Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Realistic Multi-Cell Interference Coordination in 4G/LTE

Examensarbete utfört i Kommunikationssystem
vid Tekniska högskolan i Linköping
av

Sara Örn

LiTH-ISY-EX--12/4586--SE

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Realistisk multicell-koordination av störningar i 4G/LTE
Realistic Multi-Cell Interference Coordination in 4G/LTE

Författare
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Sammanfattning
Abstract

In the LTE mobile system, all cells use the same set of frequencies. This means that a user could experience interference from other cells. A method that has been studied in order to reduce this interference and thereby increase data rate or system throughput is to coordinate scheduling between cells. Good results of this have been found in different studies. However, the interference is generally assumed to be known. Studies using estimated interference and simulating more than one cluster of cells have found almost no gain.

This thesis will focus on how to use information from coordinated scheduling and other traffic estimates to do better interference estimation and link adaption. The suggested method is to coordinate larger clusters and use the coordination information, as well as estimates of which cells will be transmitting, to make estimates of interference from other cells. The additional information from interference estimation is used in the link adaptation. Limitations in bandwidth of the backhaul needed to send data between cells are considered, as well as the delay it may introduce. A limitation of the scope is that MIMO or HetNet scenarios have not been simulated.

The suggested method for interference estimation and link adaptation have been implemented and simulated in a system simulator. The method gives a less biased estimate of SINR, but there are no gains in user bit rate. The lesser bias is since the method is better at predicting high SINR than the base estimate is. The lack of gains regarding user bit rate may result from the fact that in the studied scenarios, users where not able to make use of the higher estimated SINR since the base estimate is already high.

The conclusion is that the method might be useful in scenarios where there are not full load, but the users either have bad channel quality or are able to make use of very high SINR. Such scenarios could be HetNet or MIMO scenarios, respectively.

Nyckelord
Keywords

link adaptation, interference estimation, coordinated scheduling, LTE, 4G, radio resource management

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Contents

Abbreviations

BLEP	Block Error Probability
BS	Base Station
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check (code)
CDF	Cumulative Density Function
GSM	Global System for Mobile Communications
eNodeB	A logical node handling transmission/reception in multiple cells in LTE, might be implemented as a base station
HARQ	Hybrid Automatic Repeat-reQuest
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
QPSK	Quadruple Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RB	Resource Block
RSRP	Reference Signal Received Power
SINR	Signal to Interference plus Noise Ratio
SMS	Short Message Service
SNR	Signal to Noise Ratio
TTI	Transmission Time Interval
UE	User Equipment

Chapter 1

Introduction

The first generation of mobile telephony systems was developed in the 80's. Since then, the trend has been to offer higher and higher data rates with each new system. The second generation of systems, such as GSM, were digital. They introduced for example some low data rate services like SMS. Still, data transmission rates were not that impressive. When 3G arrived, the focus had shifted towards data transmission, and it become possible to for example use a 3G modem to access internet anywhere. Currently, a system called Long Term Evolution (LTE) is being deployed. In LTE and its continuation LTE-Advanced, data rates up to 1 Gbit/s are possible for downlink transmissions. However, even if these high data rates are theoretically possible, the actual data rate might be considerably lower if the radio link is affected by noise and interference. This makes it of interest to try to reduce interference and noise levels, to get better data rate or to increase coverage.

One source of interference is the interference coming from other transmissions in the same system, either other users belonging to the same base station or coming from other cells. In downlink LTE, there is no interference between different users belonging to the same base station, since orthogonal frequency division multiplex (OFDM) is used. Interference from other cells, on the other hand, can often be the dominant source of impairment of the radio-link [4], as all cells may use the same set of frequencies. One way to decrease this interference between cells is to use coordinated scheduling, that is to coordinate the transmissions in several cells. Since the point with this coordinated scheduling is to take into account interference caused to other cells, it is obviously important to have estimates of these interference levels when doing the coordination.

This thesis will investigate a method for coordinated scheduling in LTE, and a new method for calculating the expected interference from other cells using the information from the coordination together with traffic estimations. The interference estimation is based on an idea by Ericsson colleagues. A link adaptation method which can take advantage of the new information from interference calculation will also be studied.

1.1 Thesis outline

We first give a short background about LTE in chapter 2, with focus on scheduling and interference estimation. Therein, we also give a brief overview of literature regarding coordinated scheduling. For readers not familiar with LTE and scheduling, it will be useful to read this chapter in order to understand the rest of the thesis. Then, the result of the literature study is given in chapter 4. We give the problem description in chapter 3. Chapter 5 explains the suggested method, and chapter 6 gives the setup for simulations and the results of them. Finally, we discuss the result and some ideas for future continuations in chapter 7.

Chapter 2

Background

In this chapter, first information on some parts of LTE is given, including link adaptation, multi-antenna transmissions, and channel estimation. Then some information on scheduling follows. Last, a very brief summary of the literature study of coordinated scheduling is given. Most of the material presented in this chapter are taken from [4]. For more information, the interested reader is refered to [4] and the references therein.

2.1 LTE

LTE is a cellular mobile system, were each cell is served by an eNodeB. An eNodeB is responsible for all the radio-related functions in one or several cells. However, eNodeB is a logical node, not a physical entity, and can be implemented in different ways. One common implementation of an eNodeB is one base station handling three cells, each having their antennas on the same site but directed in different directions.

The transmission scheme used in LTE for downlink transmissions is OFDM. In OFDM, data is first modulated with for example QPSK or 16-QAM. The modulated data is then split on a large number of subcarriers with relatively low bandwidth that are transmitted in parallel. This gives a good performance even in the case of frequency selective fading. It also gives the possibility to control precisely the amount of bandwidth given to each user. These subcarriers are orthogonal to each other, that is, there is no interference between users within the same cell. However, in LTE all cells use the same set of frequencies, so there might be interference from other cells.

To compensate for different channel conditions and to avoid getting high error probability at low signal to interference and noise ratio (SINR), rate control is used for the downlink transmission. That means that the transmitter generally transmits at full power, while the data rate of the transmission is changed to compensate for the variations in channel quality. When the channel quality is good, a higher order modulation and a higher rate code are used, giving a higher data rate, with the opposite for low channel quality. In uplink, the available power is more limited and the situation is a bit different. Rate control however might give lower rates for users with low SINR. Low SINR might be due to the user being far away from the base station and therefore having lower signal strength. It might also be due to interference from other cells.

2.2 Multi-Antenna Transmission

A part of LTE is the support for techniques using multiple antennas. There can be multiple antennas both at transmitter and receiver. With multiple transmitting antennas so called beam forming can be used to maximize antenna gain in a specific direction. The antennas can also be used to use the varying statistics of the channel in order to get a better signal at the receiver, so called transmit diversity. With multiple receiver antennas, receive diversity can be used to suppress noise or dominant interferers. Standard in LTE is to have at least two receive antennas. If there are multiple antennas at both transmitter and receiver, they can be used to transmit more than one data stream in parallel. This gives higher data rate at the same bandwidth. This is often called Multiple Input Multiple Output (MIMO). The multiple antennas can also be used to let several users receive data at the same time and frequency, if the proper interference cancellation is used. This is called multiuser MIMO. LTE uses MIMO to make use of good channel conditions and get a high bit rate, instead of using very high order coding and modulation schemes.

2.3 Heterogeneous Networks

The system with relatively large cells is good for giving basic coverage of an area, but sometimes there are places where the demand for data rates is higher locally, or where there are more users, so called hot spots. It could also be hard to provide good enough coverage indoors when using large cells. In this cases, Heterogeneous Networks, HetNet, can be used. In HetNet normal base stations are used to provide basic coverage. These cells are called macro cells. At hot spots, smaller base stations with lower output power, micro or pico cells, are placed. They serve only the nearby area. Since these cells are deployed in the coverage of the larger cell, interference issues might get more important. A hot spot could for example be a town square where there are often a lot of people.

2.4 Scheduling

Scheduling deals with deciding which users who will be allowed to receive or transmit data, and with allocating the available physical resources to those users at each time instant. The scheduling is done by the eNodeB, based on measurements by and requirements from the UE. LTE generally uses dynamic scheduling. That means that for each interval of 1 ms, the eNodeB decides how to schedule its users, and sends this decision to them. Uplink and downlink scheduling are separate, but we will focus on downlink.

Resources are shared between users in both time and frequency. The minimum unit for resource allocation is a pair of two consecutive resource blocks in time. A resource block consists of twelve subcarriers in the frequency domain and one time slot in the time domain. A slot is 0.5s long and normally has 7 OFDM symbols, so that a resource block can carry $12 * 7 = 84$ symbols. The smallest physical resource in LTE is called resource element, which consists of one OFDM symbol and one subcarrier, see figure 2.1.

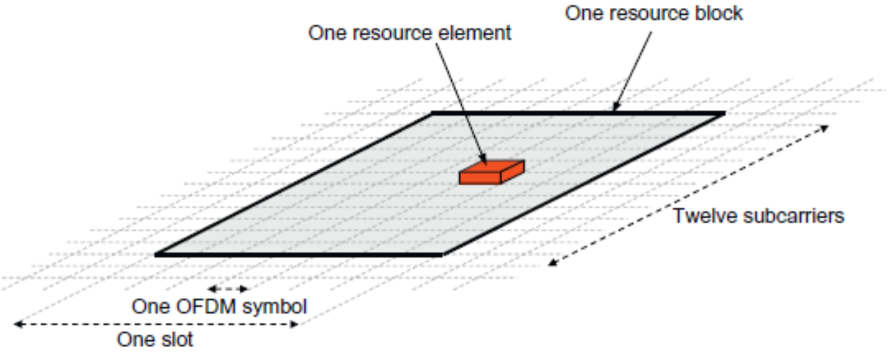

Figure 2.1. One resource block, consisting of seven OFDM symbols in time and twelve subcarriers in frequency, from [4, fig 9.2]

In order to use resources more efficiently, channel dependent scheduling might be used. In channel dependent scheduling, the fact that channel conditions vary are used: a frequency band that currently is bad for one user might be good for another. The scheduler therefore tries to give each frequency band to the user who can use it best, see figure 2.2.

