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Resource Allocation for Dynamic TDD Systems

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"Life is and will ever remain an equation incapable of solution, but it contains certain known factors."

Nikola Tesla

Contents

Abstract

Mobile telecommunication system is in constant development, as the number of users and applications is steadily increasing. Fifth generation of mobile system (5G) is supposed to bring further improvements regarding data rates, reliability, energy efficiency and security. In this thesis we will focus on increasing data rate by applying time division duplex (TDD). In attempt to increase sum-rate, we propose a system where each cell is scheduled in downlink (DL) or uplink (UL) based on the traffic demand within the cell. The flexibility of such a system requires deploying TDD instead of nowadays commonly used frequency division duplex (FFD), because it allows dynamical adaptation to asymmetric traffic requirements.

Despite advantages of dynamic TDD, it introduces higher inter-channel interference due to the fact that neighboring base stations are allowed to transmit in opposite directions. Due to this, we propose a method to avoid interference and maximize sum-rate. Two questions have to be answered, how to find scheduling and how to allocate transmit powers, which optimize a system in terms of maximal sum-rate. We will address these issues from the point of view where exists an central unit which oversees the whole system. Further, a decentralized method of optimization is proposed where scheduling and power allocation is done locally based just on limited communication with neighboring cells. Finally, we will do MATLAB simulation of all proposed algorithms and compare their results.

Chapter 1

Introduction

Over the years interest in launching the pre-standard of the fifth generation mobile network (5G) has increased. It is supposed to become reality by 2020 in several markets [1]. The improvement is driven by an increase in demand of faster and better mobile broadband services (Fig. 1). Nevertheless, the requirements of 5G are also forced by machine-type communication, or the Internet-of-Things (IoT). As a result new cases will have to be served. They are characterized by more users and more types of devices, some of which with different operating requirements. This leads to a system, where the demand of downlink (DL) and uplink (UL) rates will be changing dynamically.

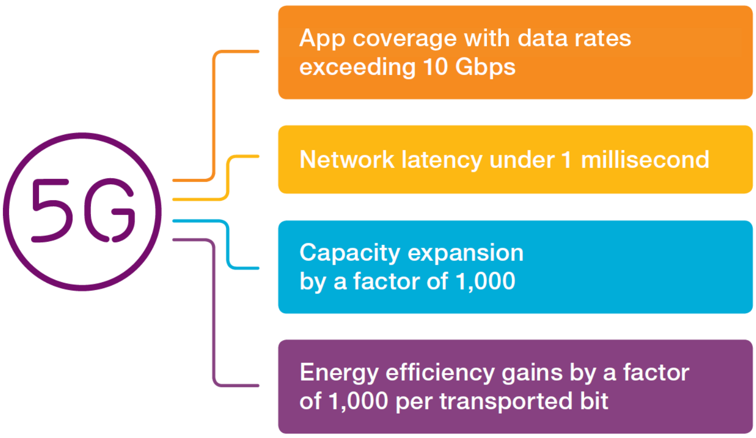

Figure 1.1: 5G requirements [1].

One of the main goals of 5G is increasing the rate, in order to meet higher traffic requirements. One of approaches of improving system capacity is applying dynamic time division duplexing (TDD). TDD shows numerous advantage in comparison to frequency division duplexing (FDD), which is nowadays more common. Frequency spectrum loss due to guard band providing an isolation between uplink and downlink and lower cost of hardware [2] are just some of reasons to use TDD instead of FDD. Further, the fact that by FDD, DL/UL capacity is determined by frequency allocation, which is set out by the regulatory authorities, makes it unsuitable to match dynamic changes of DL/UL capacity. Because of all of this, there are various proposals to use dynamic TDD, which is able to adopt to asymmetric traffic requirements.

Even though dynamic TDD promises higher capacity, the problem of inter-channel interference is arising. The main reason for this behavior is the fact that neighboring base stations can transmit in different directions at the same time. Therefore, the topics which have to be addressed are DL/UL scheduling and power allocation so that the sum-rate is maximized. In this thesis we will propose two approaches to optimize dynamic TDD:

- Centralized approach, which requires existence of a central unit which oversees the whole system. Further, it is responsible for making decisions about the scheduling and power allocation for all cells included in the system.
- Decentralized approach, where base stations try to optimize traffic locally. Each base station makes decision about its scheduling and power allocation separately. These decisions are based on the information available locally, within the cell, and by limited exchange of information with the neighboring cells.

After discussing the problem and proposing solution algorithms, results of simulations will be implemented in MATLAB.

The rest of the thesis is organized as follows:

- After a brief introduction off the problem, Chapter 2 presents literature review of the already existing work on the topic of dynamic TDD.
- In Chapter 3 we have provided a detailed description of the problem arising by application of dynamic TDD. Furthermore, two approaches for their optimization are proposed, namely centralized and decentralized.
- Chapter 4 proposes a solution algorithm for the optimization of a cellular system in a centralized manner.
- Chapter 5 presents an approach to solve the problems of dynamic TDD optimization in a decentralized manner.

- In Chapter 6 the differences between centralized and decentralized TDD are discussed. Further, advantages and disadvantages of each are presented.
- Chapter 7 outlines the cellular system models used for simulations in MATLAB. Furthermore, the obtained results are presented and commented.
- Finally, Chapter 8 draws conclusions and propose topics of future work.

Chapter 2

Literature review

Recent years are characterized by the rapid development of mobile Internet. The main driver of the development, the demand for high quality video streaming and multiple applications demanding high-speed Internet connection is constantly increasing. In the future decade further developments in this field are predicted, which leads to drastic increase of the demand. The mobile data traffic has increased by 63% in 2016 and from 4,4 exabytes (EB) per month at end of 2015 up to 7,2 EB per month at the end of 2016 (1 EB = 10006 bytes = 1018 bytes). It is predicted that, by the end of 2021 the monthly mobile data traffic will reach 49 EB [3]. Thus, the 5G is to supposed to provide an improvement of capacity by factor of 1000 until the 2020 [4].

One of the main characteristics of any radio system is the solution of maintaining communication in both direction. Time division duplex (TDD) indicate the method of downlink/uplink separation by allocation of time slots within the same frequency range. Traditional TDD scheme allocates time slots for uplink and downlink transmission in static or semi-static ratio. To satisfy the requirements, discussed in the previous paragraph, multiple improvements in TDD are considered.

In Long Term Evolution (LTE) seven different TDD configurations are defined in order to support different downlink/uplink (DL/UL) ratio of traffic (as shown in Table 2.1) [5]. Each of the defined configurations enables different DL/UL sub-frame allocation, what makes it possible to have flexible DL/UL reconfiguration. Each frame is 10 ms long and consists of 10 sub-frames. In Table 2.1 D represents a DL sub-frame, S a special sub-frame and U a UL sub-frame. These modes enable flexible DL/UP reconfiguration based on traffic rates. Seven DL/UL traffic rates are supported, that vary from UL favored configuration, DL/UL = 40%/60%, for the set 0 up to the DL favored configuration, DL/UL = 90%/10%. The possibility to maximize the system throughput, in the case where every cell can decide on one of the seven configurations is studied in [6]. The effectiveness of the proposed approach is shown when an evolutionary stable strategy (ESS) is applied. However this semi-static scheme is unable to support fast fluctuations of DL/UL traffic and to follow the dynamics of the traffic. If DL/UL is not dynamically changed, either the resources are wasted, the transmission in the cell scheduled in the mode in which the queue lengths are lower, or the requirements of the service can not be satisfied. The reason for this is that in the wireless data services, the traffic is often asymmetric and changes dynamically.

A simple example of such a behavior is that one user can stream a high quality video, requiring high DL traffic or may upload large amount of data onto the server, requesting UL traffic.

UL-DL CONFIG	SWITCH POINT PERIODICITY	SUBFRAME NUMBER									
		0	1	2	3	4	5	6	7	8	9
0	5ms	D	S	U	U	U	D	S	U	U	U
1	5ms	D	S	U	U	D	D	S	U	U	D
2	5ms	D	S	U	D	D	D	S	U	D	D
3	10ms	D	S	U	U	U	D	D	D	D	D
4	10ms	D	S	U	U	D	D	D	D	D	D
5	10ms	D	S	U	D	D	D	D	D	D	D
6	5ms	D	S	U	U	U	D	S	U	U	D

Table 2.1: Seven DL/UL configurations defined in LTE [5]

In order to solve the problem of dynamically changed asymmetric traffic rates and improve the system capacity, the new strategies of DL/UL fluctuation are proposed. They are referred to as dynamic TDD, where the DL/UL configuration can be changed in every cell or cluster of cells on a per-subframe basis, thus every 1 ms. First simulations of dynamic TDD, which have been done on single-cell scenario have shown an improvement of packet throughput performance [7]. Nonetheless, if a simulation of a system containing more cells is considered, the issue of cross-subframe cochannel interference (CCI) is noticed [8]. More precisely, due to the fact that the neighboring cells can independently choose to transmit in DL or UL, CCI is introduced, meaning that DL of a cell may interfere with UL transmissions of the neighboring cell (DL-to-UL), and the other way around (UL-to-DL).

The performance benefits from deployment of dynamic TDD applied to outdor hotspot Pico cell is studied in [9]. A dynamic DL/UL configuration scheme, which aims at minimizing the overall DL and UL delay in an autonomous manner in each cell is analyses in [10]. It is shown that relying only on local observations of a cell, it is still possible to learn and estimate current load and the interference from neighboring small cells in order to decrease the overall DL and UL delay. Although the proposed scenario shows benefits compared to the fixed scheduling scheme, by optimizing each cell separately, the maximal potential of dynamic TDD cannot be achieved due to the fact that the exact level of inter-channel interference cannot be calculated.

In [11] a cell reconfiguration scheme, based on integer linear programming, is proposed which considers both the user traffic characteristics and the CCI levels. A proposition of a long-term base station (BS) clustering scheme, that groups BSs with the similar traffic characteristics is given in [12]. A central unit (CU) is introduced which would be in charge of managing the whole network and selecting the candidates for the cluster. In order to avoid the CCI between the BSs with similar traffic profiles the BSs are arranged to the clusters depending on traffic distance between them. The DL/UL reconfiguration in the cells within one cell is done simultaneously. Even though this approach mitigates the interference, by inducing clustering, the flexibility of DL/UL scheduling is reduced. The clustering distribution calculated as optimal at one point of time, may not be the optimal solution at the next frame as the traffic is changed dynamically. This decreases the capability of the system to follow dynamically changed traffic rates. To oppose this deficit, the allocation of the cells to clusters should be done with a great frequency. This would further increase computational effort needed to optimize the system.

The important issue which has to be addressed when talking about dynamic TDD is power allocation. There is a possibility to allocate the powers in centralized or decentralized manner. The probabilistic model for power allocation, using the prior knowledge of channel state information (CSI) is introduced in [13]. They considered the architecture of cloud radio access networks (C-RANs). This optimization problem denotes solving a mixed-integer non-linear non-convex problem.

Resource allocation scheme in Heterogeneous Cloud Radio Access Networks (HCRANs) is studied in [14]. The authors propose a green allocation scheme fowling online learning based centralized and decentralized approaches. In the centralized approach, a controller integrated with the baseband processing unit is responsible for resource allocation, while in decentralized macro base stations cooperate to reach a resource allocation strategy which would be optimal for the given system. Based on the simulation results they argue that the centralized resource allocation scheme is able to achieve higher energy efficiency as well as spectral efficiency than decentralized scheme. However, both schemes show better performance than the standard resource allocation scheme. In difference to here described works, in this thesis we will address the possibilities of solving the power allocation problem applied in the scenario of dynamic TDD.

Chapter 3

Problem statement

3.1 General problem description

In attempt to increase sum-rate, we propose a system where each cell is scheduled dynamically in downlink (DL) or uplink (UL) based on the traffic demand within the cell. Unfortunately, in the scenario where each cell can freely adjust an individual DL/UL configuration, an emerging problem of CCI has to be considered. The main driver of high CCI, by dynamic TDD, is the fact that the neighboring cells can be scheduled to transmit in opposite directions, causing high interference levels. In Fig. 3.1 a scenario of two cell CCI is shown. During the same sub-frame the reception quality of Base Station b is decreased due to power leakage from the BSs which are in DL mode at the same time (BS-BS CCI). On the other hand the UL from the User equipment (UE) 3 would interfere with the DL from the BS a to the UE 0 (UE-UE CCI). Here proposed CCI avoidance scheme will target BS-BS as well as UE-UE CCI.

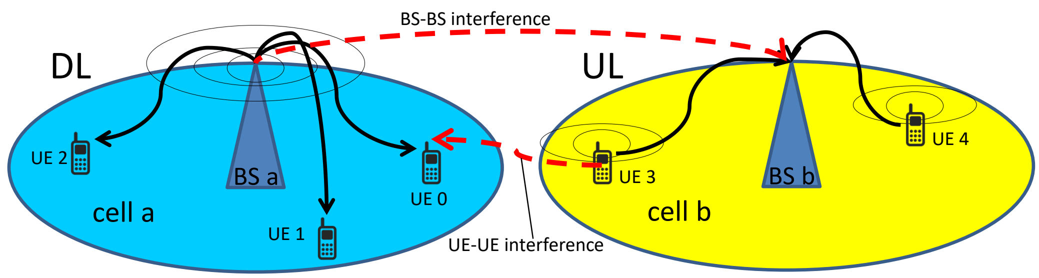

Figure 3.1: An example of CCI at two cell scenario.

3.1.1 Centralized Dynamic TDD Scheme

In this paper we consider a multicell system composed of M cells. Each cell contains one BS communicating with K_m, $m \in \{1, \cdots M\}$, users. Further we define $\mathcal{M}$ as the set of cell indexes in the given system and $\mathcal{K} = \{\mathcal{K}_1, \mathcal{K}_2, \cdots, \mathcal{K}_M\}$ as the set of user's indexes in each cell. We assume that each user is served by exactly one BS. In centralized dynamic time division duplex (dTDD) we consider that Mobility Management Entity (MME) is provided, which schedules the transmissions. Each cell has to share the information about DL and UL queue lengths, $L_{k,i}^{(DL)}$, $L_{k,i}^{(UL)}$, meaning queue lengths for the user i within the cell k, with MME. The goal is to maximize the overall sum-rate. Because the bandwidth B is the same for all channels, by maximizing spectral efficiency the sum-rate reaches the maximal value as well.

