonstrate the performance degradation of the proposed algorithm due to ICI, it can still give some insight. In Figure 4.15, the relative rate lost on a subcarrier is plotted with respect to different mobile velocities (v) and worst case SNRs (P_w), assuming noncooperative transmission strategy (TS 1) and cooperative transmission strategy (TS 2) used on the subcarrier of interest in Figure 4.15(a) and in Figure 4.15(b) respectively. The first observation is that at the mobile velocity of interest $v = 3$ km/hr regardless of P_w, relative loss due to ICI is negligible. Therefore, neglecting ICI seems to be a justified assumption for low mobility scenarios. As mobile velocity increases, especially at high transmit SNRs, the loss can increase up to 60% which is completely intolerable for a high data rate communication system. Therefore we can conclude that it is necessary to use some sort of ICI mitigation technique for high mobility scenarios. Finally as P_w increases, the performance loss when noncooperative transmission strategy is used on the subcarrier of interest is less, since CCI is the more dominant performance degrading factor.



(a) Noncooperative transmission strategy. (b) Cooperative transmission strategy.

Figure 4.15: Relative rate loss on a subcarrier due to ICI.

4.4 Feedback and Backhaul Load

In this thesis, it is assumed that the feedback and backhaul loads given in Table 4.1 are within the limits of actual capacities of the given links, and are just given for sake of comparison. However, in order to be implementable in practical systems, feedback load must be compared with the allowed overhead in uplink phase and backhaul load must be compared with the capacity of the backbone network between BSs. In this case, the number of bits used in quantization of data rates R_q can be an important design parameter. Larger R_q will increase the feedback and backhaul loads, while smaller R_q may decrease the performance due to the quantization errors. As a future work, this tradeoff can be investigated through numerical simulations.

Chapter 5

Conclusions

In this thesis, a cooperative data transmission and scheduling scheme, which offers a promising solution to mitigate CCI in multicellular MIMO-OFDMA networks with a frequency reuse factor of 1, is proposed. The performance of the proposed algorithm is compared with the conventional frequency reuse and non-cooperative transmission schemes with PFS and MRS scheduling techniques. The numerical results demonstrate that the proposed method can outperform other schemes when CCI is the performance limiting factor, by providing significant diversity gains.

MIMO and OFDMA methods increase the system performance significantly. However, for full efficiency they need full CSI at the base stations which is impractical to implement because of the necessary feedback load. Hence, the proposed algorithm is designed to work with little channel state information at the transmitter and with limited feedback from users to base stations. Random transmit beamformers and MMSE receiver beamformers are used to increase the performance under these conditions. CCI is the most important performance degrading factor in multicellular systems. Instead of the traditional frequency reuse method, a more efficient cooperative transmission method with power allocation based on distances between users and base stations, is proposed. In order not to increase the feedback load, the backbone network between base stations is used for the information exchange instead of the uplink phase as much as possible.

Our investigation of characteristics of the transmission strategies, firstly demonstrate that cooperative transmission scheme can provide all the users with acceptable SINR levels regardless of their locations in the cells. This is especially important for the cell edge users that typically suffer from CCI the most.

Sometimes, mitigating CCI with orthogonal transmission may not be enough to provide a cell edge user with acceptable SINR levels due to shadowing affects. For example, there can be an obstacle between a user and its own base station, however the user might have a better channel from the other base stations. Unlike orthogonal transmission strategy, cooperative transmission can exploit spatial diversity, i.e., the better channels of the two neighboring base stations, to increase the coverage area. Secondly, the statistical results about transmission strategies demonstrates that cooperative transmission is used more often when CCI level is high and fairness between users should be satisfied, which were the aims of the proposed algorithm.

The numerical results demonstrate the advantages of the proposed cooperative transmission scheme over noncooperative schemes. Firstly, it exploits multiuser diversity at both low and high CCI regimes, since all subchannels can be used systemwide and adaptively with noncooperative and cooperative transmission strategies. Secondly, cooperative transmission with the proposed power allocation can provide significant spatial diversity gains. Hence, with MSR scheduling the cooperative scheme always outperforms other noncooperative schemes regardless of the CCI levels. Under PFS at high CCI levels, the cooperative scheme again has a better performance than the noncooperative schemes. However, at low CCI levels noncooperative and adaptive frequency reuse may have a better sum rate performance.