There are different methods of scheduling that can be used, depending on the goal of the scheduling. One method is to schedule the users that maximize the total data throughput. The max-C/I or maximum rate scheduler tries to do that by always assigning a resource block to the user who has the best channel quality. If the variations in channel quality is only coming from fast fading effects, this will in average give all users the same data rate. There will be variations in data rate, but they will be fast. Generally that is not a problem, especially not for packet based services where higher variations in data rate can be tolerated. On the other hand, there might be differences in average channel quality, for example from shadowing or because a user is far away from the eNodeB. A user might then have a lower channel quality most of the time and therefore seldom get scheduled.

Another method of scheduling is to let the users take turns in using the shared resource, so called round-robin scheduling. This does not take channel quality into account when deciding which user to schedule, but might do it when deciding which frequencies to give to the scheduled users. This method is fair in the sense that all users get the same amount of resources. However, they may still get

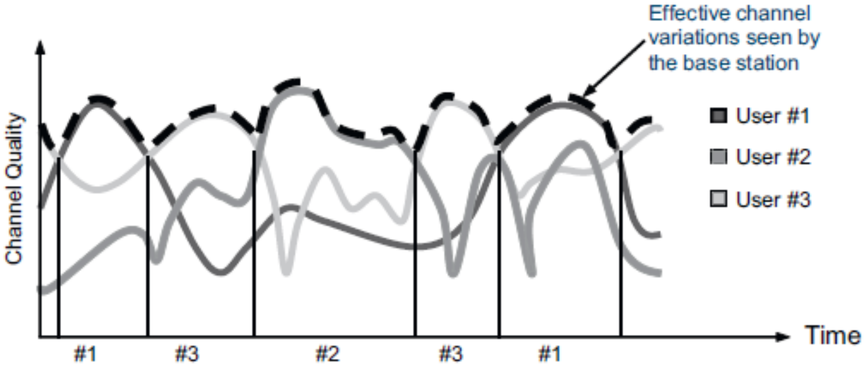

Figure 2.2. channel dependent scheduling. Taken from [4, figure 6.2]

different resulting data rate. It also results in a lower total throughput than that of the max-C/I scheduling [4].

The proportional fair scheduler tries to take into account both instant channel conditions and the need from users to have some minimum throughput. It can be seen as a compromise between the two earlier mentioned schedulers. The proportional fair scheduler assigns resources to the user with the best channel quality, relative to the average channel quality for that particular user. That way a user will get resources when its channel is relatively good, regardless of whether it is better than the other users' channels or not. See figure 2.3 for a example of the three mentioned schedulers.

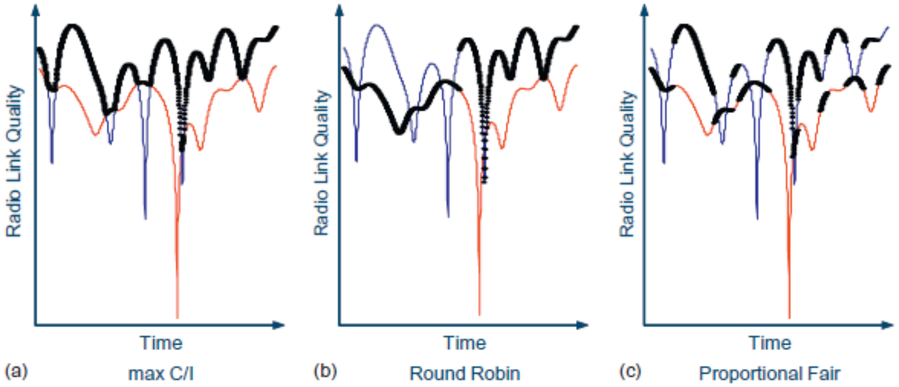

Figure 2.3. Example of the scheduling of two users with different average channel quality, with different scheduling methods: a) max C/I, b) Round Robin scheduling, c) Proportional Fair. The selected user is shown with bold lines. Figure is taken from [4, figure 6.3]

2.5 Coordinated Scheduling

Even if LTE is designed so that all cells can use the same set of frequencies, that could mean large variations in the data rate to the users, depending on how much they are interfered by other cells. By coordinating the transmissions in neighboring cells, it is possible to reduce interference to users who are most interfered by other cells. It therefore gives higher fairness between users in a cell or higher total throughput in the system. The idea behind the coordination is that if the transmissions in a cell are causing a lot of interference in another cell, the total system throughput might be higher if the interferer stops transmitting. That would be the case if the gain from being able to send with higher rates in the interfered cells is higher than the loss from muting the other cell. Coordinated scheduling can also increase fairness between users by increasing data rates of the users with the lowest channel quality, at the expense of users with better channel quality and therefore higher data rates. Coordinated scheduling is generally done for predefined groups of cells, as it is computationally hard to do it ideally [3]. These groups will be called clusters.

In LTE, there is no higher node above the eNodeB which can do the coordinated scheduling. In order to be able to coordinate different cells, the eNodeBs of those cells must therefore be able to communicate with each other. In some cases, one eNodeB is responsible for several cells, such as in the three-sector site case. This gives a natural small cluster of three cells. In the case of HetNet, a macro base station can form a cluster with the picos in its cell.

If coordination is done between cells belonging to different eNodeBs, the so called backhaul network has to be used for communication between the eNodeBs. Then the bandwidth of the backhaul and the delay ut introduces needs to be considered when studying the coordinated scheduling.

2.6 Channel Quality Estimation

In order to do scheduling that takes interference levels and channel qualities into account, it is obviously necessary for the scheduler to know those levels. Estimates of channel qualities are also needed in the link adaptation as explained below. There are two different sources of information on channel quality. One is the Channel-Quality Indicator (CQI). This is a report sent by the user, at regular time intervals or when requested by the eNodeB. There are three different modes available for this report, and it is the eNodeB who tells the UE which mode to use. The channel quality indicator can be an average of the values for the entire carrier, information on the chosen best frequencies together with an average, or information on the bands specifically asked for by eNodeB. According to [4], these reports are mostly useful if the radio channel is relatively constant. Another information source is Reference Signal Received Power measurement (RSRP) which is a measurement by the UE of a reference signal sent by each cell. The value is measured on a number of subcarriers ranging from six up to all subcarriers [2]. The exact implementation is up to the UE, and the value might be averaged over time. Often, only some of the strongest interferers can be measured separately. For the weaker interferers, an average interference can be obtained by measuring total received interference and subtract the individually measured stronger interferers.

2.7 Link Adaption

Link adaption is about compensating for varying channel conditions by adapting the used coding, modulation and mapping of data to antenna ports.

Link adaptation is done for an interval of 1 ms. This is the same time interval as used in the scheduling. In each such time interval, one or two transport blocks with information is sent to the physical layer, where it is processed and transmitted. The size of the transport blocks depends on instantaneous channel quality estimates. If the channel quality is bad, more coding bits are needed to be able to find and correct errors from the channel. Also, a lower order modulation is needed, giving fewer information bits per modulated symbol. In the case of bad channel quality, the transport block will therefore be chosen to be small.

The first processing that is done on the information bits in the transport block is to add a 24 bit long cyclic redundancy check (CRC) code. This code is only used for detecting errors. It is used in the HARQ process, which requests retransmissions if errors are detected in the received data. After the CRC attachment, a turbo code is added, to correct errors from transmission, and then the data is modulated. The modulation formats used in LTE are QPSK, 16QAM and 64QAM [4]. These modulations make it possible to transmit 2, 4 or 6 bits per modulated symbol, respectively. A higher modulation gives higher bit rates for the same bandwidth but is more sensitive to channel quality. When modulation and coding have been chosen, the symbols as given from modulation are mapped to antenna ports. Finally, the modulated symbols are sent, on the resource blocks that are allocated to the user by the base station.

2.8 Literature Overview

Coordinated scheduling in order to increase throughput has received quite a lot of attention in literature. A common approach is to start by formulating the optimization problem of choosing which user each base station should transmit to and at which frequencies. Since this problem is computationally hard, as shown in [3], it is common to form some kind of greedy algorithm. Often the algorithms are distributed to be calculated for groups of neighboring cells, which will be called clusters. The coordination might also be done in two different time scales, in order to avoid the need for immediate communication between cells, as in [5], [7]. Some methods, for example an internal study [1], let each cell do their scheduling of users first and send that decision to the coordinating scheduler. That scheduler then decides the allowed power level for each transmission. In other methods, for example [5], [7], the coordinated scheduling is done first, possibly using only long term channel information. Then, each cell schedules the given user if it has data and some other if it has not. Some authors try to takes fairness between users into account. A common assumption is that the interference to users from other cells is perfectly known, or at least that the interference from the largest interferer is known.

In an internal study [1], a method of coordinated scheduling was studied by simulations of systems with one or several clusters. The authors found some gain with the proposed method, but when simulating a system with several clusters, the gains were small. It was also found that the gain was smaller with smaller clusters.