In order to define spectral efficiency, the following notation will be introduced: $P_{k,i}^{(DL)}$ is the DL transmit power of the user k, i, and $P_{k,i}^{(UL)}$ is UL allocated transmit power to the user k, i. Further, a notation for the channel gain between i-th user and k-th base station, $|G_{k,i}|$, as well as $\sigma_{k,i}^2$, representing the noise variance, are introduced. Finally the $I_{k,i}^{(DL)}$, $I_{k,i}^{(UL)}$ are out of cell interference power suffered during the DL and UL mode respectively. The signal to noise plus interference ratio (SINR) of the DL and UL for each user is expressed by the equation

$$\gamma_{k,i}^{(x)} = \frac{P_{k,i}^{(x)} |G_{k,i}|^2}{I_{k,i}^{(x)} + \sigma_k^2}, \tag{3.1}$$

where $x \in \{DL, UL\}$, $k \in \mathcal{M}$ and $i \in \mathcal{K}_m$.

Further $r_{k,i}^{(x)}$ represents weighted spectral efficiency function of the user i in the cell k,

$$r_{k,i}^{(x)} = w_{k,i}^{(x)} \ \log_2 \left(1 + \gamma_{k,i}^{(x)}\right), \tag{3.2}$$

where the weight $w_{k,i}$ will be defined later based on the queue length. To calculate the sum-rate of the whole system, it is to sum the weighted rates of all the users in the cells, i.e.

$$R = \sum_{k \in \mathcal{M}_s} \sum_{i \in \mathcal{K}_k} r_{k,i}^{(x)} , \qquad x \in \{DL, UL\}, \tag{3.3}$$

where $\mathcal{M}_s$ is a subset of $\mathcal{M}$ that contains the indexes of cells cooperating in the interference avoidance scheme. In this case of overall centralized system, where all the cells are included in one calculation scheme, $\mathcal{M}_s = \mathcal{M}$.

In interest of defining the interference, let $\boldsymbol{\beta}$ be a vector of M elements defining whether the the cell is transmitting DL or UL. Where each element of the vector $\beta_k \in \{0, 1\}$, 1 meaning the cell is transmitting DL and 0 UL.

Further the notation for channel gains is introduced:

- $Q_{k,i}^{(m)}$: channel gain between the user i in cell k and the base station m
- $C_{k,i}^{(m,j)}$: channel gain between the user i in cell k and the user j in cell m
- $H_k^{(m)}$: channel gain between the BS k and the base station m.

Now the DL interference power can be written in the form

$$I_{k,i}^{(DL)} = \sum_{m \in \mathcal{M} \backslash k} \beta_m \sum_{j \in \mathcal{K}_m} P_{m,j}^{(DL)} |Q_{k,i}^{(m)}|^2 + \sum_{m \in \mathcal{M} \backslash k} (1 - \beta_m) \sum_{j \in \mathcal{K}_m} P_{m,j}^{(UL)} |C_{k,i}^{(m,j)}|^2. \tag{3.4}$$

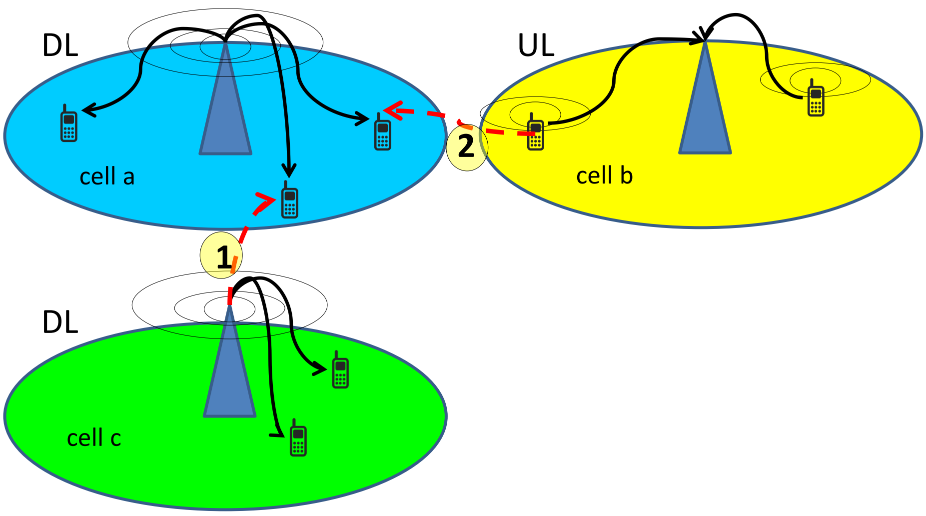

Figure 3.2: Interference for the cell transmitting in DL.

The first part of the equation (2.4) identifies the interference coming from the other cells also operating in DL, i.e. the BS-UE CCI as shown in the Fig. 3.2 (1). On the other hand the interference caused by UL transmissions in remaining cells (UE-UE CCI) is described by the second part of the equation, Fig. 3.2 (2). In a similar way the interference power suffered by a cell transmitting in UL can be described as

$$I_{k,i}^{(UL)} = \sum_{m\in\mathcal{M}\backslash k} (1-\beta_m) \sum_{j\in\mathcal{K}_m} P_{m,j}^{(UL)} |Q_{m,j}^{(k)}|^2 + \sum_{m\in\mathcal{M}\backslash k} \beta_m \sum_{j\in\mathcal{K}_m} P_{m,j}^{(DL)} |H_k^{(m)}|^2, \tag{3.5}$$

where the first sum represents the interference suffered because of UL transmission in other cells, Fig. 3.3 (1) and the second part of the equation marks the CCI originating from the fact that some BSs in the system are transmitting in DL (BS-BS CCI), Fig. 3.3 (2).

Nevertheless, in order to achieve the maximal weighted spectral efficiency, the optimal values of transmit powers, $P_{(k,i)}^{(DL)}$ and $P_{(k,i)}^{(UL)}$, have to be calculated. Seeing that, the constrains regarding transmit power have to be introduced. If $P_{max}^{(BS)}$ is the maximal total DL transmit power of each BS and $P_{max}^{(UE)}$ maximal UL transmit power of each user, the following constrains have to be satisfied

$$0 \leq \sum_{i\in\mathcal{K}_k} P_{k,i}^{(DL)} \leq P_{k,max}^{(BS)} \ , \qquad \forall k \in \mathcal{M} \tag{3.6}$$

and

$$0 \leq P_{k,i}^{(UL)} \leq P_{max}^{(UE)} \ , \qquad \forall k \in \mathcal{M} \ \wedge \ \forall i \in \mathcal{K}_m. \tag{3.7}$$

Furthermore, the elements of the vector $\boldsymbol{\beta}$, denoting whether during the subframe, the cell transmits in downlink or in uplink, have to fulfill the following condition,

$$\beta_k \in \{0,1\} \ , \qquad \forall k \in \mathcal{M}. \tag{3.8}$$

Now we focus on the objective of this thesis, maximizing the overall weighted spectral efficiency, i.e.

$$\begin{aligned} &\max_{\{\boldsymbol{\beta},\boldsymbol{P^{(DL)}},\boldsymbol{P^{(UL)}}\}} R\left(\boldsymbol{\beta},\boldsymbol{P^{(DL)}},\boldsymbol{P^{(UL)}}\right) = \\ &= \max_{\{\boldsymbol{\beta},\boldsymbol{P^{(DL)}},\boldsymbol{P^{(UL)}}\}} \sum_{k\in\mathcal{M}_s} \left(\beta_k \sum_{i\in\mathcal{K}_k} w_{k,i}^{(DL)} \ \log_2\left(1+\frac{P_{k,i}^{(DL)}|G_{k,i}|^2}{I_{k,i}^{(DL)}+\sigma_{k,i}^2}\right) \right. \\ &\qquad \left. + (1-\beta_k) \sum_{i\in\mathcal{K}_k} w_{k,i}^{(UL)} \ \log_2\left(1+\frac{P_{k,i}^{(UL)}|G_{k,i}|^2}{I_{k,i}^{(UL)}+\sigma_{k,i}^2}\right)\right), \end{aligned} \tag{3.9}$$

subject to 3.6, 3.7 and 3.8.

3.1.2 Decentralized Dynamic TDD Scheme

In this section we will consider the decentralized cell reconfiguration scheme, i.e. without a MME. That means that every cell independently

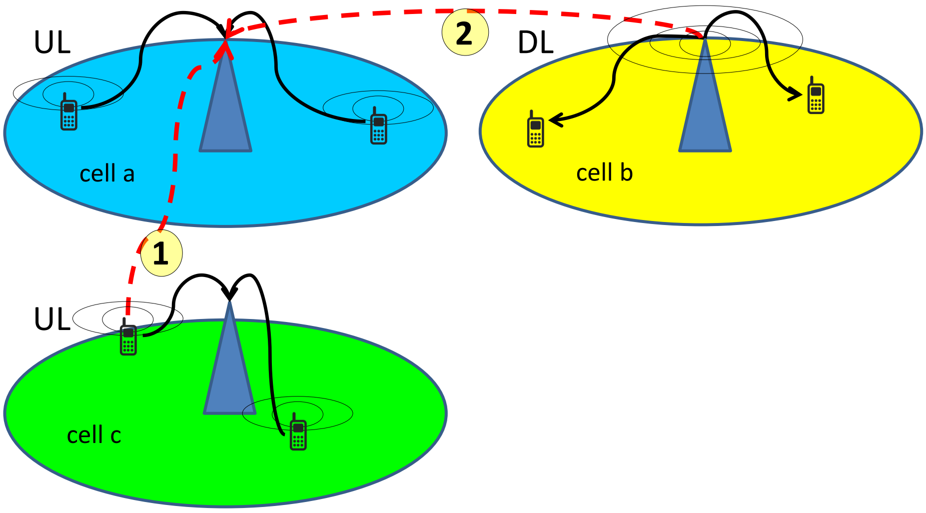

Figure 3.3: Interference suffered by a cell transmitting in UL.

calculates the maximal sum-rate and makes the reconfiguration decision. In the interest of avoiding significant performance degradation, BSs share information about the channel (transmit power and channel gain), between the neighboring cells. Since the maximization of the weighted spectral efficiency in the centralized scenario requires solving 2^M equations and, as it will be shown later, decentralized only $2M$, it is obvious that it leads to the decrease in computation effort. However absence of central unit, which would contain all the information about the system, in general causes decrease in achievable efficiency. The main cause of the decrease of the efficiency when using a decentralized scheduling is that even though the cell k communicate with the neighboring cells it can not predict the behavior of the cells which are outside of its surrounding cells.

This loss can be more precisely explained using an example system shown in the Fig. 3.4. Because the most interference power is originating from the transmissions of surrounding cells, at the time of making the DL/UL decision each cell tries to predict the behavior of neighboring cells. For example the cell 1 makes an prediction about the decision in the cell 7 based on the known statistics of past transmissions. However due to the fact that the cell 7 takes into account also the details of traffic in the cells 8, 9 and 10, which are not available to the cell 1 it is possible that the cell 7 makes different decision than the cell 1 has expected.

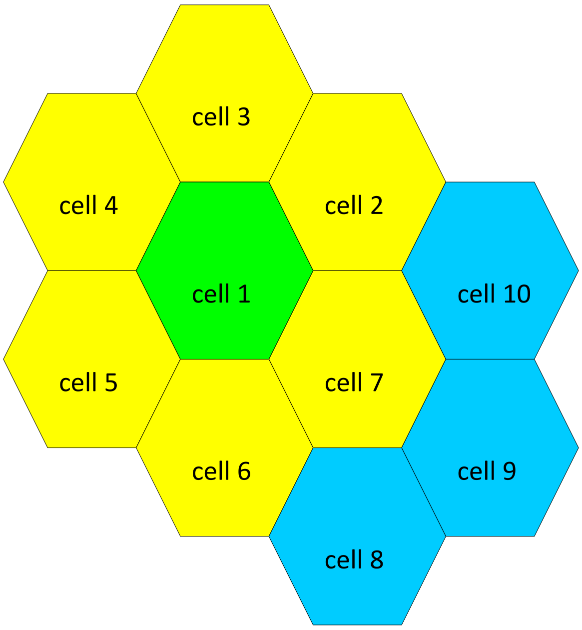

Figure 3.4: An example of an cellular system.

3.1.2.1 Proposed scenario

Intending to decrease high computational effort required for maximization of spectral efficiency (3.9) we propose a new calculation scheme. The scheme is proposed where a decision about transmitting in DL or UL, is made locally in each cell. In order to optimize the system, cells try to predict whether the transmission in DL or in UL will lead to higher spectral efficiency. As previously discussed, besides the affinities of the users within the cell, the achievable spectral efficiency also depends on the inter-channel interference caused by the transmission of the other cells. In this approach we will focus just on the influence of the surrounding cells, since generally they are the cause of the major part of the interference in each cell. Consequently, when making the decision, besides the locally available data, cells exchange the essential information with the surrounding cells.

We denote N as the number of cells neighboring one cell. Further, the number of possible schedulings taken in one cell and its surroundings is equal to 2^{N+1}. In order to decrease computational effort, the cells consider achievable spectral efficiency in these scenarios, not directly taking into account whatever the cells outside of of its neighboring are doing. We define c as the index of the scheduling set in a neighborhood. Accordingly, approximation of the spectral efficiency achievable in the case c for each cell k ($\hat{R_{k,c}}$, $k \in \mathcal{M}$

and $c \in [1, \cdots, 2^{N+1}]$), is calculated. The calculation is done taking into account the mean value of the spectral efficiency in the cell during the past transmissions with the same DL/UL scheduling. Cells share its preferences of operating in DL/UL with the neighboring cells and based on that fact and the level of spectral efficiency which would be achieved in that case, each cell makes the decision.