This issue can be explained with the fairness of the scheduling methods. Since joint scheduling is performed for all the users in the proposed cooperative scheme, fairness is maintained systemwide. In noncooperative schemes, all BSs only schedule the users in their own cells based on the feedback from their own users only, therefore fairness is maintained within a cell. The systemwide fairness property sometimes decreases the spectral efficiency at low CCI levels, since base stations may have to expend resources for the users in other cells. However, minimum achieved data rates are always higher for the proposed cooperative scheme. This is very important for practical systems, since there are always QoS requirements of users, where users' minimum data rates requirements should be satisfied. However, the mentioned gains come with a price. The proposed algorithm still requires more computations and data rate feedback by the users compared to noncooperative schemes. In addition, there must be continuous information exchange between BSs, which happens only during handoff operations for noncooperative schemes.

We also proposed some modifications to the algorithm considering performance versus complexity and feedback load tradeoffs. In the best random beamforming method, users calculate the achievable data rates on each subchannel with all the random beamformer matrices in the codebook and feed back the achievable rates with the index of the chosen random beamformer matrix. However, the numerical results demonstrate that, the performance improvement is not significant enough to justify the increase in the computation and feedback loads per subchannel. In the feedback reduction method, the cell is partitioned into two regions based on the proposed power allocation algorithm. In order to reduce the feedback load, the algorithm is modified in such a way that cell edge users only calculate and feed back cooperative data rates, since they typically have very low noncooperative data rates. The numerical results demonstrate that especially at high transmit SNR there is no loss in sum rates. Hence, computational complexity and feedback load can actually be halved for cell edge users. A final modification we offer is adaptive power control, where users consider both the proposed and uniform power allocation and chose the best. This modification can increase the performance at the expense of an extra rate calculation and an extra 1 bit indicating the best power control in the feedback per subchannel.

Our future work will mainly consist of investigating the practical issues about the algorithm to make it implementable in practical systems. An important point to consider is that distances between base stations and users should be determined accurately and this information must be present at both sides, since it is necessary for the power allocation algorithm. Synchronization is also very important for cooperative systems. The perfect frequency and timing synchronization assumptions should be verified, otherwise performance loss due to synchronization errors may have to be investigated. We want the mobile stations to be as simple as possible. Hence, we assume a simple linear receiver structure. The CCI mitigation is mainly done on transmitter side. It would be interesting to compare the proposed scheme with a noncooperative scheme where users attempt to mitigate CCI at the expense of increased complexity. In the proposed algorithm, users always have full buffers and for cooperative transmission user data can be shared among the cooperating base stations over the backhaul, which is our traffic assumption. However, a detailed analysis with different traffic models that are used in everyday applications might be necessary.

Feedback and backhaul loads should be within the capacity of the given links. Otherwise, methods to reduce these loads without decreasing downlink spectral efficiency below the targeted values should be investigated. Since fair schedulers are preferred in real world systems, there seems to be no problem in using the feedback reduction method for cell edge users. For inner cell region users, reduction may be achieved by defining a threshold for data rates. The cooperative data rates can be fed back only when the achievable data rate is under this threshold for that subchannel, but this may cause the pairing problem stated before. Another method can be omitting the noncooperative transmission strategy completely especially for high CCI regimes, where it is used very rarely. Finally, since small scale fading effects are not as significant as large scale fading effects, the achievable data rates on different subchannels for the same user might be correlated. Hence, data rates can be fed back for smaller number of subchannels.

Since our main aim is to implement a practical system, the proposed algorithm is rather suboptimal due to limited CSI assumed at the transmitter side. In order to investigate the performance loss due to this suboptimality, it may be a good idea to compare it with the optimum system without subchannelization and assuming full CSI at base stations, where optimal bit, subcarrier and power allocation can be employed. This will provide a theoretical upper bound on the performance of a cooperative multicellular MIMO-OFDMA network.

The last issue to be considered is the ICI problem, which is an important performance degrading factor for multicarrier systems. The simulations in this thesis are done at very low mobility scenarios, where ICI can be shown to be negligible, with perfect frequency synchronization. However, WiMAX is planned to be used under high mobility scenarios such as on a car going with 120 km/hr on highway or even on a high speed train with speeds over 300 km/hr. Simple analysis shows that ICI becomes significant on these high speeds. It is hard to exactly find the effect of ICI for the proposed algorithm, due to PUSC permutation causing subchannels to be composed of diverse subcarriers, adjacent subcarriers can be used by different base stations scheduling different users with different power allocation and transmission strategy. However, it may be possible to find simpler upper bounds for the rate loss caused by ICI, and if these losses are significant, the algorithm must be improved to mitigate the ICI as well.

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