Chapter 3

Problem Description

When doing coordinated scheduling by splitting cells into clusters and coordinating only cells inside the same cluster, only the other cells in the same cluster will be able to take advantage of the coordination. Cells outside the cluster might get lower interference if an interferer is silent, but they do not have that knowledge in advance. That means that they must always assume that all cells outside the cluster are transmitting when doing link adaptation. This is also how the basic estimation of SINR for a user is done, since the reference signal is transmitted for all cells at the same time. When doing coordinated scheduling, estimates of how much interference a user will actually experience at the time of data transmission is used. But these estimates require knowledge of which cells are going to transmit data at that time. If both the interfering and the interfered cell are in the same cluster, that information can be obtained from the coordinated scheduler. But the coordinated scheduler uses those interference estimations to make its decision. If instead the cells are not in the same cluster, they have no information on whether the other will transmit or not, since there are generally no layers above the eNodeBs in LTE.

This thesis will focus on how to use information from coordinated scheduling and other traffic estimates to do better interference estimation and link adaption for the downlink. The suggested method is to:

- Coordinate larger clusters in order to reduce border effects. Then the cells cannot be assumed to have delay free communication. Therefore coordination has to be done some time in advance, before the cell scheduling. The idea is to coordinate all cells beforehand and send this coordination decision to the cells, so that all the cells know which cells are allowed to transmit. Since this coordination is done some time beforehand, it cannot take immediate channel and traffic conditions into account.

- Make estimates of interference from other cells. For this, take into account both coordination decisions if available, and estimates of which cells will be transmitting.

- Make a link adaptation which can make use of more of the information generated in interference estimation, not only the final SINR estimate.

The suggested solutions will be studied by implementing and simulating them in a system simulator. The goal is to increase system throughput, without increasing the unfairness between users regarding their achieved data rates.

Chapter 4

Literature study

In this chapter, summaries of some other work regarding coordinated scheduling are given.

4.1 Computational Complexity for an Ideal and a Heuristic Scheduling Method

In this article [3], the authors first formulate the problem of network-wide scheduling and load balancing. An assumption is that each base station only transmits to one UE at a time. The first formulation uses load balancing, which implies that a user may be served by any base station. This problem is shown to be very complicated. The problem is then simplified by assuming that each UE only belongs to one predetermined base station. Binary power control of the cells is used: a cell may only transmit at two different powers, where the lower power can be zero or some other suitable value. Binary power control is shown to be optimal if the channel capacity is linear to the SINR. The problem is also split into an outer and an inner problem, to be optimized one at a time. Still, the simplified problem is shown to have too large computational complexity for being useful in practical systems.

This leads the authors to propose a heuristic method for distributed coordinated scheduling. The suggested method consists of three steps. In the first step, each base station makes a list of UEs that could be the best for that base station to transmit to. The first selected user is the one that would be the best if all the neighboring cells were transmitting. The selection of the best user is then repeated for the cases that one of the neighboring cells at a time is muted. In the second step, each base station transmits its list of chosen users to all its neighbors. In the third step, each base station calculates a locally optimized solution for itself and all the neighboring cells, by using the lists from the first step. The base station then finds one of its users belonging to this optimal solution, and schedules it. If the cell has no user in the optimal solution, it may not transmit at all. This means that all cells solve the problem for themselves and their neighbors, but discards the part of the solution belonging to neighbors. The authors end by concluding that even this simplified scheme has large computational complexity.

This method requires delay free communication between a cell and all its neighbors since the coordinated scheduling is done after the cell scheduling. Since all cells transmit information to all their neighbors, it is not possible to split the cells into groups where all cells in the group have delay free communication only with the other cells in the group. The assumption of linear channel capacity can not be assumed to hold in a real system. This thesis will still use binary power control. An internal study [1] found that the gains of using power control with more levels than on/off is limited. It is interesting that the computational complexity was found to be high even in the simplified scheme suggested by the authors. This high complexity was a reason for choosing a very simple method of coordinated scheduling in this thesis, in order to be able to simulate a system with several clusters in reasonable time.

4.2 Radio Resource Allocation for Multi-Cell OFDMA System

In this paper [7], the authors propose an algorithm for coordinated scheduling for downlink OFDM systems. The proposed algorithm makes decisions on two levels: at a larger level that is called radio network controller, RNC, and at base station level. The RNC controls a number of base stations, and makes decisions on a larger time scale. It assigns channels to each base station and makes recommendations of which user to schedule by using a greedy algorithm that starts with the cell that is considered to be most under-assigned. These assignments of channels and recommendations of which user a cell should transmit to are then sent to the cells. Each cell decides on which of its assigned channels it should schedule each user on, taking instant channel conditions into account. If the user indicated by the RNC does not have data, the cell chooses another. This can be done without changing the interference to other cells, since the interference condition in other cells is not affected by which user the cells transmit to. Therefore, if an indicated user has no data, it is better to transmit to any user than not at all. The simulations in this paper are done for one cluster.

This algorithm gives no guarantee that a user or cell is given some minimum amount of resources, which makes it impractical for actual systems. An advantage with the algorithm is that there is no need to know the interference from each other cell to a user: only the interference from the largest interferer is estimated, the rest is considered as noise. This is good in order to reduce the amount of overhead data. Still, channel quality information for each user for each subband has to be sent to the RNC. If there is a delay in the transmission between cell and RNC, this information might be outdated before it is used, especially if the superframe coordination pattern is chosen to be valid for a longer time.

4.3 Resource Allocation for Guaranteed Bit Rate Services

In this paper [6] the authors propose a multi-cell algorithm that takes into account the need for minimum rates, the amount of communication that are reasonable and possible between nodes, and fairness between users. The scheduling is done on two different timescales. On the larger time scale, called a superframe, power control between base stations in a group are done, as well as allocating resources to them. Here, only long term channel conditions are taken into account. On the smaller time scale, called frame level, each BS allocates its available resources to its users, considering instant channel conditions.

First, the paper assumes narrowband services, where each user should be assigned a predefined number of resource blocks during the super frame. On superframe level one base station at a time is considered. For each user of the base station and for each resource block, the number of additional bits that would be sent if the RB was allocated to that user is calculated. In this calculation, the interference caused by transmissions on RBs allocated to base stations in previous steps is considered. An allocation of the RBs to the users of the current base station is done by solving an optimization problem. A requirement here is that all users must get a preset number of RBs. This is repeated for all base stations. When all assignments are done, a power control algorithm tries to increase throughput by checking if reducing power of the major interferer of a user increases throughput. The final result of this larger time scale allocation is an allocation for one frame that is repeated for the whole superframe. Using this allocation, each base station solves a similar optimization problem for its users. Now instantaneous channel conditions are taken into account, and the objective is to maximize the total throughput.

The solution for the narrowband is then used as a start for considering elastic services. Elastic services means that each user needs at least a fixed amount of data but could make use of more. In this case, the narrowband allocation is done first to make sure each user gets the resources it needs. After that, the remaining RBs are allocated to maximize overall throughput, with power control and base station scheduling done the same way as for the narrowband case.

Unlike for example the previously mentioned study [7], this paper addresses the issues of guaranteeing a minimum bit rate and fairness between users. This would obviously be useful in a practical system. However, this leads the authors to a method that contains an optimization problem. Since implementing solution methods of optimization problems is beyond the scope of this thesis, we will try a much less sophisticated method of giving a minimum amount of resources to all cells. In the simulation results in [6], the authors used a simplified model where the population of users is static and all users always have data. Also, they also assumed ideal link adaptation and simulated only one cluster.

4.4 Internal studies

Two internal studies [1] was used as main motivation for the work in this thesis. In one of the studies, coordinated scheduling was studied for both one and several clusters. A greedy algorithm was used with the cell scheduling as input, to decide if it was beneficial to mute some of the cells in a cluster. The authors found some gains, but when simulating more than one cluster, the gains were small. It was found to be better to use larger clusters. Ideal link adaptation and very high load of the system were assumed. Another internal study by the same authors used coordinated scheduling with non-ideal link adaptation and found no gains. One reason was believed to be that the interference reductions coming from the coordination were not known to cells outside the cluster.

Chapter 5

Algorithms and implementation

In this chapter, the chosen method will be described. First, an overview of the suggested method is given. Then the suggested method for coordinated scheduling, interference estimation and link adaptation are explained more in detail.

5.1 Overwiew

The suggested method is to use two levels of coordinated scheduling together with the normal cellwise scheduling, see figure 5.1. The first level coordinates a larger group of cells, in order to reduce border effects between scheduling areas and make the coordination known to as many cells as possible. This will be called the pre-muting. The second level is the coordination done between the cells in a cluster. This will be called the cluster scheduling. The first larger scale coordination is done before the normal cell scheduling, due to the delay that are assumed between clusters. In this larger scheduling, a pre-muting pattern is decided for all the cells, figure 5.1 a). The pre-muting pattern is sent to all cells, so that all cells will have knowledge of the muting pattern for all other cells as well as their own. The cells then make their scheduling of users, figure 5.1 b), on the resources they are not pre-muted on. When doing the estimates of the users channel quality that are necessary for the scheduling, the cells can then make use of the known muting pattern for other cells, as described in chapter 5.3. After the cells have scheduled their users, they make their scheduling decisions known to the cluster. Then the second level of coordination is performed, figure 5.1 c). This means that this coordination can make use of the result of the cell scheduling. Thus, it is now known which user each cell will transmit to, as well as current channel conditions. When doing the scheduling, the cluster calculates how much interference the transmissions to the scheduled users will cause other users in the cluster. Using this, it decides if it is beneficial to mute more cells than the ones already pre muted in the first coordination round. When the cells then transmit they will have exact knowledge of which cells in the same cluster that are transmitting. For cells outside the cluster, it is known if they are pre muted or not.