3.1.2.2 Power allocation

Once the optimal scheduling is determined, we calculate the transmit powers which optimize the system. The calculation is again to be done in decentralized manner. All the cells share the information about the channel gains and the transmit powers with the neighboring cells. Firstly, the initial values of the transmit powers are assumed. If $\mathcal{M}_k$ represents the subset of $\mathcal{M}$, containing the indexes of the cells neighboring the cell k, each cell calculates the level of inter-channel interference originating from the interference with its surrounding cells.

When cell k is about to allocate the transmit powers assigned to the users in the cell, the neighboring cells supply it with the necessary information needed to calculate the interference, channel gains $Q_{k,i}^{m}$, $Q_{m,j}^{k}$, $C_{k,i}^{m,j}$ and H_k^m as well as the transmit powers $P_{m,j}^{(DL)}$ and $P_{m,j}^{(UL)}$, where $m \in \mathcal{M}_k$, $j \in \mathcal{K}_m$. If the cell is scheduled in DL the interference power suffered by each of the users communicating with the base station k, is calculated by,

$$\hat{I}_{k,i}^{(DL)} = \sum_{m \in \mathcal{M}_k} \beta_m \sum_{j \in \mathcal{K}_m} P_{m,j}^{(DL)} Q_{k,i}^{(m)} + \sum_{m \in \mathcal{M}_k} (1 - \beta_m) \sum_{j \in \mathcal{K}_m} P_{m,j}^{(UL)} C_{m,j}^{(k,i)}, \quad (3.10)$$

where $i \in \mathcal{K}_k$. Further, in the case of the cell k transmitting in UL, the interference originating from the surrounding cells is determined,

$$\hat{I}_{k,i}^{(UL)} = \sum_{m \in \mathcal{M}_k} (1 - \beta_m) \sum_{j \in \mathcal{K}_m} P_{m,j}^{(UL)} Q_k^{(m,i)} + \sum_{m \in \mathcal{M}_k} \beta_m \sum_{j \in \mathcal{K}_m} P_{m,j}^{(DL)} H_k^{(m)}. \quad (3.11)$$

So determined interference powers represent an approximation of the real interference suffered by the user in cell k since the interference originating outside of the neighborhood $\mathcal{M}_k$ is not considered. Further, while keeping all the other transmit powers constant, the transmit powers assigned to the users in cell k are determined so they maximize the spectral efficiency inside cell k and its neighborhood,

$$\max_{\{\boldsymbol{P_k}\}} \hat{R}(\boldsymbol{P_k}) = \max_{\{\boldsymbol{P_k}\}} \sum_{m \in \mathcal{M}_k, k} \left(\beta_m \sum_{i \in \mathcal{K}_m} \log_2 \left(1 + \frac{P_{m,i}^{(DL)} G_{m,i}}{I_{m,i}^{(DL)} + \sigma_{m,i}^2} \right) + (1-\beta_m) \sum_{i \in \mathcal{K}_m} \log_2 \left(1 + \frac{P_{m,i}^{(UL)} G_{m,i}}{I_{m,i}^{(UL)} + \sigma_{m,i}^2} \right) \right), \tag{3.12}$$

where $\boldsymbol{P_k}$ denotes the vector of DL or UL transmit powers assigned to the users communicating with base station k. In addition the constrains concerning the allocated power to each user have to satisfy the conditions (3.6), (3.7) and (3.8).

In the same way the transmit powers assigned to the other cells in the system are calculated. Once all transmit powers are calculated, they are compared with the previously assumed values. If the difference between any power level and the value, formerly assigned to the same user, is greater than the small constant δ the process is iterated until the conditions defined as,

$$\beta_k |P_{k,i}^{(DL)}(n+1) - P_{k,i}^{(DL)}(n)| < \delta, \ \forall\ k \in \mathcal{M}, \ i \in \mathcal{K}_k \tag{3.13}$$

and

$$(1-\beta_k)|P_{k,i}^{(UL)}(n+1) - P_{k,i}^{(UL)}(n)| < \delta, \ \forall\ k \in \mathcal{M}, \ i \in \mathcal{K}_k, \tag{3.14}$$

are satisfied.

Chapter 4

Optimization of the centralized TDD

The problem of optimization the TDD, i.e. maximization of spectral efficiency, includes the allocation of transmit powers, as well as the DL/UL scheduling. At the beginning, power allocation is determined, while the optimal scheduling, $\boldsymbol{\beta}$, is kept constant and optimized later.

We aim to solve the problem of maximization of the multivariable spectral efficiency function (3.9), considering power constrains, (3.6) and (3.7). This can be efficiently done using the method of Lagrange multipliers. For each condition one Lagrange multiplier [15] has to be created, so λ_k, $\xi_{k,i}$ and $\mu_{k,i}$, $k \in \mathcal{M}$ and $i \in \mathcal{K}_m$, will be defined. Furthermore the Lagrangian function can be written written as

$$\begin{aligned}\mathcal{L}\left(\{P_{k,i}^{(DL)}, P_{k,i}^{(UL)}, \lambda_k, \xi_{k,i}, \mu_{k,i}\}\right) &= R\left(\boldsymbol{\beta}, \boldsymbol{P^{(DL)}}, \boldsymbol{P^{(UL)}}\right) + \\ \sum_{k\in\mathcal{M}} \beta_k \lambda_k \left(P_{k,max}^{(BS)} - \sum_{i\in\mathcal{K}_k} P_{k,i}^{(DL)}\right) &+ \sum_{k\in\mathcal{M}} (1-\beta_k) \sum_{i\in K_k} \xi_{k,i}\left(P_{max}^{(UE)} - P_{k,i}^{(UL)}\right) + \\ \sum_{k\in\mathcal{M}} \beta_k \sum_{i\in K_k} \mu_{k,i} P_{k,i}^{(DL)} &+ \sum_{k\in\mathcal{M}} (1-\beta_k) \sum_{i\in K_k} \mu_{k,i} P_{k,i}^{(UL)}.\end{aligned} \tag{4.1}$$

Suppose that $P_{k,i}^{(DL)*}$ and $P_{k,i}^{(UL)*}$ are local solutions of (3.9). Than there are Lagrange multipliers λ_k^*, $\xi_{k,i}^*$ and $\mu_{k,i}^*$, such that the following conditions are satisfied at $(P_{k,i}^{(DL)*},\ P_{k,i}^{(UL)*},\ \lambda_k^*,\ \xi_{k,i}^*,\ \mu_{k,i}^*)$

$$\nabla_{P_{k,i}^{(DL)}, P_{k,i}^{(UL)}} \mathcal{L}\left(\{P_{k,i}^{(DL)*},\ P_{k,i}^{(UL)*},\ \lambda_k^*,\ \xi_{k,i}^*,\ \mu_{k,i}^*\}\right) = 0 \tag{4.2}$$

$$\beta_k \lambda_k^* \left(P_{k,max}^{(BS)*} - \sum_{i \in \mathcal{K}_k} P_{k,i}^{(DL)*} \right) = 0, \qquad \forall k \in \mathcal{M} \tag{4.3}$$

$$(1-\beta_k)\xi_{k,i}^* \left(P_{max}^{(UE)*} - P_{k,i}^{(UL)*} \right) = 0, \qquad \forall k \in \mathcal{M} \wedge \forall i \in \mathcal{K}_k \tag{4.4}$$

$$\beta_k \mu_{k,i}^* P_{k,i}^{(DL)*} = 0, \qquad \forall k \in \mathcal{M} \wedge \forall i \in \mathcal{K}_k \tag{4.5}$$

$$(1-\beta_k)\mu_{k,i}^* P_{k,i}^{(UL)*} = 0, \qquad \forall k \in \mathcal{M} \wedge \forall i \in \mathcal{K}_k \tag{4.6}$$

$$\lambda_k^* \geq 0, \qquad \forall k \in \mathcal{M} \tag{4.7}$$

$$\xi_{k,i}* \geq 0, \qquad \forall k \in \mathcal{M} \wedge \forall i \in \mathcal{K}_k \tag{4.8}$$

$$\mu_{k,i}^* \geq 0, \qquad \forall k \in \mathcal{M} \wedge \forall i \in \mathcal{K}_k. \tag{4.9}$$

The conditions (4.2 –4.9) are known as the Karush–Kuhn–Tucker (KKT) conditions [15]. Since 3.9 is not in general a convex function, this method returns more solutions. More precisely all local maximum values, as well as the local extremes laying on the interval bordering area are returned as the solutions. Further it is to choose the solution which maximize the total spectral efficiency function (3.3).

Solving the previously described maximization problem (3.9) requires providing a solution for system of equations (4.2 –4.6) while taking intro account the inequality constrains (4.7 –4.9). Furthermore, in order to describe the system precisely the following notation is introduced: J is defined as a total number of users in the system, d as a number of cells transmitting in DL and p as number of users transmitting in UL. By derivations of Lagrange function (4.1) J equations are obtained (4.2), further (4.3) provides d equations, (4.4) p and finally (4.5) and (4.6) provide another J equations. On the other hand solving the inequalities includes d inequalities 4.7, p from 4.8 and J inequalities 4.9. Therefore, the whole system consists in total out of $2J + d + p$ equations and $d + p + J$ inequalities.

Furthermore, for solving the system of equations, MATLAB Symbolic Math Toolbox is used to create and solve equations with symbolic variables. While numerical solution returns approximated solution, here applied symbolic calculation gives the exact solution. Further it returns all the possible solutions of the system of equations and in the case of infinitive number of solutions, parameterized solutions and their conditions are specified. In addition when system of equalities is solved, the solutions are checked, if inequities constrains (4.7 –4.9) are satisfied. The solutions which correspond to all the previously defined constrains are than compered by evaluating the function of overall spectral efficiency (3.3). Lastly, the solutions for the transmit powers which provide the highest value of the function, are selected as the optimal solution of the power allocation.

Besides the power allocation, we have to determine the optimal scheduling. In order to calculate it, a search over all possible DL/UL schedulings is done and the results are compared so that the one is found which leads to the highest spectral efficiency (3.3). Therefore, calculation over 2^M schedulings has to be done, where M is the total number of cells in the system.

Chapter 5

Optimization of the decentralized TDD

The centralized optimization scheme, discussed in the previous section requires high computational cost. In order to solve this problem, here we present a decentralized approach, which is supposed to decrease computational cost, but at the expense of drop of the total spectral efficiency.

In difference to the centralized scheduling, in decentralized optimization problem, each cell makes the DL/UL decision on its own, based on the locally available data and limited information exchange with the surrounding cells. Each cell k contains the pre-available information of the average spectral efficiency for a cell in each of the 2^{N+1} schedulings, $\hat{R}_{k,c}$, N being the number of cells bordering one and where c denotes the specific scheduling.

Furthermore, during the decision making process each cell considers the time interval of one sub-frame and defines a timing marker t_k, k being index of the cell. This marker divides the transmission time into the interval when the cell would operate in DL and UL. The timing marker is normalized to the time of the one transmission interval, and takes values between 0 and 1. In this manner, the time markers represent a desire of a cell to transmit in DL or UL. Time of one sub-frame is divided so that:

- $0 \leq t \leq t_k$ cell k transmits in DL
- $t_k < t \leq 1$ cell k transmits in UL

It is obvious that $t_k = 0$ indicates that during the whole period the cell is operating in UL and $t_k = 1$ in DL. The marker in each cell is moved iteratively until one of the extremes is reached, and so one scheduling is chosen for the whole period.

To summarize, the timing markers, dividing the transmission interval which are moved during the process of DL/UL allocation, are introduced, but on the end of the process the scheduling is made in the manner that every cell transmit in DL or UL during the whole sub-frame. The algorithm responsible for moving the makers is explained in the following section.

At the beginning each cell randomly selects the position of its timing marker by uniformly choosing the values $t_k \in (0,1),\ k \in \mathcal{M}$. Secondly, after the initialization phase, the gradient descent algorithm is applied in order to iteratively select optimal DL/UL choice. We assume that there is a token which circles between the cells presented in the system. Having a token denotes the right of the cell to calculate and set transmit powers to the users within the cell.

One cell at the time has a token to change the position of its timing marker with a desire to achieve higher spectral efficiency. To do so we propose three methods. Later we will compare three of them, by simulating their performance.

5.1 Approach 1

When cell k has a token, it receives the information about position of the timing markers of the surrounding cells. Knowing that for the $t < t_k$ the cell k schedules DL and $t > t_k$ UL, it tends to determine the DL/UL scheduling in the surrounding cells on the left and on the right side of the its marker, t_k. When $t_{k,a}$, $a \in [1, \cdots, N]$, denotes the values of the time markers of the cells neighboring cell k, cell a, bordering k operates in:

$$\text{if } t_{k,a} < t_k,\ \text{UL left and right from } t_k, \tag{5.1a}$$
$$\text{if } t_{k,a} = t_k,\ \text{DL left and in UL right from } t_k, \tag{5.1b}$$
$$\text{and}$$
$$\text{if } t_{k,a} > t_k,\ \text{DL left and right from } t_k. \tag{5.1c}$$

Furthermore, the spectral efficiency levels left ($R_{l,k}$) and right from t_k ($R_{r,k}$) are defined so that $R_{l,k} = R_{k,c}$, c corresponding to the scheduling left from the time marker t_k, and $R_{r,k}$ taking average value of the scheduling right from the marker. Therefore if the marker t_k is decreased, the interval assigned for the scheduling corresponding to $R_{r,k}$ is enlarged.

Finally when $R_{l,k}$ and $R_{r,k}$ are determined, the step by which the time marker t_k moves is expressed as

$$\Delta t = \varepsilon \Delta R, \tag{5.2}$$

where

$$\Delta R = R_{r,k} - R_{l,k}, \tag{5.3}$$

and the step size factor ε is defined,

$$\varepsilon = \left| \frac{(t(n) - t(n-1))}{\Delta R(n) - \Delta R(n-1)} \right|, \tag{5.4}$$

n meaning the iteration number. Finally, the position of the timing marker after the movement is calculated by

$$t(n+1) = t(n) - \varepsilon \Delta R. \tag{5.5}$$

As the starting value of factor ε, $\varepsilon = 0.01$ is taken. In this manner after one cell changes the position of its timing marker, the other cells also move their markers to adopt to the new scheduling layout. The calculation is done for each cell iteratively until all markers take either value 0 or 1.

The proposed algorithm is shown in Alg. 1.