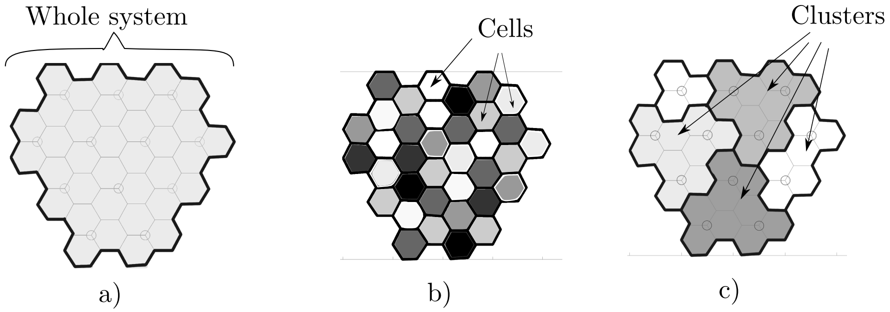

Figure 5.1. Different amounts of coordination between cells: a) The whole system b) No coordination c) Coordination in clusters

5.2 Pre-muting Pattern

The first stage of scheduling is not mainly intended to give actual scheduling gains, from reducing interference levels. Instead, it is meant to make it possible to do a better link adaptation. This is done by trying to mute cells only on resources that they will not need. That way, the muting pattern serves mostly to make it known to all cells, beforehand, when another cell will be quiet. Ideally, the pre-muting pattern should be able to guess exactly how much resources a cell will need. In practice, some traffic estimate has to be used. The amount of allocated resources can then be adapted to how much the cell really has used by feedback from the cells.

5.2.1 Algorithm

The basic idea for the pre muting algorithm is to use a traffic estimate for each cell to calculate the amount of resources a cell is estimated to need. Each cell will then be assigned that amount of resources, plus some additional resources. This additional amount serves two purposes. The first purpose is to always give a cell some minimum amount of resources, even if is estimated not to need any resources. The second purpose is to help adapting the amount of resources that are allocated to a cell by considering how much of the resources that the cell actually used; if the cell used more than it was estimated to need, the estimate was too low. Then the amount of allowed resource should be increased in next assignment.

The resources that are given are the number of transmitting time intervals, TTI, that a cell is allowed to send on during a muting pattern. The muting pattern was chosen to be eight TTIs, that is eight ms, long. During a muting pattern, a cell might be muted a number of times, depending on how much interference it is estimated to cause other cells. Regardless of the interference it causes, a cell will be guaranteed a minimum amount of unmuted time, it will never be muted all the time. For each TTI during one pre muting pattern, a cell is muted or not muted on all RBs, not per subband, see figure 5.2. The muting is thus done only over time, not over frequency. This is chosen partly because the RSRP measurements used as channel estimates are not necessarily available per subband, partly to give less computation, and partly in order to send less data over the backhaul.

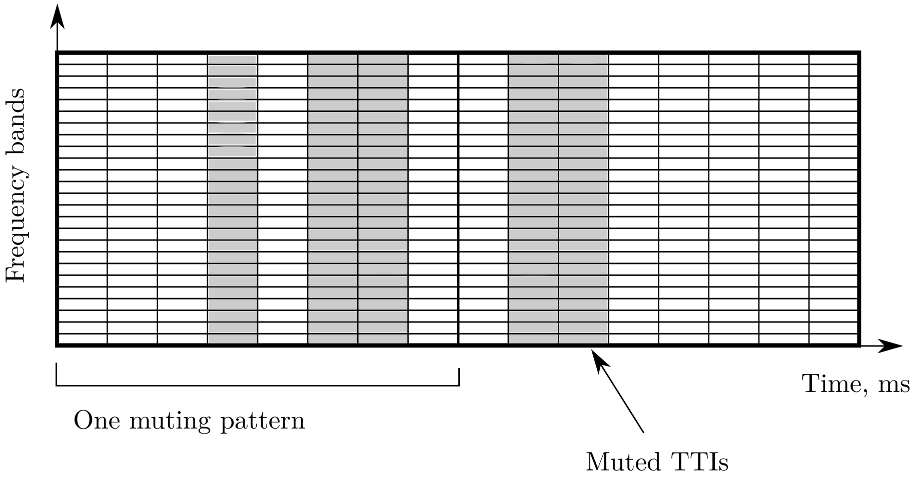

Figure 5.2. Example of muting patterns for one cell

When the number of TTIs a cells is allowed to transmit on are decided, the probability that the cell should be muted on a TTI are calculated. For the first TTI, the probability is simply $\frac{N_{\text{muted}}}{N}$, where N_{muted} represents the number of muted TTIs in the muting pattern and N the total number of TTIs in the muting patttern. For subsequent TTIs in the pattern, probabilities are also scaled to account for how many TTIs a cell has already been muted on. This scaling gives about the correct number of muted TTIs for each cell in a pattern. It was chosen to be more important to give each cell the decided number of TTIs than to minimizing interference. Therefore the algorithm prioritizes to give each cell the correct number of TTIs to transmit on, by using the scaling. If it is possible, it also gives some consideration to the interference between cells; when a cell is muted, the cell that was most interfered by it has a larger probability of being allowed to transmit. The most interfered cell is defined as the cell that has the largest numbers of users that state the given cell as their largest interferer. Since this information has to be reported a time before it is used due to the delay, it might be outdated. The idea behind this choice of definition of ‘interfered’ is that a cell that previously had many users that was interfered by the given cell probably still is interfered by it to some amount, even if the user population and channel conditions have changed a bit.

5.2.2 Traffic Estimate

The traffic estimate used to determine the amount of muting of a cell is an important part of the algorithm. The traffic estimate that we will use is the probability that a cell is muted by the cluster, given that it has data to send. If it does not have data, it is considered to not be muted.

$$P_{\text{premuted}} = \begin{cases} P_{\text{clustermuted}}, & \text{cell has data} \\ 0, & \text{cell has no data} \end{cases}$$

The assumption is that the cluster scheduler has some good method of calculating which cells should be muted, since it knows the instantaneous traffic conditions and cell scheduling decisions. Therefore, it would be good to try to predict these decisions, and use them in the pre-muting. That would make the cluster information known to cells both in and outside the cluster in advance. Using this traffic estimate also gives the pre-muting pattern some degree of fairness if the cluster scheduler has that, and reduces the risk that the two levels of scheduling are working against each other.

5.3 Interference Estimation

The purpose of interference estimation is to estimate the SINR a user will have at the time of transmission. The suggested method makes use of the probability that each cell is going to transmit and the interference it will cause by doing this. The algorithm first estimates sending probabilities, and chooses a suitable set of interfering cells to use. For these cells, a cumulative density function, CDF, of estimated interference is calculated. This CDF can either be used in the new link adaption, or be used to choose a SINR value.

Different amounts on scheduling information might be available when doing the estimation depending on if the estimation is done during cell scheduling, cluster scheduling or transmission.

When used for cell scheduling and cluster coordination, only pre muting information is available. When transmitting, the cluster scheduling information can be used. This interference estimation method can also be used without coordination. In that case, no pre or cluster muting information is used. The cells still have knowledge of the scheduling done by other cells in the cluster.

5.3.1 Sending Probability Estimation

In the interference estimation method, the probability that each cell is going to transmit is used. If coordination is used and a cell is pre-muted, it is known that it will not transmit. Otherwise, the probabilities are calculated from the amount of resources the cell has used in the past, filtered by an exponential filter:

$$P_{\text{send}} = \max(\alpha * u/S + (1-\alpha) * P_{\text{send, old}})$$

where $\alpha = \max(\text{alphaPrameterValue}, 1/\text{nofUsesOfFilter})$, u is the used number of subband and S is the total number of subbands. This filter was chosen because it is simple to implement and does not require old values to be stored.

Since wideband estimation is used, a probability of for example 0.5 means either that a cell has been transmitting on half of the subbands all the time, or that it has been using all subbands half of the time. The impact on other cells are the same in both cases; for a given subband and time, there is a probability of 0.5 that the cell will cause interference.

In the case when the SINR is calculated after the cluster scheduling is done, a cell will know exactly how much the other cells in the same cluster will transmit. In that case, this information will be used instead of the estimated probabilities. The known transmitting probability for a cell in the cluster can still be something else than 0 or 1, if the cell is not going to use all the subbands.

5.3.2 Choosing Cells

Not all the cells will be used when generating the CDF. The cells that are known or estimated to be transmitting with probability zero can be removed, since they will obviously not case any interference. Cells with sending probability one can also be ignored, but in that case the interference they will cause are added to the background noise. Of the rest of the cells, only the ones that give the strongest interference are used. This is because the RSRP measurements in a realistic system can only be obtained for the strongest interfering cells. It also reduces the amount of needed computations. For the weaker cells not included, an average of their interference can be calculated and added to the background noise level.

5.3.3 Estimating Actual Interference

For the chosen cells, all possible combinations of cells transmitting or not are calculated, see figure 5.3. Each such combination will be called an event. For each event, an interference level can be calculated as the sum of the RSRP measurements of the cells that are transmitting. That means that for each event, both probability that it occurs and the interference level it would cause are known.

These events are then sorted in ascending order of interference to form a probability density function, PDF. This can be used in the suggested link adaptation method. If a single SINR estimate is desired, the events are instead used to calculate a discreet cumulative density function, CDF, of estimated interference. When using the CDF to get an SINR value, a probability should first be chosen. This probability is the desired probability of that the true interference is not higher than the one estimated. At this probability, an interference value is found. Due to lack of time, no interpolation between points in the CDF has been implemented. Therefore, the implementation that has been studied is such that the returned interference is the one for the closest point with higher interference. This interference I_{prob} is then used to scale the basic SINR estimate done from CQI reports, so that $SINR_{\text{est}} = SINR_{\text{base}} * I_{\text{prob}}/I_{\text{max}}$, where I_{max} is the maximum interference, regarless of whether it is feasible or not.