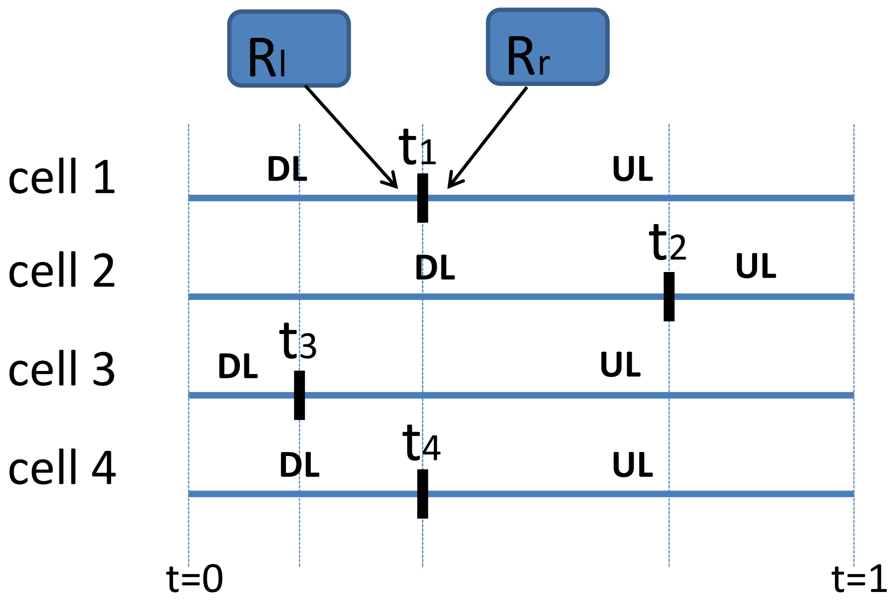

Figure 5.1: Visual representation of gradient descent in decentralized TDD.

The proposed algorithm is summarized on the model used for the simulations. Fig. 5.1 shows the case when cell 1 has a token to make a move. It owns the information about the times chosen by the surrounding cells (cells: 2,3 and 4) and the average spectral efficiency achieved by all of the 16 combinations. The cell considers the spectral efficiency on the left and on the

Algorithm 1 Decentralized scheduling: Fist approach

Require: $M > 0$ ▷ M is a number of cells
Require: $K > 0$ ▷ K is a number of users per cell
Require: $R \leftarrow \mathbb{R}^{M \times K}$ ▷ Matrix to hold the values of the average of the previous spectral efficiency
neighborhood ▷ Matrix to hold the indexes of the neighbours of the each cell
main
$t(1, M) \leftarrow [0, \cdots, 1]^{1 \times M}$ ▷ vector to hold the values of the time markers
do
  for $k = 1 : M$ **do**
    $sch_{Left}, sch_{Right} \leftarrow$ SCHEDULINGREGARDINGTOKEN$(t, k, [m, neighborhood(k, :)])$
    $R_{left}, R_{right} \leftarrow$ values of $R(k, :)$ corresp. sch_{Left}, sch_{Right}
    $\Delta R(k) \leftarrow R_{right} - R_{left}$
    if $\Delta R_{previous}(k) == 0 \vee \Delta R(k) - \Delta R_{previous}(k) == 0$ **then**
      $\varepsilon \leftarrow 0.01$
    else
      $\varepsilon \leftarrow \left| \dfrac{t(k) - t_{previous}(k)}{\Delta R(k) - \Delta R_{previous}(k)} \right|$
      $\Delta R_{previous}(k) \leftarrow \Delta R(k)$
    end if
    $t(k) \leftarrow t(k) - \varepsilon \Delta R(k)$
    $t_{previous}(k) \leftarrow t(k)$
  end for
while all elements of t $\neq 0 \vee 1$ ▷ $t(k) = 0$ means the cell k in UL, $t(k) = 1$ the cell k in DL

Algorithm 2 Function to determine the scheduling in a neighbourhood left and right of the timing marker belonging to the cell with the token

```
function SchedulingRegardingToken(t, k, surrounding)    ▷ Function to determine the scheduling in the cells listed in surrounding, left and right of the time marker belonging to the cell k
    for m ∈ surrounding do
        if t(m) < t(k) then
            schedulingLeft(m) ← UL
            schedulingRight(m) ← UL
        else if t(m) == t(k) then
            schedulingLeft(m) ← DL
            schedulingRight(m) ← UL
        else if t(m) > t(k) then
            schedulingLeft(m) ← DL
            schedulingRight(m) ← DL
        end if
    end for
    return schedulingLeft, schedulingRight
end function
```

right side of the marker ($R_{l,k}$, respectively $R_{r,k}$). In this scenario $R_{l,k}$ corresponds to the average level of spectral efficiency achieved by cell 1 in the case when the cells are transmitting in the following mode: cell 1: DL, cell 2: DL, cell 3: UL, cell 4: DL, and $R_{r,k}$: cell 1: UL, cell 2: DL, cell 3: UL, cell 4: UL. Further marker t_k is moved by ΔR and the token is given to each cell $c_2, \cdots, c_{10}$, one after the other. This procedure is than repeated until all the markers reach the value 0 or 1. In the simulation model the values of spectral efficiency, $R_{k,c}$, are assigned uniformly so that $R_{k,c} \in [0, 10]$, $k \in \mathcal{M}$ and $c \in [0, \cdots, 2^{N+1}]$.

The results of the decentralized scheme will be compared with the solution which would be optimal for the given values of average spectral efficiency. By optimal solution, here is meant the solution which maximizes the sum of average spectral efficiency for all the cell in the system. When selecting the $R_{k,c}$ it is to notice that each index c of the scheduling in the neighborhood, besides the scheduling of the cell k implies the specific scheduling of the other cells in the neighborhood. When maximizing the sum of average spectral efficiency in all the cells, attention has to be paid that the scheduling in each cell is consistent with the scheduling of other cells,

$$\hat{R}_{optimal} = \max_{c=[1,\cdots,2^{N+1}]} \sum_{k \in \mathcal{M}} R_{k,c}. \tag{5.6}$$

5.2 Modified decentralized approach

In the previous section, when discussing approach 1 the disadvantage of the selfish behavior of the cells is shown. More precisely, one of the reasons of efficiency decline is that every cell moves the timing marker entirely based on the influence it will have on its own spectral efficiency, and not considering whether it has positive impact on the whole system.

Aiming to improve the decentralized scheme, we propose a new approach which includes tighter collaboration between the cells. More specifically, a new algorithm for calculating spectral efficiency on the left $R_{l,k}$ and on the right side $R_{r,k}$ of the cell's timing marker, what directly influence ΔR (5.3) is introduced.

Further two approaches of achieving improvements in decentralized TDD will be discussion, and the results will be compared.

5.2.1 Approach 2

When cell k has the token to make a move of its timing marker t_k, firstly it calculates the spectral efficiency achieved in the cell by determining the scheduling on the right $R_{r,k}$ and on the left $R_{l,k}$ side of t_k of the neighboring cells as described in (5.1). Secondly every cell a, bordering cell k, determines the scheduling of its neighbors left an right from t_k. As explained before, cell k operates in DL left and in UL right from its own time marker t_k. The scheduling in the other cells, surrounding cell a is done in the same manner.

Finally, as all the cells in the neighborhood have calculated their own spectral efficiency left $R_{l,a}$ and right $R_{r,a}$ from t_k, cell k computes the total spectral efficiency in the neighborhood,

$$R_{l,total} = R_{l,k} + \sum_{a\in[1,\cdots,N]} R_{l,a}, \text{ and} \tag{5.7a}$$

$$R_{r,total} = R_{r,k} + \sum_{a\in[1,\cdots,N]} R_{r,a}, \tag{5.7b}$$

where N denotes the number of cells bordering one cell. Further the difference between the spectral efficiencies is calculated,

$$\Delta R_{total} = R_{r,total} - R_{l,total}, \tag{5.8}$$

the step size factor, ε is determined by equation (5.4), the size of the step, Δt by (5.2) and finally the position of the timing marker after the re-positioning process by (5.5). The process is repeated until all the time markers reach the value 0 (meaning the cell transmitting in UL) or 1(the cell transmitting in UL).

Here proposed algorithm for optimizing the DL/UL scheduling is shown in Alg. 3.

Algorithm 3 Decentralized scheduling: Second approach

Require: $M > 0$ ▷ M is a number of cells
Require: $K > 0$ ▷ K is a number of users per cell
Require: $R \leftarrow \mathbb{R}^{M \times K}$ ▷ Matrix to hold the values of the average of the previous spectral efficiency

neighborhood ▷ Matrix to hold the indexes of the neighbors of the each cell
main
$t(1, M) \leftarrow [0, \cdots, 1]^{1 \times M}$ ▷ vector to hold the values of the time markers
$\Delta R_{previous} = 0^{1 \times M}$
do
  for $k = 1 : M$ **do**
    $R_{left}, R_{right} \leftarrow \textsc{LeftRightSpecEff}(t, R, neighborhood)$
    $\Delta R(k) \leftarrow R_{right} - R_{left}$
    if $\Delta R_{previous}(k) == 0 \vee \Delta R(k) - \Delta R_{previous}(k) == 0$ **then**
      $\varepsilon \leftarrow 0.01$
    else
      $\varepsilon \leftarrow \left| \frac{t(k) - t_{previous}(k)}{\Delta R(k) - \Delta R_{previous}(k)} \right|$
      $\Delta R_{previous}(k) \leftarrow \Delta R(k)$
    end if
    $t(k) \leftarrow t(k) - \varepsilon \Delta R(k)$
    $t_{previous}(k) \leftarrow t(k)$
  end for
while all elements of t $\neq 0 \vee 1$ ▷ $t(k) = 0$ means the cell k in UL, $t(k) = 1$ the cell k in DL

5.2.2 Approach 3

In the proposed decentralized TDD optimization schemes, one neighborhood is composed of $N+1$ cells, where N is the number of neighbors per cell. Each cell is considering 2^{N+1} schedulings, possible to occur in the neighborhood. Further when the time markers are deployed up to $N+2$ schedulings are visible on the interval $t \in [0, 1]$. Despite all of this, at each iteration,

Algorithm 4 Function to calculate sum of spectral efficiency in a neighborhood left and right of the timing marker belonging to the cell with the token

```
function LeftRightSpecEff(t, R, neighborhood)
    for m ∈ neighborhood(k, :) do
        sch_left, sch_right ← SchedulingRegardingToken(t, k, [m, neighborhood(m, :)])
        R_left,temp, R_right,temp ← values of R corresp. sch_Left, sch_Right
        R_left ← R_left + R_left,temp
        R_right ← R_right + R_left,temp
    end for
    return R_left, R_right
end function
```

when cell k is about to make a move it has in sight just two schedulings, right and left from timing marker t_k.

We propose an optimizing scheme which enables a decision making cell to consider all the schedulings within its neighborhood on the interval zero to one. When cell k has a token, firstly it calculates the spectral efficiency experienced inside the cell by summing all the spectral efficiency levels left, forming $R_{l,k,wholeInteval}$, and right,$R_{r,k,wholeInteval}$, from t_k scaled by time each scheduling is presented in the interval. Secondly, all cells a, bordering the cell k, calculate in the same manner its spectral efficiency left $R_{l,a,wholeInteval}$ and right $R_{r,a,wholeInteval}$ from t_k. Finally the calculated values are summed up forming the levels by which the decision of moving the marker left or right will be made,

$$R_{l,wholeInterval} = R_{l,k,wholeInteval} + \sum_{a \in [1,\cdots,N]} R_{l,a,wholeInteval}, \text{ and} \tag{5.9a}$$

$$R_{r,wholeInterval} = R_{r,k,wholeInteval} + \sum_{a \in [1,\cdots,N]} R_{r,a,wholeInteval}. \tag{5.9b}$$

Further the timing marker is moved following (5.2 - 5.5).

We expect to achieve an improvement in optimization quality with respect to the previously described approaches, due to the fact that more schedulings will be considered in each iteration. The fact is that when cell k makes a decision to move the timing marker left/right it is not just giving a greater time interval to the scheduling directly right/left of the marker but also gives bigger chances to all the other intervals right/left from t_k to be increased when the remaining cells move their markers. Consequentially, not only direct advantage of moving the marker is considered, but also the potential benefit which depends on the actions on other cells.

The algorithm of the approach 3 is to see in Alg. 5.

Algorithm 5 Decentralized scheduling: Third approach

Require: $M > 0$ ▷ M is a number of cells
Require: $K > 0$ ▷ K is a number of users per cell
Require: $R \leftarrow \mathbb{R}^{M \times K}$ ▷ Matrix to hold the values of the average of the previous spectral efficiency

neighborhood ▷ Matrix to hold the indexes of the neighbours of the each cell
main
$t(1, M) \leftarrow [0, \cdots, 1]^{1 \times M}$ ▷ vector to hold the values of the time markers
do
  for $k = 1 : M$ **do**
    $R_{left}, R_{right} \leftarrow \textsc{TotaScaledSpecEff}(t, R, neighborhood)$
    $\Delta R(k) \leftarrow R_{right} - R_{left}$
    if $\Delta R_{previous}(k) == 0 \vee \Delta R(k) - \Delta R_{previous}(k) == 0$ **then**
      $\varepsilon \leftarrow 0.01$
    else
      $\varepsilon \leftarrow \left| \dfrac{t(k) - t_{previous}(k)}{\Delta R(k) - \Delta R_{previous}(k)} \right|$
      $\Delta R_{previous}(k) \leftarrow \Delta R(k)$
    end if
    $t(k) \leftarrow t(k) - \varepsilon \Delta R(k)$
    $t_{previous}(k) \leftarrow t(k)$
  end for
while all elements of t $\neq 0 \vee 1$ ▷ $t(k) = 0$ means the cell k in UL, $t(k) = 1$ the cell k in DL

5.2.3 Power allocation

Once the optimal scheduling is calculated, the transmit powers are allocated in a distributed manner. In order to optimize the power allocation, each cell separately decides about the powers assigned to the users in the cell. While doing so, the base station k communicates just with the neighboring base stations by exchanging the information about the channel gains $Q_{k,i}^{(m)}$, $Q_{m,i}^{(k)}$, $C_{(k,i)}^{m,j}$ and $H_k^{(m)}$ as well as the transmit powers $P_{m,j}^{(DL)}$ and $P_{m,j}^{(UL)}$, where $m \in \mathcal{M}_k$, $j \in \mathcal{K}_m$.

Algorithm 6 Function to calculate total scaled spectral efficiency in a neighbourhood left and right of the timing marker belonging to the cell with the token

function TotaScaledSpecEff($t, R, neighborhood$)
    for $m \in neighborhood(k, :)$ **do**
        $R_{left,temp}, R_{right,temp} \leftarrow$ SpecEffPerCell($t, k, [m, neighborhood(m, :)]$)
        $R_{left} \leftarrow R_{left} + R_{left,temp}$
        $R_{right} \leftarrow R_{right} + R_{left,temp}$
    end for
    return R_{left}, R_{right}
end function

Algorithm 7 Function to calculate total scaled spectral efficiency per cell left and right of the timing marker belonging to the cell with the token

function SpecEffPerCell($t, k, surrounding$) ▷ Function to calculate the spectral efficiency on the whole period left and right of the time marker belonging to the cell with the token. Spectral efficiency is further scaled to the time interval the scheduling occurs.
    $t_{surrounding} \leftarrow$ elements of t belonging to surrounding, sorted ascending
    $sorted_{surr} \leftarrow$ elements of *surrounding* sorted to corresp. $t_{surrounding}$
    $R_{temp} \leftarrow 0$
    for $m \in sorted_{surr}$ **do**
        $sch_{left}, sch_{right} \leftarrow$ SchedulingRegardingToken($t, m, [m, neighborhood(m, :)]$)
        $R_{temp} \leftarrow$ value of $R_{temp} + R(k, :)$ corresp. sch_{left} scaled by interval of appearance
        if t(m) == t(k) **then**
            $R_{left} \leftarrow R_{temp}$
            $R_{temp} \leftarrow 0$
        end if
    end for
    $R_{right} \leftarrow R_{temp}$
    return R_{left}, R_{right}
end function

Each cell k, when allocating the power levels to its users, aims to maximize the spectral efficiency within the cell k and the cells surrounding it. Consequentially the powers $P_{k,i}^{(DL)}$, $P_{k,i}^{(UL)}$, $k \in \mathcal{M}$, $i \in \mathcal{K}_k$ are allocated so that the spectral efficiency is maximized (3.12). Further the variables have to satisfy conditions (3.6) and (3.7), while keeping the power levels assigned to the users outside of the cell k constant.

The presented optimization problem is solved using the method of Lagrange multipliers. Similarly to what we considered in Chapter 4 the Lagrange function is defined as

$$\begin{aligned}\hat{\mathcal{L}}\left(\{\boldsymbol{P_k}, \lambda_k, \xi_{k,i}, \mu_{k,i}\}\right) = \hat{R}\left(\boldsymbol{P_k}\right) + \sum_{m\in\mathcal{M}_k,k} \beta_m \lambda_m \left(P_{m,max}^{(BS)} - \sum_{i\in\mathcal{K}_m} P_{m,i}^{(DL)}\right) + \\ \sum_{m\in\mathcal{M}_k,k} (1-\beta_m) \sum_{i\in\mathcal{K}_m} \xi_{m,i} \left(P_{max}^{(UE)} - P_{m,i}^{(UL)}\right) + \sum_{m\in\mathcal{M}_k,k} \beta_m \sum_{i\in\mathcal{K}_m} \mu_{m,i} P_{m,i}^{(DL)} \\ + \sum_{m\in\mathcal{M}_k,k} (1-\beta_m) \sum_{i\in\mathcal{K}_m} \mu_{m,i} P_{m,i}^{(UL)} \ ,\end{aligned} \tag{5.10}$$

where $\hat{R}\left(\boldsymbol{P_k}\right)$ is the approximation in decentralized manner of the total spectral efficiency (3.12) and $\lambda_k, \xi_{k,i}, \mu_{k,i}$ are the Lagrange multipliers.

If we suppose that $P_{k,i}^{(DL)*}$ and $P_{k,i}^{(UL)*}$ are local solutions of (5.10) and the corresponding Lagrange multipliers, λ_k^*, $\xi_{k,i}^*$ and $\mu_{k,i}^*$, such that the conditions (4.3 –4.9) are satisfied at ($P_{k,i}^{(DL)*}$, $P_{k,i}^{(UL)*}$, λ_k^*, $\xi_{k,i}^*$, $\mu_{k,i}^*$) and

$$\nabla_{P_{k,i}^{(DL)}, P_{k,i}^{(UL)}} \hat{\mathcal{L}}\left(\{\boldsymbol{P_k^*},\ \lambda_k^*,\ \xi_{k,i}^*,\ \mu_{k,i}^*\}\right) = 0 \tag{5.11}$$

is fulfilled. For solving the system of equations MATLAB Symbolic Math Toolbox is used to solve equations with symbolic variables, which return more solution sets. Further the sets of solutions are checked: if the Lagrange multipliers do not satisfy inequities constrains (4.7 –4.9), the solution set is ruled out. As the function of spectral efficiency in a neighbourhood (3.12) is not generally convex, by solving the Lagrange function (5.10) multiple local maxima are returned. Lastly, the spectral efficiency (3.12) is calculated, and the set of solutions which maximizes it is found.

Firstly we assume that all the users are allocated with the transmit power zero. Secondly the transmit powers are allocated using the method of Lagrange multipliers as described above. Because in the fist step was assumed that transmit powers are equal zero, interference calculated during power allocation in the second step are significantly lower than the interference when the transmit powers take real values. In order to avoid the uncontrolled increase of interference, the transmit powers are increased gradually.

We define $P_{k,i,Lagrange}(n)$ as the transmit powers calculated as optimal at each iteration cycle n by the method of Lagrange multipliers. Than the powers assigned to the users are calculated,

$$P_{k,i}(n+1) = P_{k,i}(n) + \min(n\Gamma, 1)(P_{k,i,Lagrange}(n+1) - P_{k,i}(n)), \quad (5.12)$$

where Γ is a constant which dictates the speed by which the transmit powers are changing the values,

$$\Gamma > 0. \quad (5.13)$$

In this manner, the transmit powers are changing gradually leaving the space for all base stations to adapt to the new interference levels.

Further, the new power levels are compared with the previous if the conditions (3.13) and (3.14) are satisfied. If the constrains are not fulfilled the process of power allocation is iteratively continued until the requirements are met.

Algorithm 8 Decentralized method of power alocation

Require: $M > 0$ ▷ M is a number of cells
Require: $K > 0$ ▷ K is a number of users per cell
Require: $\Gamma > 0$

$\boldsymbol{P_{k,i}} \leftarrow 0$ ▷ $k \in \mathcal{M}$, $i \in \mathcal{K}_k$
do
  for $k \in \mathcal{M}$ **do**
    $\boldsymbol{P_{k,i,Lagrange}(n+1)} \leftarrow$ optimal solutions of 5.10
    $P_{k,i}(n+1) = P_{k,i}(n) + \min(n\Gamma, 1)\,(P_{k,i,Lagrange}(n+1) - P_{k,i}(n))$
  end for
  $\Delta P_m ax \leftarrow 0$
  for $k \in \mathcal{M}$ **do**
    for $i \in \mathcal{K}_k$ **do**
      $\Delta P_{k,i} \leftarrow P_{k,i}(n+1) - P_{k,i}(n)$
      if $\Delta P_{k,i} > \Delta P_{max}$ **then**
        $\Delta P_{max} \leftarrow \Delta P_{k,i}$
      end if
    end for
  end for
while $\Delta P_{max} > \delta$

Chapter 6

Centralized vs. Decentralized

While aiming to maximize total spectral efficiency of a cellular system in the case when dynamic TDD is applied, multiple obstacles have to be considered. First of all, emerging problem of inter-channel interference has to be solved. Further, allocation of optimal transmit powers is to be considered. In order to find a solution for these questions, we have proposed two optimization methods, first centralized and than decentralized method. Both approaches are explained in details in Chapter 4 and 5.

We have stated earlier that the centralized solution requires higher computational effort. However, due to the fact that it has an insight in the whole system, an optimal solution is found. Therefore, we assume that the decentralized scheduling achieves lower total spectral efficiency.

In order to determine which method is better to use and in which conditions, we will analyze both approaches and compare them. The considered criteria of comparison are the computation effort needed to optimize the system and the performance of each method. While the first criterion will be determined theoretically based on the algorithms presented in previous chapters, performance will be compared after running simulations in MATLAB and obtaining results of both approaches.

We will investigate complexity of the algorithms as a function of the input size. In this way, the computational cost which does not depend neither on the hardware nor on the software used to run the optimization process, will be obtained. In the end, we will get a function of computational cost over the size of the input. The input size in this case is the number of cells and users within the cells.

To calculate computational effort we will examine the number of mathematical operations and their complexity. At first we will concentrate on the centralized approach.

In the centralized approach the Lagrange function $\mathcal{L}$ is computed. It consists of between $2MK + M$ and $3MK$ variables:

- MK variables representing the transmission powers, $P_{k,i}$.
- MK Lagrange multipliers, $\mu_{k,i}$.
- maximal M multipliers λ_k depending on the number of cells transmitting in DL.
- maximal $3MK$ multipliers $\xi_{k,i}$.

Now, in order to maximize the Lagrange function first, the derivatives of the function over the transmit powers are calculated. Secondly, conditions (4.4)-(4.9) have to be satisfied. This leads to the system of equations that includes:

- MK equations deriving from setting the derivatives of Lagrange function to zero (4.2).
- MK equations deriving from the Lagrange multipliers conditions (4.5) and (4.6).
- a maximum of M equations deriving from the condition limiting the maximal power allocated to each BS operating in DL (4.3). The exact number of equations is equal to the number of cells transmitting in DL.
- finally, a maximum $3MK$ equalities determined by constrain (4.4).

Because in general this system provides multiple solutions, additional inequalities have to be solved:

- MK inequalities by constraint (4.9).
- between M and MK inequalities determined by (4.8) and (4.7).

When determining computational complexity we are interested in the worst case scenario. This implies analysing the scenario where the optimization algorithm is the most complex. Which occurs when all cells operate in UL, leading to a system of $5MK$ equations.

The complexity of solving the system of n equation is $\mathcal{O}(n^3)$. Because we are solving the system of $5MK$ equations, we can state that the complexity of allocating the powers in centralized manner is $\mathcal{O}((5MK)^3)$. Further, finding a scheduling which maximizes spectral efficiency, requires checking all possible scheduling scenarios. Therefore, the above described process has to be repeated 2^M times. Finally, we can state that the total computational cost as a function of input size is $\mathcal{O}(2^M(5MK)^3)$.

On the other hand, about the decentralized method, first we have to analyse scheduling optimization. Each cell determines its scheduling by performing fixed number of basic arithmetic operations. Because the complexity increases linearly when input is increasing we have $\mathcal{O}(M)$. Secondly power allocation is done similarly to the centralized method but on local level. Correspondingly, complexity of the method is lower. Analyzing the applied algorithm as we have done for the centralized approach, we determine that computation cost of one iteration cycle, calculating powers for all users once, is $\mathcal{O}(M(5K)^3)$. Due to the fact that powers are allocated gradually, complexity of the whole process is $\mathcal{O}(nM(5K)^3)$, where n is a constant denoting number of iteration cycles. Consequently, the complexity of the decentralized TDD is $\mathcal{O}(M) + \mathcal{O}(nM(5K)^3)$. Further, n is a constant and it does not depend on the input and term $\mathcal{O}(M)$ becomes negligible as the size of the model increases. Therefore, total computational cost of the centralized TDD can be approximate as $\mathcal{O}(M(5K)^3)$.

We may now summarize the results of this chapter. The computational complexity of the analyzed methods, as a function of size of the used cellular model, is:

- Centralized TDD: $\mathcal{O}(2^M(5MK)^3)$.
- Decentralized TDD: $\mathcal{O}(M(5K)^3)$.

It is obvious that optimizing TDD in a centralized manner requires higher computational effort. The difference becomes especially significant as the size of the cellular system grows. In order to have a wider representation of advantages of both approaches, in next chapter we will analyze and compare the performance of each method by performing MATLAB simulations.

Chapter 7

Results

7.1 Centralized TDD

In this section the results of optimal power allocations and DL/UL scheduling, applied on specific scenarios will be demonstrated and discussed. The presented calculation model is suitable for scenarios where users are at the minimum distance of 50 m from a BS, where the path loss model works.

The model is generated assuming that the BSs are placed 1000 m away from each other. The users are positioned in the area between 50 and 500 m away from the BS, they are communicating with. We introduce the following notation:

- $d_{k,i}$: distance between user i and its own base station k
- $q_{k,i}^{m}$: distance between user i, serviced by cell k, and the BS m
- $c_{k,i}^{m,j}$: distance between user i in cell k and user j in cell m
- h_{k}^{m}: distance between BS k and BS m.

Furthermore, the channel gains are defined as:

- $D_{k,i} = \left(\frac{500\text{m}}{d_{k,i}}\right)^2$
- $Q_{k,i}^{m} = \left(\frac{500\text{m}}{q_{k,i}^{m}}\right)^2$
- $C_{k,i}^{m,j} = \left(\frac{500\text{m}}{c_{k,i}^{m,j}}\right)^2$

- $H_k^m = \left(\frac{500\text{m}}{h_k^m}\right)^2$.

The transmit powers $P_{k,i}^{(DL)}$ and $P_{k,i}^{(UL)}$ are normalized to the value of noise variance, $\sigma_{k,i} = 1$. The maximal DL transmit power per BS is set as $P_{k,max}^{(BS)} = 10K_k$, where K_k denotes the number of users communicating with base station k. On the other side, the maximal UL transmit power per UE is $P_{max} = 10$.