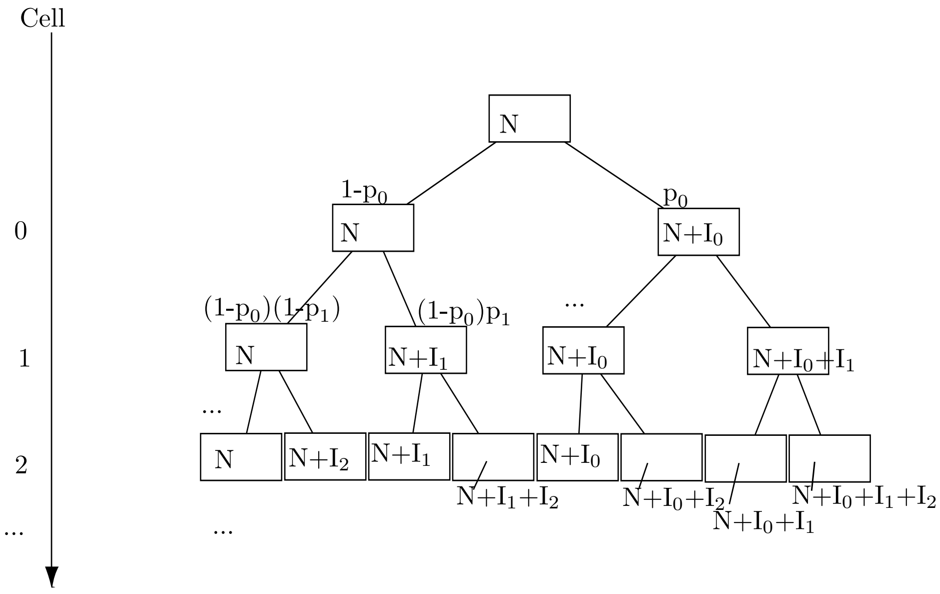

Figure 5.3. Probability tree with all events for the first three cells. Here, p_i is probability that cell i is transmitting, I_i is the interference cell i will cause if transmitting, and N is background noise.

Example 5.1: An example of SINR estimation

Note that this is just meant to illustrate how the interference is calculated, not to use realistic values.

There are three strong cells to be used. Probabilities of transmitting for these three cells are $p_0 = 0.5$, $p_1 = 0.9$, $p_2 = 0.2$. Background noise $N = 0.1$, and interference from cells is $I_0 = 1$, $I_1 = 2$, $I_2 = 5$. From this, a probability tree of all possible events is generated, figure 5.4.

From this probability tree, a PDF is generated. See figure 5.5.

The CDF is generated, and in this case, the probability that actual interference is not above the estimated is desired to be 85 %. From this, an interference level is found by using the next data point with a probability higher than 0.85. In this case, this gives an interference of 7.1, see figure 5.6.

The highest possible interference is found to be 8.1. This gives the scaling factor used to scale a basic SINR estimate, which gives $SINR_{\text{est}} = SINR_{\text{base}} * 7.1/8.1 \approx 0.88 SINR_{\text{base}}$.

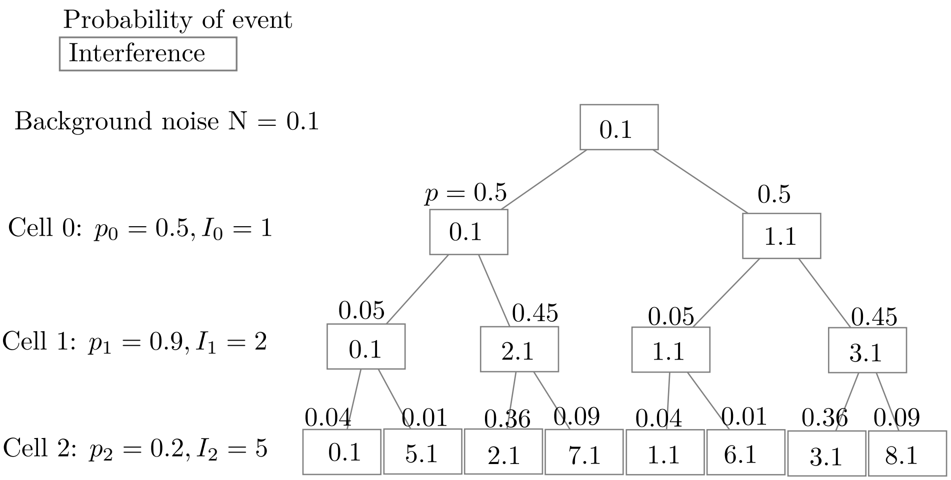

Figure 5.4. Probability tree with all events for the three cells, each with its probability and interference.

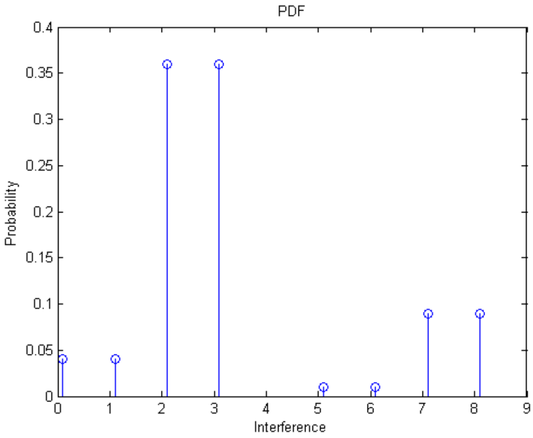

Figure 5.5. PDF showing interference and probability for the events.

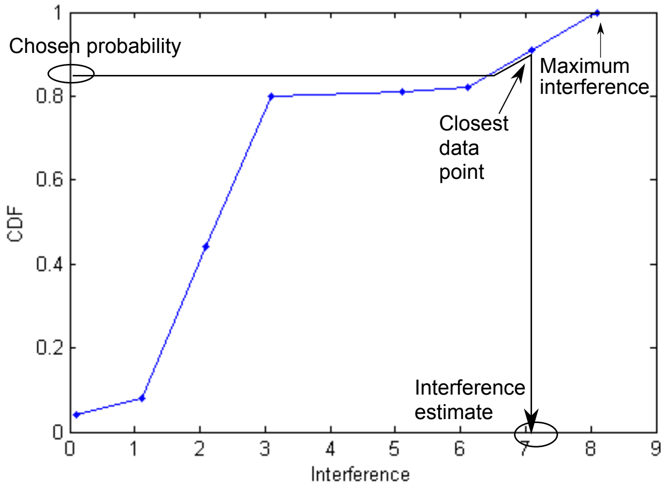

Figure 5.6. How to get the maximum and probable interference from CDF of the events.

The total number of events generated will be 2^n, for n cells. This rapid increase of events as the number of cells increases is another reason to only use the most interfering cells in the calculation.

5.4 Link Adaptation

In order to make use of the entire PDF generated in SINR estimation, a modified link adaptation method is suggested. The part of the link adaptation that is modified from the standard implementation is the one choosing coding and modulation scheme depending on channel qualities information. There are two slightly different versions of the method using different metrics. Both methods start with the lowest modulation. For that modulation, higher coding rates are tried until the metric that is used no longer increases, or a format that gives enough bits is found. If the highest coding rate is chosen, the next modulation is tried, with increasing coding rates, and so on. The algorithm is described in appendix A.

In the first version studied, block error probability (BLEP) for all the events is weighted together. Then the highest rate modulation and coding scheme (MCS) with lower BLEP than a given threshold is used. In the second version, the expected value of successfully received bits is maximized. This second method will be called the TBS version as the transport block size is used togheter with the BLEP to get the expectation value. For both methods, the possible combinations of modulation and coding are ordered such that each combination requires higher SINR than the previous one in order to give the target BLEP. Therefore, if one combination gives too high error probability, there is no need to try those with higher rate.

5.4.1 BLEP

In his method, the probability of getting errors in the transport block, BLEP, is used to choose MCS. For a given MCS, the BLEP that is given by the SINR of each event is calculated. Then these error probabilities are weighted together, using the probabilities that the events that caused them would happened as weights. This gives a total error probability for all the possible values of SINR. As long as this total BLEP is below a chosen threshold, the next code rate is tried. If the BLEP gets higher than the threshold even before all events are considered, the calculations for that MCS are aborted in order to save calculation time, since there is no possibility that MCS will be used. For pseudocode for the algorithm, see A.1.

5.4.2 TBS

This method is similar to the previous one but instead of using a BLEP target, the MSC that maximizes the expectation of the number of bits that can be received is chosen. For each event, the probability of successful reception of the transmitted transport block is calculated from the block error probability P_{be}. Then these probabilities are weighted together, using the probability that the event that caused them would happen, $\mathrm{p}(event)$, as weight. This gives a total probability of successful reception, P_{s}, for all the possible events with their corresponding values of SINR. This total probability is then multiplied with the size if the transport block for the current MCS, $\mathrm{tbs}(mcs)$, to get the expected value of received bits. As in the previous method, the MCSs are tried one by one in ascending order of rate as long as the next coding gives a higher value than the last one.

$$\max_{mcs} \mathrm{E}\left[\text{number of received bits}\right] = \max_{mcs} \mathrm{tbs}(mcs) * \mathrm{P}_{\mathrm{s}}(mcs)$$

where

$$\mathrm{P}_{\mathrm{s}}(mcs) = \sum_{events} (1 - \mathrm{P}_{\mathrm{be}}(event, msc)) * \mathrm{p}(event)$$

For pseudocode for the algorithm, see A.2.