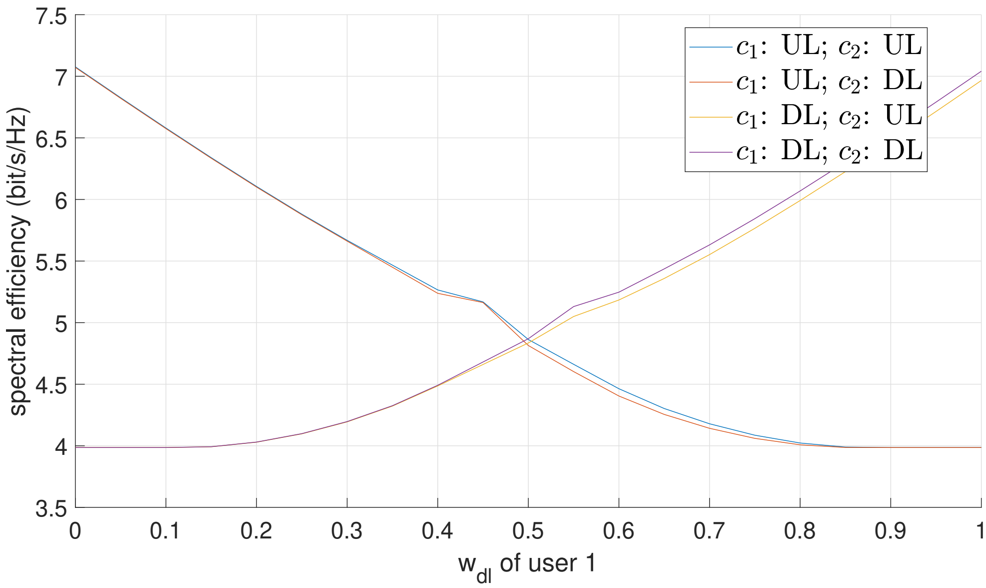

Figure 7.1: Spectral efficiency when weights denoting the queue length are changing during the time.

The first simulation is done in order to test the behavior of the system when the values of weighs, denoting the rate between the queue length in DL and in UL, are changing during the time. If $L_{k,i}^{(DL)}$ are downlink queue lengths for the user i within the cell k and $L_{k,i}^{(UL)}$ uplink, the weights are calculated as,

$$w_{k,i}^{(DL)} = \frac{L_{k,i}^{(DL)}}{L_{k,i}^{(DL)} + L_{k,i}^{(UL)}}, \tag{7.1a}$$

$$w_{k,i}^{(UL)} = \frac{L_{k,i}^{(UL)}}{L_{k,i}^{(DL)} + L_{k,i}^{(UL)}}. \tag{7.1b}$$

We consider the system of two cells, with one user each. The users are positioned 200 m away from the own base stations. Furthermore, a simulation is set so that the downlink weight of the user in the cell one is changing the value from zero to one while the user in the cell two has the constant weight of 0.5 in DL and UL. The level of spectral efficiency over the $w_{1,1}^{(DL)}$ is shown in the Fig. 7.1. Because the queue lengths in the cell two are the same for DL and UL, the scheduling of the cell two does not play a significant role. We notice that when $w_{(DL)} = 0$, i.e. the downlink queue has the length zero, the scheduling $BS_1 : UL$; $BS_2 : UL$ and $BS_1 : UL$; $BS_2 : DL$ achieve the highest total spectral efficiency. Further, due to the lower level of inter-channel interference if the cell are not scheduled to the same mode, slightly higher spectral efficiency is achieved in the case $BS_1 : UL$; $BS_2 : UL$ than $BS_1 : UL$; $BS_2 : DL$, and respectively for the case when both cells are scheduled in DL. The difference in spectral efficiency is small because the system consists just of two users, positioned on the great distance from each other, 600 m and as a consequence the inter-channel interference has a low influence on the overall spectral efficiency.

Further, by the rest of the simulation cases the DL/UL weights are set to the value $w_{k,i}^{(DL)} = 0.5$ and $w_{k,i}^{(UL)} = 0.5$, denoting the equal values of queue lengths in downlink and in uplink. The cases where the users are changing the positions inside the cell are simulated. The simulations are done so the assignment of the users to the base stations is fixed, i.e. the users do not change the BSs during the simulation.

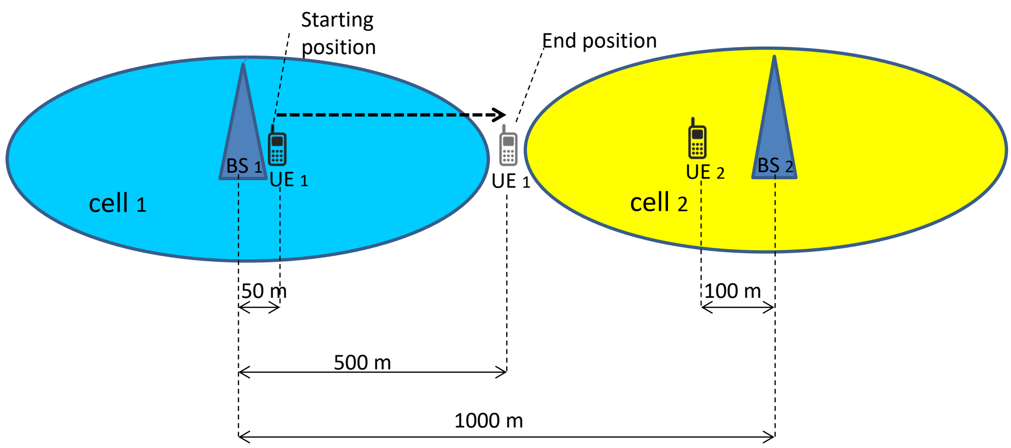

Figure 7.2: System representation for the centralized TDD: one user moves towards another cell.

The first considered scenario includes two cells, where each cell has one

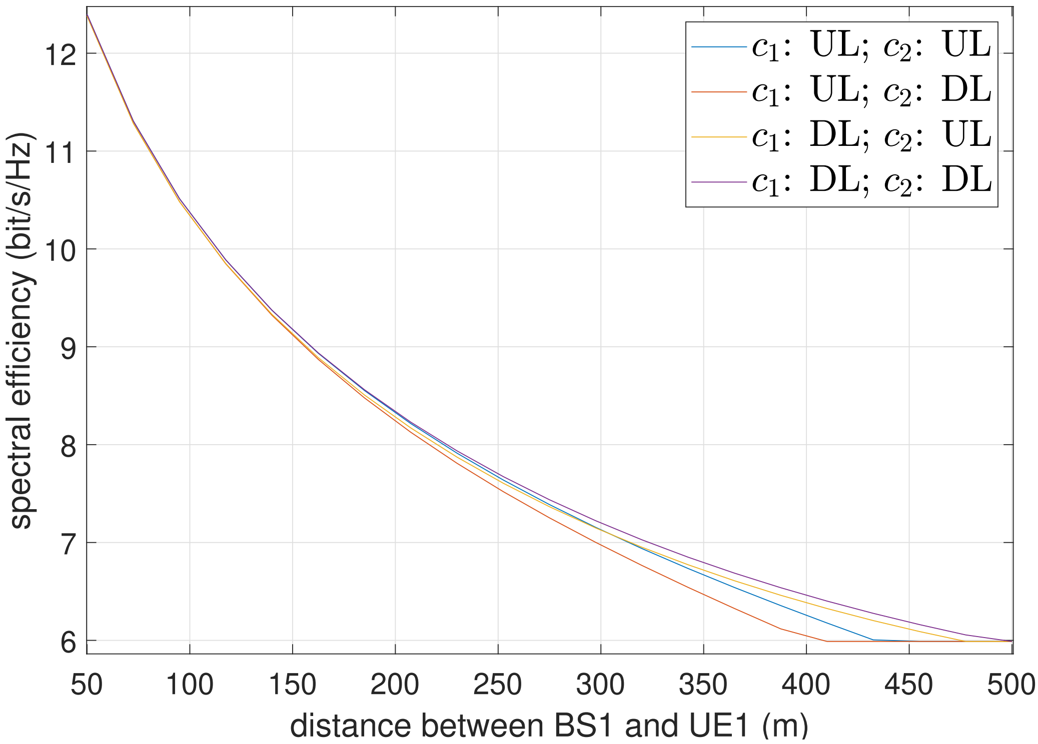

Figure 7.3: Spectral efficiency for the centralized TDD: one user moves towards another cell.

user (see Fig. 7.2). Fig. 7.3 shows the total spectral efficiency for the optimized system as a function of the distance between BS_1 and UE_1, where c_1 denotes the cell 1. The user in cell 1 is moving from the distance of 50 m to the distance of 500 m regarding its own base station. On the other side the user in the cell 2 is fixed at 100 m away from BS_2. At the beginning as the distance between the users is large, almost the same spectral efficiency level is achieved with all DL/UL scheduling possibilities. The reason for that is the low level of inter-channel interference due to the distance between the users. On the other side by shifting the user 1 towards the cell 2 the interference increases, and the decline of BS1-UE1 channel gain leads to the decline of spectral efficiency. It is noticeable that the scheduling c_1 : UL, c_2 : DL achieves the lowest spectral efficiency rate. The reason for this behavior is the shortest distance between the transmitter (UE_1) and receiver (UE_2). By reaching the distance of 500 m between BS_1 and UE_1, due to the high interference, the power allocated to UE_1 is brought down to 0. Further it means that inter-channel inference is lowered to 0 and all scheduling schemes reach the same level of spectral efficiency.

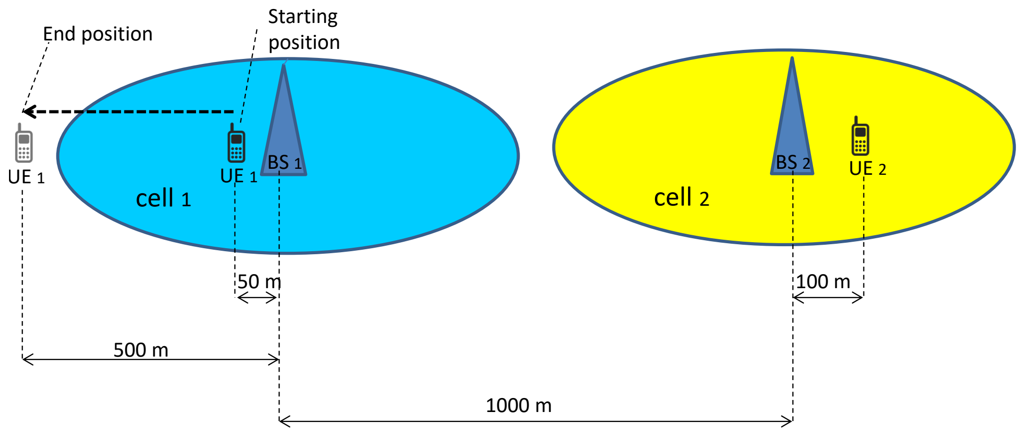

Figure 7.4: System representation for the centralized TDD: one user moves away from the other cell.

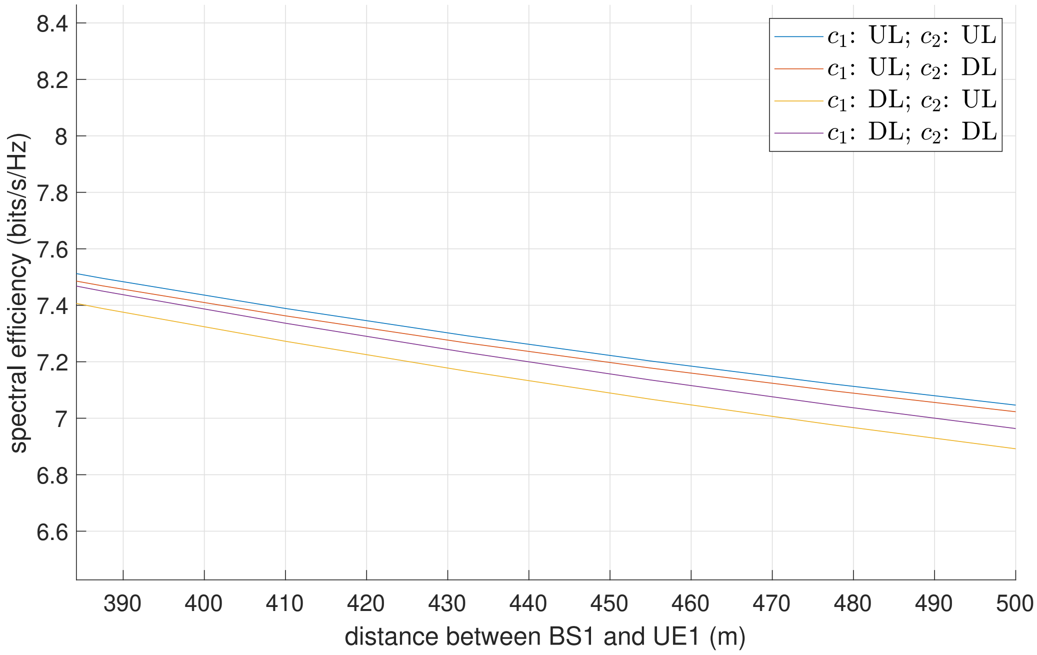

Figure 7.5: Spectral efficiency for the centralized TDD: one user moves away from the other cell.

The second considered case is the scenario of two cells with one user in each, where the user in cell a is moving away from BS_1. The user moves from distance 50 to 500 m away from BS_1, while the user in cell 2 is fixed 100 m away from BS_2 (see Fig. 7.4).

Observing the results of the described scenario (see Fig. 7.5) we notice that, as expected, when UE_1 moves away, the spectral efficiency drops because of the smaller channel gain between BS_1 and UE_1. In difference to the previous scenario, now as the the users are getting away from each other, interference is not increasing and the maximum power is allocated for both users during the whole interval. It is noticeable that by choosing the allocation c_1: DL, c_2: UL the smallest spectral efficiency is achieved and the scheduling c_1: UL, c_2: UL leads to the optimization of the system. Indeed, the first case corresponds to having the receiver and the transmitter at the smallest distance from each other. On the other hand, by the scheduling c_1: UL and c_2: UL, the only inter-channel interference is occurring between UE_1 and UE_2, which are at the great distance from each other. In particular, when $d = 500$ m, they are 1600 m away from each other.