5.5 Cluster Scheduling

The cluster scheduler was implemented in a previous study at Ericsson Research, and has not been modified. The coordination done by the cluster is done after cell scheduling, so it is known which users the cells will be transmitting to. The scheduler uses a greedy algorithm to decide if it is better to mute some cells, considering the gains in the other cells in the cluster. A proportional fair metric is used when calculating the gains. The cluster scheduler may not, in the current implementation, override the decision of the pre muter. That means that it can only mute additional cells, not allow pre muted cells to transmit.

5.6 Backhaul usage

As mentioned earlier, the used clusters are defined to have delay free communication between their cells. Between clusters, on the other hand, the backhaul network that has to be used might have a limited bandwidth. Therefore, the suggested method aims to limit the amount of data that has to be sent between clusters. Table 5.1 shows the amount of data that has to be sent over backhaul. Floating point numbers are assumed to be 32 bits which gives 7 digits precision, and no overhead is included. Here, n is the number of cells in the system, and m is the length of muting pattern.

Table 5.1. Backhaul Usage

Used in	Data	Description	bits/TTI
SINR estimation	Transmission probability estimates	One probability per cell to all other cells, once per TTI	$32n^2$
Pre muting	Cluster muting probabilities	One probability per cell to pre coordinating entity, once per muting pattern	$32n/m$
	Usage of allowed TTIs to transmit	One usage ratio per cell to pre coordinating entity, once per muting pattern	$32n/m$
	Muting pattern	One bit per cell per TTI in muting pattern, to all cells once per muting pattern	n^2
			Sum: $33n^2 + 64n/m$

With $n = 27$ and $m = 8$, this still makes $33 * 27^2 + 64 * 27/8$ bits/TTI = 24273 bits/tti ≈ 3 mb/s to be sent in total, with the largest part needed for SINR estimation. As the backhaul needs to be able to transmit data at the very least at the same data rate as given to users, that is 100 mb/s, this does not seem unrealistic. It could also be decreased by not sending the transmitting probabilities for SINR estimation every TTI. Note that in the current implementation, all transmitting probabilities needs to be transmitted to all other cells even thou only the probabilities for a few of the strongest cells are actually used. This is since the probabilities are transmitted beforehand due to the delay, and at that time it is not known which cells will be taken into account in the probability estimation.

5.7 Limitations

Both of the coordination rounds will mute cells completely, not use power control. Power control gives only small benefit, according to [1]. It will be assumed that it is known how much each user is interfered by each cell if that cell transmits, that is, ideal RSRP measurements will be assumed. MIMO will not be used, only SIMO (as two receiver antennas at the UE is standard in LTE).

Chapter 6

Simulations

In this chapter, we present the simulation results, and discuss the results.

6.1 Simulation Setup

SINR estimation and link adaption as described above have been simulated in a system simulator. Since the link adaption aims to compensate base SINR for variations in load, a model where users arrive according to a Poisson process was used in order to get a non static user population. For a definition of Poisson processes, see for example [8]. The load of the system was changed by changing the arrival rate of users, and only arrival rates that give a stable number of users in the system have been included. File download traffic was used, with two different file sizes. Table 6.1 shows some simulation parameters.

6.2 SINR Estimation and Link Adaption

The SINR estimation and link adaption methods have been evaluated by using the setup described above, and no coordinated scheduling. Cells are still considered to have information of the cell scheduling done by other cells in the same cluster. Therefore, at the time of transmission, the cells know the exact transmission probabilities for other cells in the same cluster.

In plots, the base SINR estimate will be labeled Base, and the suggested sending probability based SINR estimate will be called Prob. When link adaptation is used, Prob will denote the probability SINR estimate used to give a single SINR value, used with the standard link adaptation. Prob+bler will then mean the probability based SINR estimate used with the BLER target version of the suggested link adaptation, and Prob+TBS that it is used with the link adaptation version that maximizes expected value of TBS.

Presented plots, SINR values, interference, FTP bit rates and cell throughputs have been normalized, with the same scaling used in all graphs.

Table 6.1. Simulation parameters

Simulation parameters	
Data generation	File download traffic model: a user requests and downloads one file and is then removed. File size: 0.1 Mbyte and 1 Mbyte. Initial mean waiting time before starting download: 1.0 s.
Transceiver antennas	1x2
Deployment	9 sites, 3 sectors per site
Scheduling	Proportional fair in time
BLER target	10%
Simulation time	20 s

Algorithm parameters	
Probability estimation filtering coefficient	0.05
Delay in communication between clusters	5 ms
Number of cells to use in CDF generation	6
Probability to get SINR from	0.9

6.2.1 SINR Estimation

First, a scenario with a file size of 100 kbyte was simulated in order to get bursty traffic and variation in load. In order to get larger differences in FTP bit rate, as described in next subchapter, also a larger file size of 1 Mbyte was simulated.

Figures 6.1 and 6.2 shows the CDF of the difference between actual and estimated SINR for the base and suggested probability based SINR estimates, $SINR_{\text{diff}} = SINR_{\text{real}} - SINR_{\text{est}}$.

Four respectively three different loads, produced by different arrival rates, were used for the 0.1 Mb and 1 Mb cases. As can be seen, the suggested SINR estimation method gives a considerable less biased SINR estimate. The method seems to work well for all the simulated loads, and both the file sizes. The difference between the base and prob methods is larger for lower loads.

Figure 6.3 shows the CDF of the estimated SINR for the smaller file size. The base estimate almost never gives a value higher than the normalized value that is slightly less than 0.5. The probability based method is able to estimate also higher values. Also before the base estimate reaches its highest value, the estimates are lower. This is reasonable, since the probability based estimate uses the base estimate but scales it to account for non-sending cells, so it can never give a lower SINR value than base. Since the real SINR is higher for lower loads, the error gets more biased. When using larger files, as in figure 6.4, the base estimate have more time to adapt and are able to give higher SINR estimates.

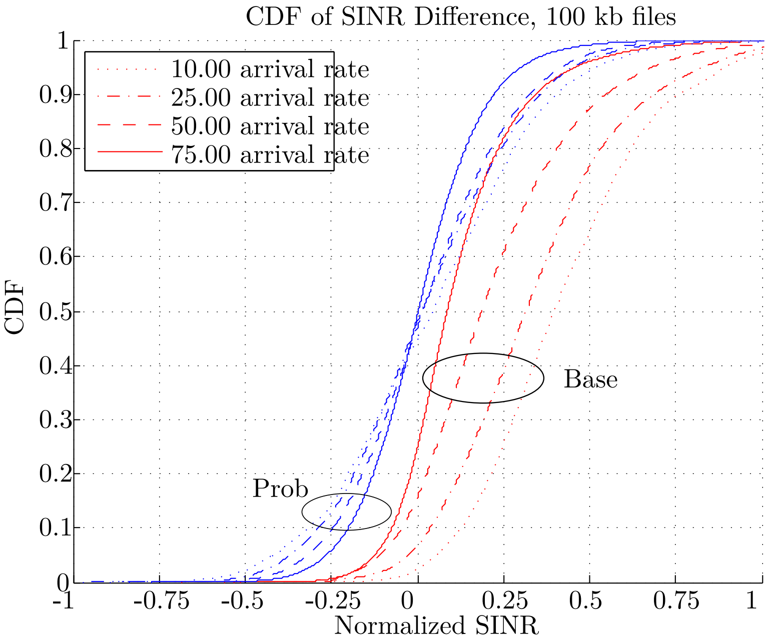

Figure 6.1. CDF of SINR difference for the base and prob methods, using 0.1 Mb files

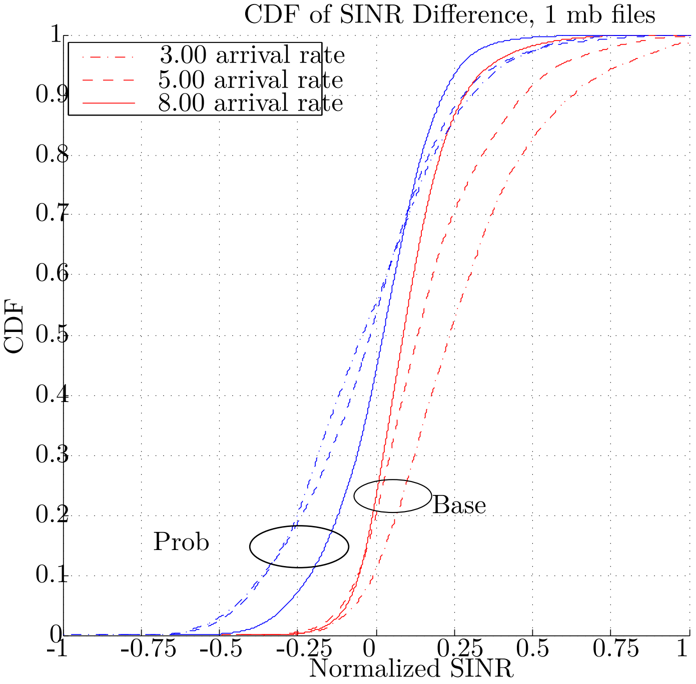

Figure 6.2. CDF of SINR difference for the base and prob methods, using 1 Mb files