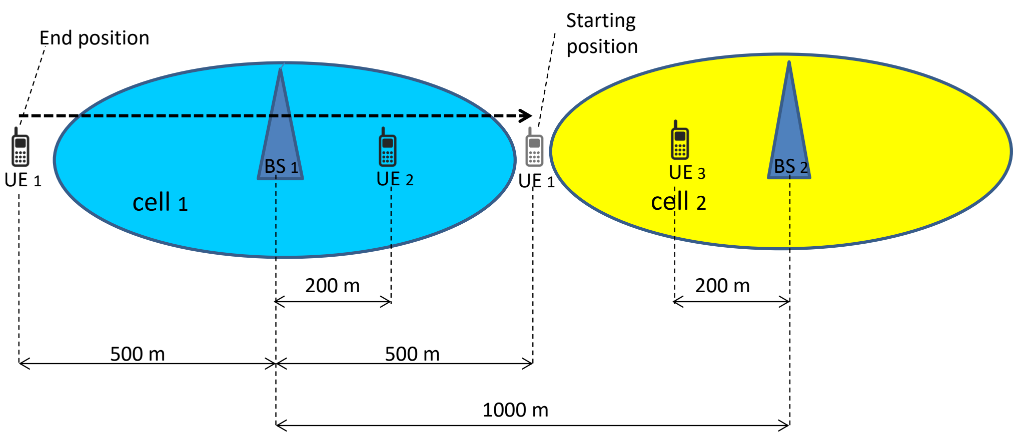

Figure 7.6: System representation for the centralized TDD: two users in cell 1, one UE moves towards BS_2.

The last considered scenario includes two cells where one cell has two users and the other one one user (see Fig. 7.6). While UE_2 and UE_3 are fixed at 200 m from their own base stations, UE_1 moves from 500 m on the opposite side of BS_2 to 500 m towards BS_2, regarding the BS_1. It should be noted again that the model is not suitable to calculate the spectral efficiency on the interval 50 m around the BS.

Notice that scheduling c_1: DL, c_2: DL gives the highest spectral efficiency as UE_1 is on the opposite side of BS_1 (see Fig. 7.7). As UE_1 comes closer to BS_2 scheduling c_1: UL, c_2: UL maximizes the function up to around 350 m when power allocated to user in cell 2 reaches maximum again, interference increases and scheduling c_1: DL, c_2: DL takes again the lead in optimizing the system.

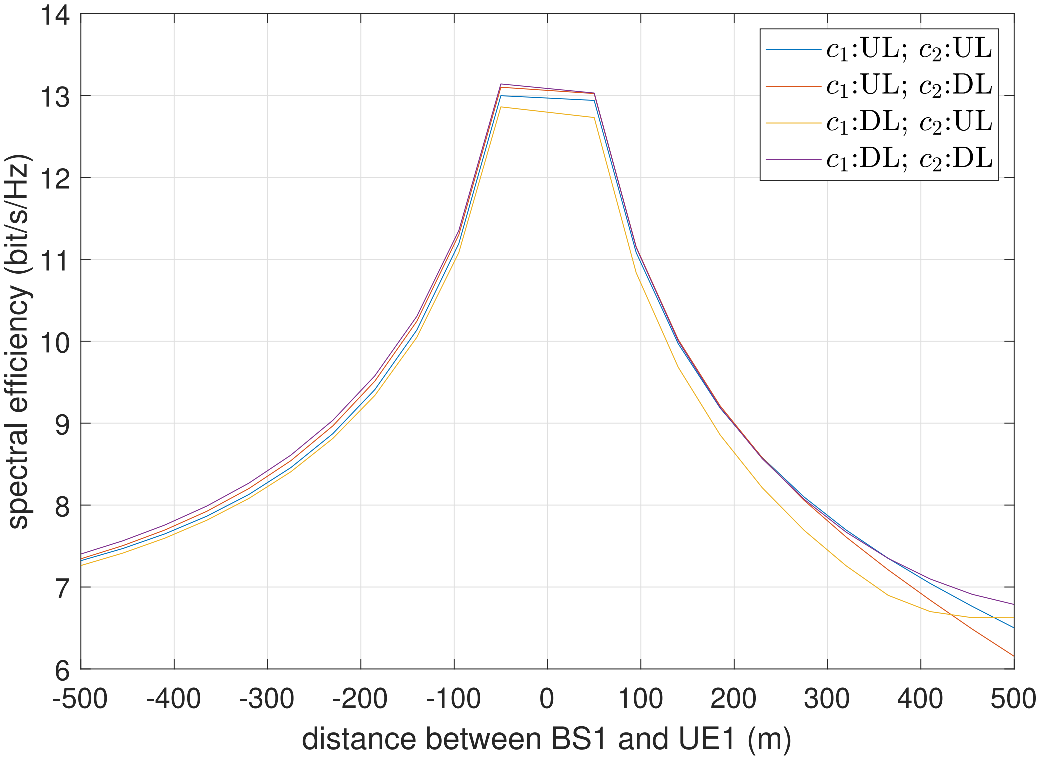

Figure 7.7: Spectral efficiency for the centralized TDD: two users in cell 1, one UE moves towards BS_2.

In Fig. 7.8 we see power allocation for the four schedulings. When BS_1 is transmitting in UL (schedulings c_1: UL, c_2: UL and c_1: UL, c_2: DL) for UE_1 and UE_2 is allocated the maximum power except when UE_1 comes close to BS_2 which is transmitting in DL (c_1: UL, c_2: DL). In that scenario power allocated to UE_1 is lowered because it causes strong interference with receiving signal at user in BS_2. Furthermore, when both cells are in UL (c_1: UL, c_2: DL), the power allocated to the user in cell 2 is lower as the UE_1 is closer than 200 m to the BS_1, in order to decrease inter-channel interference. Further, by the schedulings c_1: DL, c_2:UL and c_1: DL, c_2:UL it is to notice the power distribution between UE_1 and UE_2. As the UE_1 moves away from BS_1, its power is decreased in favor of UE_2 because it has a higher channel gain. On the other side, UE_1 getting closer to the other base station has a greater influence on its allocated power. As the distance UE_1-BS_1 exceeds the distance of 200 m not only the channel gain of UE_2 is getting higher compared to UE_1 but getting closer to BS_2 increases also the inter-channel

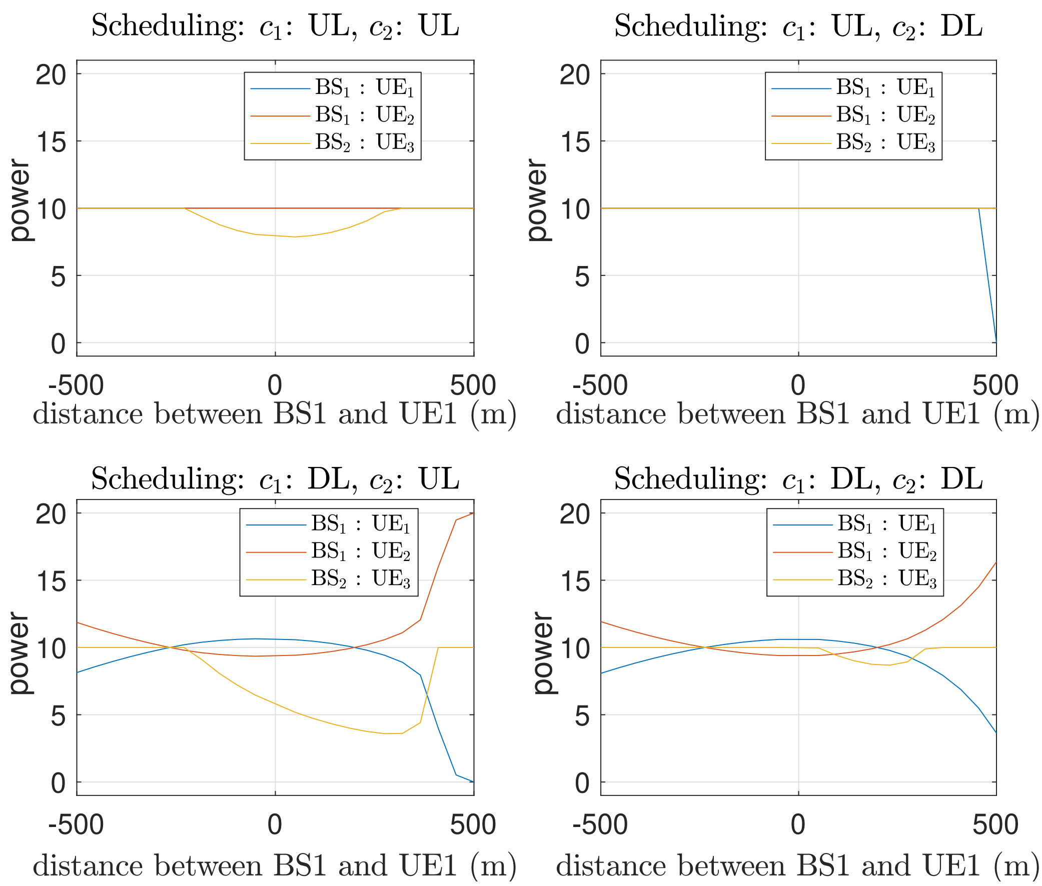

Figure 7.8: Power allocation for the centralized TDD: two users in cell 1, one UE moves towards BS_2.

interference.

7.2 Decentralized TDD

7.2.1 Approach 1

The model is done considering that the cells have triangular shape (see Fig. 7.9), meaning that each cell has $N = 3$ neighbours and so has to consider $2^4 = 16$ schedulings.

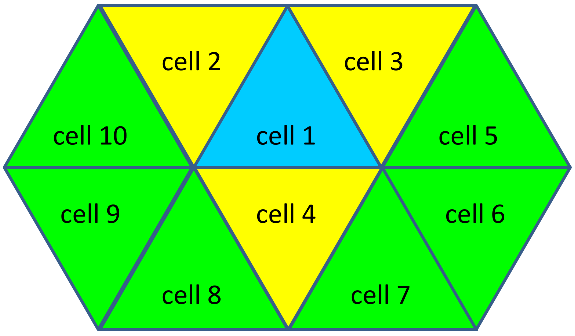

Figure 7.9: An example of cell positioning in decentralized TDD

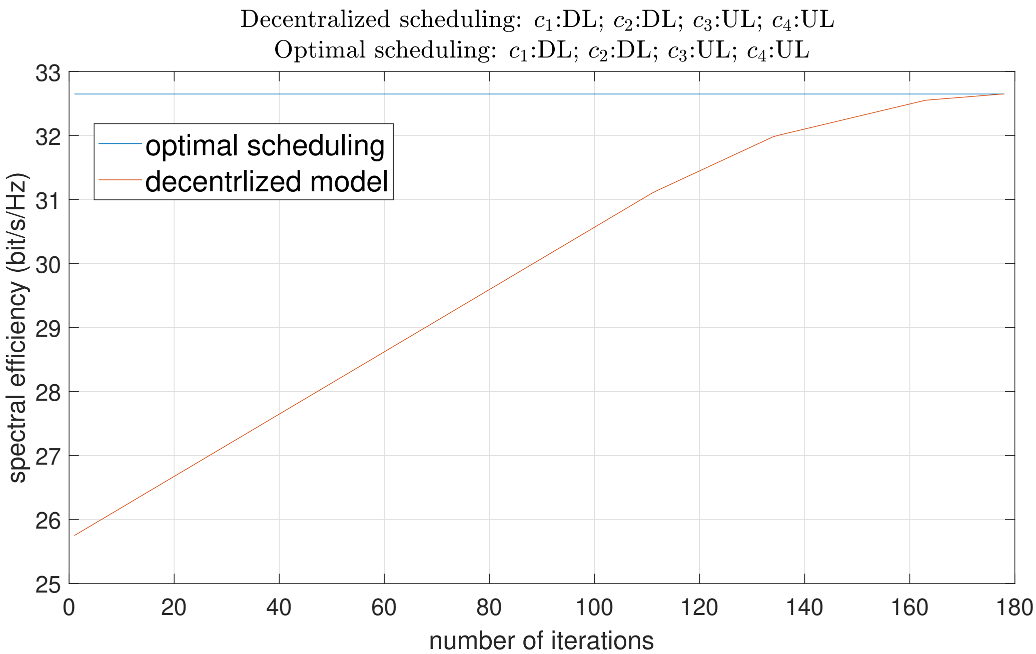

Figure 7.10: Spectral efficiency for decentralized TDD, 4 cells, calculated by approach 1.

Firstly, a simulation on 4 cells is done. In Fig. 7.10 we see the comparison between the decentralized approach and the optimal solution. After 180 iteration steps the function reaches the value of the optimal solution.

Although this example shows that the algorithm is able to select the optimal solution in general this is not a case. As the time markers for each cell are moving independently and with different step sizes, some markers reach the boundary faster than the others. When a cell achieves time 0 or 1 its marker stay still, while the other cells continue to move their markers in

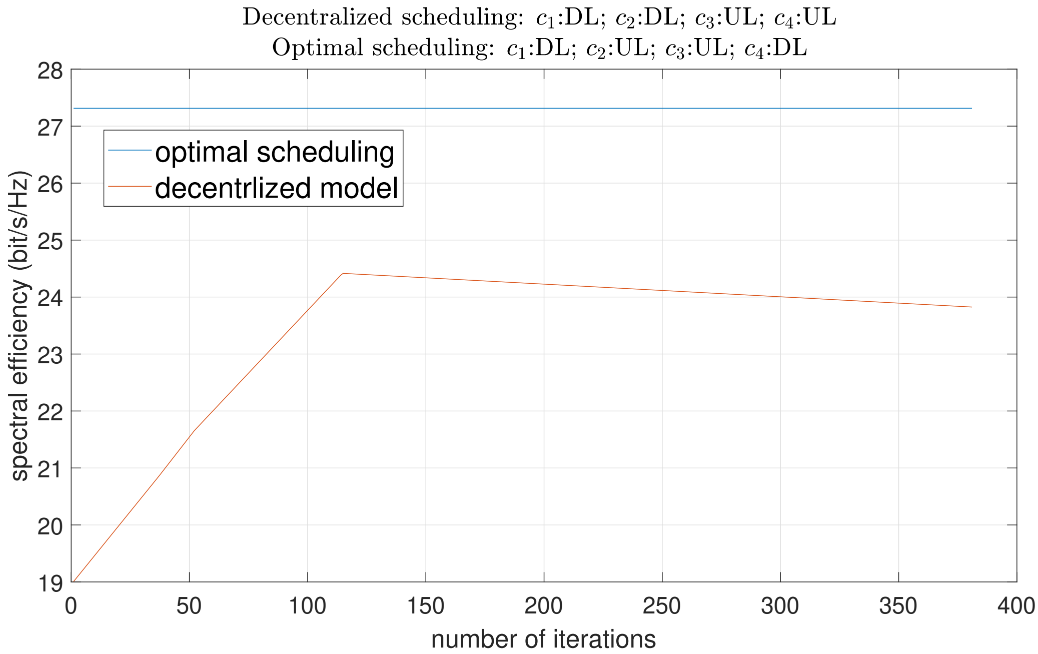

Figure 7.11: Visualization of disadvantage of approach 1 of the distributed scheduling on spectral efficiency.

other to increase own spectral efficiency. This behavior can cause a decline of overall spectral efficiency. This scenario is demonstrated in Fig. 7.11. The function is increasing up to the point when three cells have made their DL/UL decision (timing markers reached the value 0 or 1). At that point just the forth cell is left to make a choice. While it moves the marker to increase own spectral efficiency it does not consider the decline of the overall function.