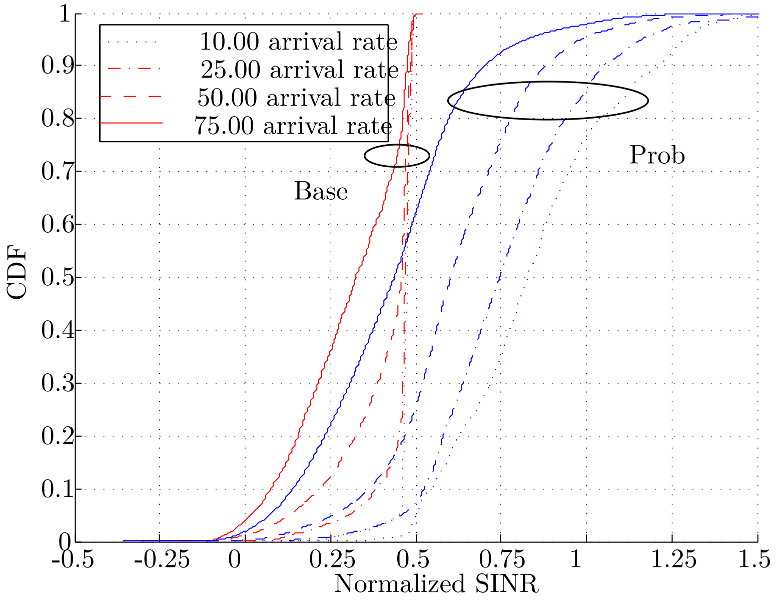

Figure 6.3. Estimated SINR, base and prob estimate, using 0.1 Mb files

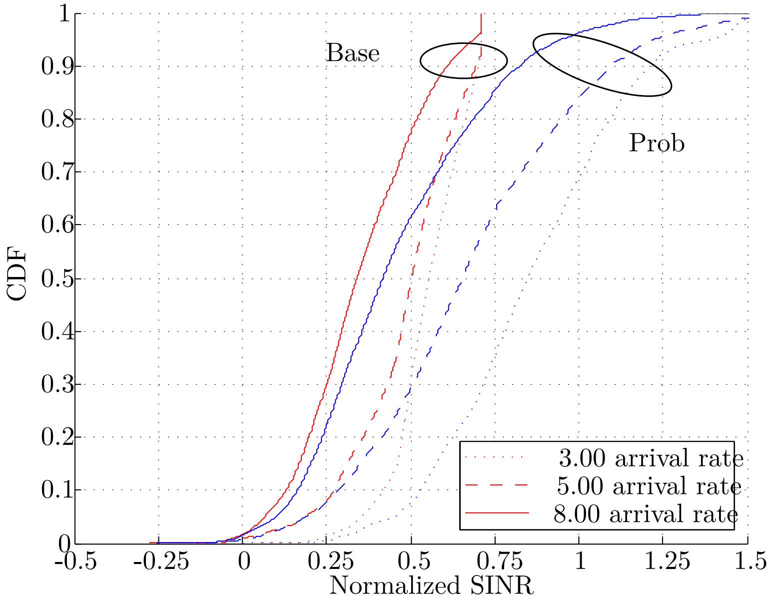

Figure 6.4. Estimated SINR, base and prob estimate, using 1 Mb files

In figure 6.5, it can be seen that the prob SINR estimate follows the real SINR quite well, while the base estimate is more biased.

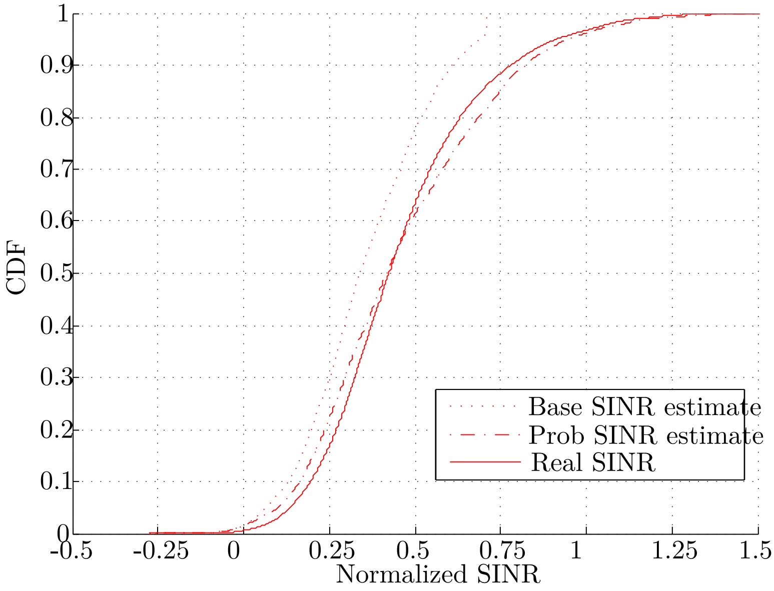

Figure 6.5. Estimated and real SINR for 1 Mb files and arrival rate 8.0

6.2.2 Link Adaption

As seen in figure 6.6, the suggested estimation of SINR gives a slightly lower FTP bit rate. All the users also have quite similar bit rates. One reason for that in this case might be that the bit rate is limited by the TCP slowstart, that limits the speed with which the server sends data in the beginning of a file download. This also gives a similar bit rate to most users, especially in the lower load cases. The cell throughput is the same in all cases, as a fixed arrival rate is used, and therefore it is not possible to get a higher throughput than letting users through in the same rate as they arrive.

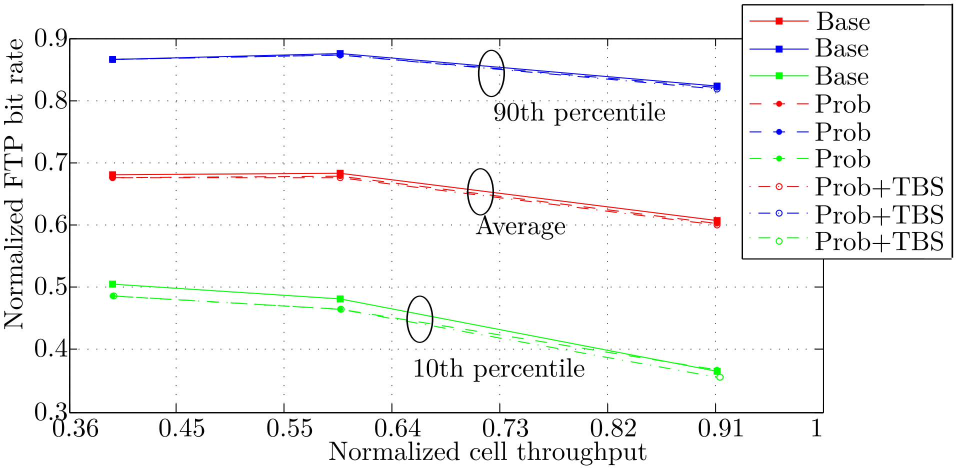

Figure 6.6. Normalized FTP bit rate for different loads, for the 0.1 Mb case

The difference in bit rate between users gets larger with the larger file size, as seen in figure 6.7. However, there is still almost no gain from the suggested methods. This might stem from the fact that MIMO is not used. As LTE is meant to user MIMO to make use of good channel qualities, the modulation and coding schemes available does not give an increased data rate when the SINR exceeds approximately the SINR value normalized as 0.5 in this chapter. That implies that a user does not benefit from knowing that it for example has SINR of 0.65 instead of the 0.5 estimate provided by base estimator. If a user has very good channel and gets to know it, it cannot benefit from it, but if the estimation is wrong and the channel is bad, the user will get a high error rate, thus decreasing the bit rate. The BLER version of the link adaptation is not shown in graphs, but have similar performance as the TBS version shown.

The results that have been shown use the delay of 5 ms between clusters. This delay is however not the source of lack of gains, as simulations with no delay shown similar results.

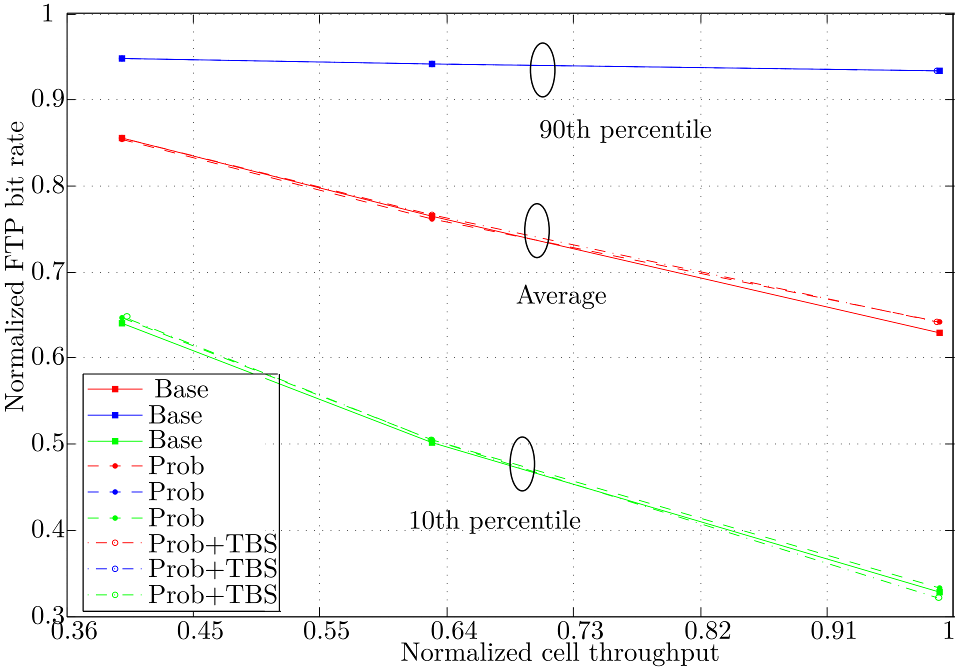

Figure 6.7. Normalized FTP bit rate for different loads, for the 1 Mb case

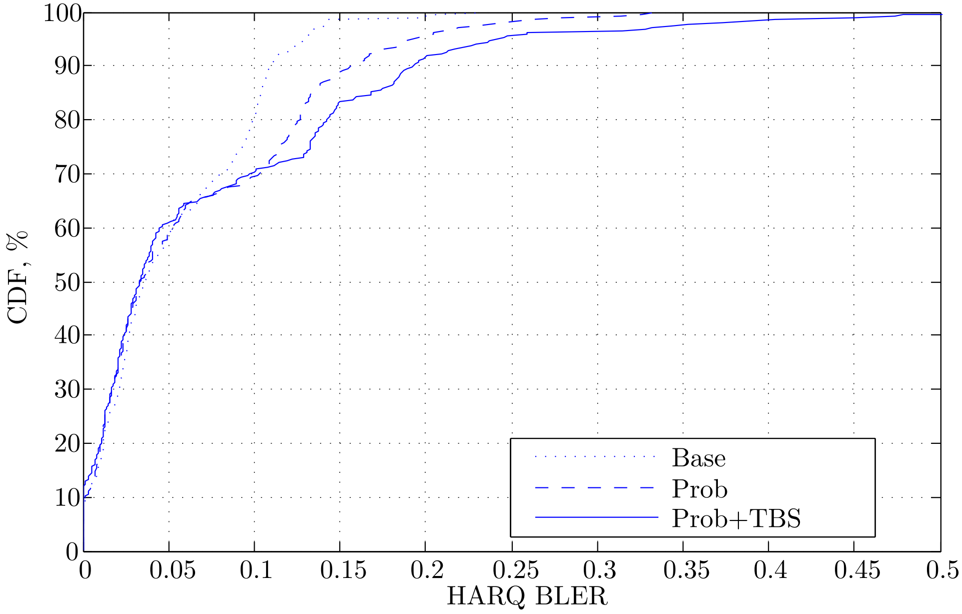

Figure 6.8. CDF of BLER per user, arrival rate 8.0

Figure 6.8 shows a CDF of BLER on HARQ level per user, for the higher load case and larger file size. The three methods have about the same number of users with low BLER, up to about 0.05. The new SINR estimate then gives more users a higher BLER even if used with the standard link adaptation. The base estimates only rarely give BLERs that exceeds 0.15. When using also the suggested link adaptation, there are even higher BLERs present. As the target BLER that is used in the standard link adaptation is 0.1, the ideal behavior would be to have all users around that number.

A possible explanation for this behavior is that the BLERs up to around 0.05 arises from users having a channel quality allowing them to use the highest MCS, and knowing it. As they are not able to use the channel quality fully due to the available MCSs, they get too low error rate compared to the target. The higher error rates would then come from the users with a lower channel quality. They will choose an estimated BLER close to the target, and if the base estimate is used, also tend to get a real value close to that. It is guessed that the higher BLERs present in the prob estimation case comes from the case when the estimation algorithm erroneously have assumed that a large interferer will not be transmitting, giving too high SINR. In the new link adaptation case, some even higher error rates are present, as the link adaptation then always accounts for the possible cases with higher SINR. As 90% have been used as the level in CDF to choose SINR from in the prob case, most of the additional possibilities accounted for in the new link adaptation will have a higher SINR. This will give a more aggressive choice of MCS. See figure 6.9, an example of a CDF from a simulation. This is just one CDF from one time instant in one simulation, but the general look, with relatively few event that have significant probability, seems to be typical.

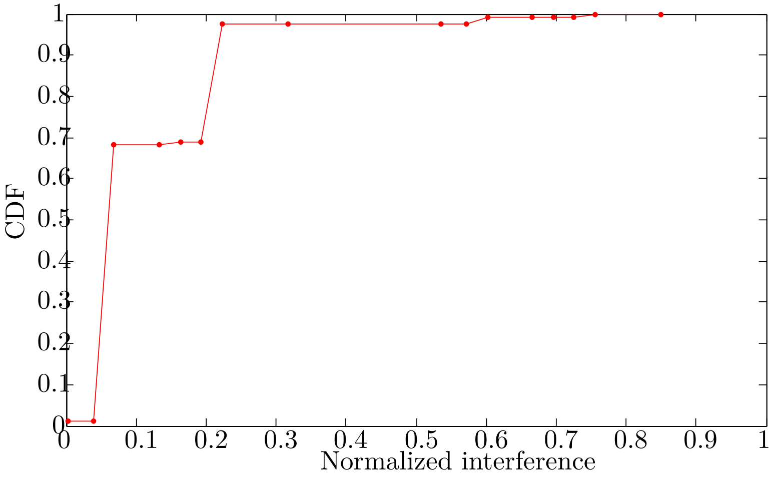

Figure 6.9. Example of a CDF of interference, generated in SINR estimation

This higher BLERs given when the SINR is estimated wrong will obviously cause lower bit rate for the affected users. When the estimates are correct the users will, as described earlier, often not be able to take advantage of them. These facts toghether could be an explanation for the lack of gains regarding user bit rate.

6.3 Pre-muting

It was decided to not do larger simulations of the coordinated scheduling. Partly that was because of lack of time, and partly since there was no gain in user bit rate in making it known to users that they had a better SINR. To further increase the SINR of users by coordinated scheduling would then not be needed in the studied scenarios, and there was not time to investigate other types of scenarios.

Chapter 7

Conclusions

In this thesis, we have suggested and simulated a SINR estimation and link adaptation that takes into account whether other cells will be transmitting or not to do more accurate link adaptation. We have also suggested a method for coordinated scheduling, to be used to aid in the link adaptation.

Simulations have been done for scenarios of 27 cells in three clusters. Users arrived according to a Poisson process, and downloaded one file each before being removed from the system. MIMO and HetNet scenarios was not used, the first to limit the scope of the thesis and the second due to lack of time. In this setup, the suggested SINR estimation method were able to do a considerable less biased estimate for all the studied levels of load, compared to the base estimation. However, this did not lead to any gains in user bit rate.

The BLER per user of the studied method has the same amount of users with low BLER as when using the base SINR estimate. The users with BLER above the target have higher BLERs in the studied method. This is reasonable since the SINR estimates and link adaption methods will give a more aggressive link adaptation.

As the SINR estimation compensates a base estimate for which cells are believed to not be transmitting, the method gives a difference only if all cells are not transmitting all the time. Therefore, low load scenarios were studied. But at these lower loads, the SINR for a user might be quite high, so there is not so much gain in bit rate from knowing if the SINR is even higher than estimated by the base estimation. This means that the method will cause losses in user bit rate when the estimates are too high, without being able to give gains when it is correct. As this seems to be the case in the studied scenarios, they might be unsuited to give gains in user bit rate with the suggested method.

The suggested methods would be more useful in cases were the system are not fully loaded, but users still can have a bad channel quality, or were users can make use of very high SINR. The first might be the case if HetNet is used. The second might be the case if MIMO is used to transmit several data streams in parallel.

The conclusion is that the studied method gives good SINR estimates but does not give higher user bitrate in the studied scenarios, so it might be interesting to try it with HetNet or MIMO.

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Appendix A

Pseudocode

Main function:
Input: aNumberOfDesiredBits, PDF
Output: aCodeRateIndex, aModulation

```
for aModulation in modulations do
    aCodeRateIndex = getCodeRate(aModulation, aNumberOfDesiredBits, PDF)
▷ this function is described in next subchapters
    if aCodeRateIndex < maxCodeRateIndex then
        return aCodeRateIndex, aModulation
    end if
end for
return aCodeRateIndex, aModulation
```

A.1 BLEP version

function getCodeRate:
Input: aNumberOfDesiredBits, PDF, modulation
Output: aCodeRateIndex

```
for aCodeRateIndex in codeRates do
    probSum =0
    for aEvent in PDF do
        eventSinr = aEvent.getSINR
        probSum += blep(eventSinr, modulation, aCodeRateIndex)
        if probSum ≤ BLEP_THRESHOLD then
            return aCodeRateIndex-1                        ▷ Previous format
        end if
    end for
    nrofBits = getNumberofBitsInFormat(aCodeRateIndex, modulation)
    if nrofBits ≤ aNumberOfDesiredBits then
```

```
        return  aCodeRateIndex                    ▷ do not need more bits
    end if             ▷ this format was ok but we could use a larger: try next.
end for
return aCodeRateIndex                                     ▷ largest format
```

A.2 TBS version

function getCodeRate:
Input: aNumberOfDesiredBits, PDF, modulation
Output: aCodeRateIndex

```
highestTbsExpectation = 0
for  aCodeRateIndex in codeRates do
    probOfSucess =0
    for  aEvent in PDF do
        eventSinr = aEvent.getSINR
        eventProb = aEvent.getProbability
        probOfSucces += (1-blep( eventSinr, modulation, aCodeRateIndex ))*
eventProb
    end for
    nrofBits = getNumberofBitsInFormat(aCodeRateIndex, modulation)
    currentExpectation = probOfSucces* nrofBits
    if currentExpectation> highestTbsExpectation then
        highestTbsExpectation=currentTbsExpectation
    else
        return aCodeRateIndex
    end if
    if nrofBits $\leq$ aNumberOfDesiredBits then
        return  aCodeRateIndex                    ▷ do not need more bits
    end if             ▷ this format was ok but we could use a larger: try next.
end for
return aCodeRateIndex;                                    ▷ largest format
```