The results of the system of ten cells is shown in Fig 7.12. Again the negative effect of the previously described selfish behavior is demonstrated by the decline of the function at the points when one of the cells makes a decision (at iteration 38 and 108).

7.2.2 Approach 2

The simulation of the proposed decentralized TDD is done on the model of ten triangular cells (see Fig. 7.13). In Section 7.2.1 we have observed drop of total efficiency as each cell has done scheduling. On the other side, here simulated algorithm solves this issue (Fig. 7.13), by basing its decisions on the total spectral efficiency within its neighborhood. In the previous approach of of the cells The initial positions of the timing markers are assigned

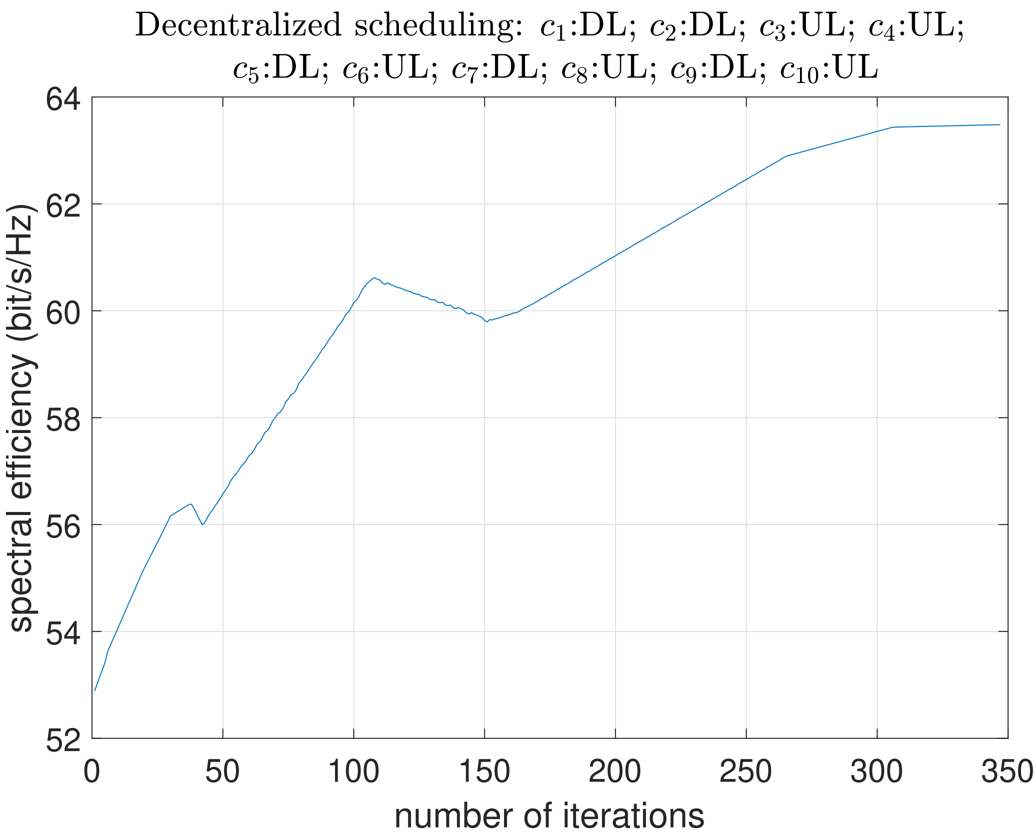

Figure 7.12: Spectral efficiency for decentralized TDD for 10 cells scenario, calculated by approach 1.

uniformly in the interval $t_k \in [1, 0]$ and the values of the spectral efficiency are set $R_{k,c} \in [0, 1]$.

Due to the higher collaboration between cells, each cell, when moving the timing marker considers how does its decision influence the other cells in the neighborhood. This leads to a higher spectral efficiency.

7.2.3 Comparison of the proposed decentralized TDD schemes

Three previously discussed approaches of decentralized TDD are compared. The model consists of ten triangular cells. The simulation is done on the sample of 100 scenarios. In each scenario the initial values of the time markers and spectral efficiency are assigned uniformly so that $t_k \in [0, 1]$ and $R_{k,c} \in [0, 1]$, $k \in \mathcal{M}, c \in [0, \cdots, 2^{N+1}]$, $N = 3$ being the number of cells bordering one cell. For each probe all three schemes optimize the system by

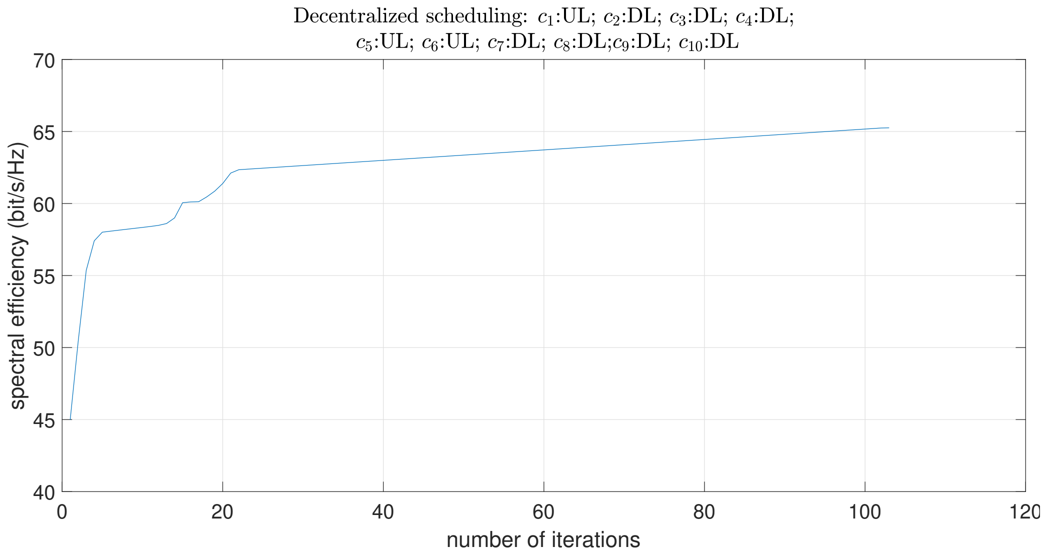

Figure 7.13: Spectral efficiency for approach 2 of decentralized TDD, model of 10 cells.

the given data. The achieved spectral efficiency by each approach over the probe number is demonstrated in the Fig. 7.14. It is obvious that the scheme considering just the spectral efficiency of the cell moving the marker (scheme 1) achieves the lowest results. On the other hand the two following schemes show similar results. To make the comparison more precise, an simulation with higher number of scenarios is done, and the average spectral efficiency per scheme is calculated and compared.

When a simulation on 500 samples is analyzed we came to following conclusions:

- As expected, the scheme one achieves the lowest spectral efficiency, $\overline{R}_{scheme1} = 59.327$.
- The scheme two resulted with the average spectral efficiency $\overline{R}_{scheme2} = 66.777$.
- Scheme three, applied on the same scenarios achieves average spectral efficiency of $\overline{R}_{scheme3} = 67.454$.

We notice that the scheme three shows the highest success rate being $\approx 12\%$ higher than the scheme one and $\approx 1\%$ higher than the average spectral efficiency achieved by the scheme two.

Figure 7.14: Comparison of the spectral efficiency achieved by the proposed decentralized scheduling schemes.

7.2.4 Power Allocation

The decentralized scheme of power allocation is simulated on the system of ten cells. The cells are assumed to have equilateral triangular shape with the altitude 900 m. Consequentially each cell is bordered by up to three cells with which it communicates. The base stations are placed in the center of each cell, therefore, the neighboring cells base stations are distanced by 600 m from each other. Further we place five users in each cell. The users are placed uniformly within the interval 50 m to 300 m away from the center of their own cell. The DL/UL scheduling is done as described in Section 5, and during the power allocation it is taken as constant.

The values of transmit power $P_{k,i}^{(DL)}$ and $P_{k,i}^{(UL)}$ are normalized to the

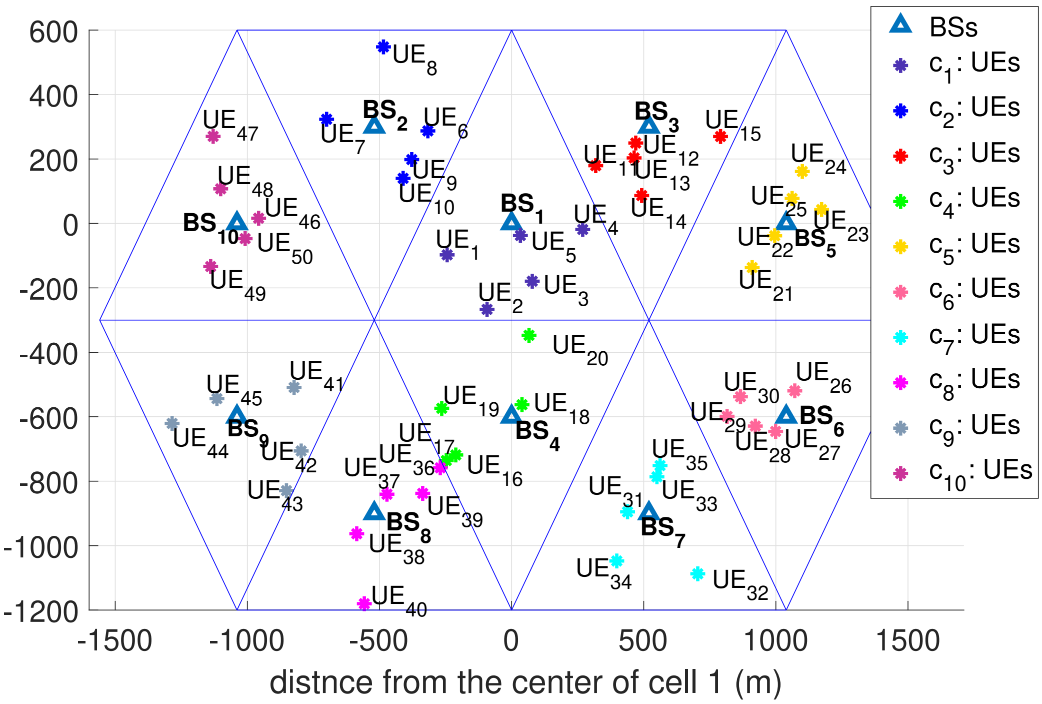

Figure 7.15: Position of the users in simulation with 10 cell for the case of decentralized power allocation.

noise variance $\sigma_{k,i} = 1$. Each base station is allocated with the maximal DL transmit power $P^{(BS)}_{k,max} = 10K_k$, $k \in M$, K_k denoting the number of users in cell k. Further the maximal transmit power allocated to each user transmitting in uplink is $P^{(UL)}_{max} = 10$.

The channel gains are determined as described in Section 7.1.

The simulation model is shown in Fig. 7.15. The scheduling is set so that all the cells transmit in in downlink. The allocated powers are shown in Table 7.1. We notice that in the first cell the users two and four are allocated with power zero, as they are placed far away from the base station and the channel gain is lower than between the other users and the BS_1. Additionally, being positioned close to the BS_4 and BS_3, leads to the higher inter-channel interference, and consequentially decreases the spectral efficiency of the communication with the user. On the other side the power allocated for user five is taking the highest value due to its small distance from the base station.

The effect of inter-channel interference on power allocation is best observed in cell 8. Even though user 36 and 40 are at a similar distance from BS_8, user 40 is allocated power $P^{(DL)}_{40} \approx 7$ and user 36 power $P^{(DL)}_{36} = 0$. The reason is that UE_{36} being close to BS_4 originates high inter-channel

$UE_1 : 2.66$	$UE_2 : 0$	$UE_3 : 15.01$	$UE_4 : 0$	$UE_5 : 32.33$
$UE_6 : 7.71$	$UE_7 : 12.12$	$UE_8 : 11.32$	$UE_9 : 10.89$	$UE_{10} : 7.94$
$UE_{11} : 0$	$UE_{12} : 20.08$	$UE_{13} : 22.68$	$UE_{14} : 7.23$	$UE_{15} : 0$
$UE_{16} : 6.16$	$UE_{17} : 0$	$UE_{18} : 38.48$	$UE_{19} : 5.13$	$UE_{20} : 0.21$
$UE_{21} : 2.43$	$UE_{22} : 14.34$	$UE_{23} : 11.00$	$UE_{24} : 8.54$	$UE_{25} : 13.69$
$UE_{26} : 15.35$	$UE_{27} : 16.52$	$UE_{28} : 12.69$	$UE_{29} : 0$	$UE_{30} : 5.43$
$UE_{31} : 15.68$	$UE_{32} : 2.70$	$UE_{33} : 12.98$	$UE_{34} : 9.38$	$UE_{35} : 9.26$
$UE_{36} : 0$	$UE_{37} : 18.69$	$UE_{38} : 18.36$	$UE_{39} : 5.95$	$UE_{40} : 6.99$
$UE_{41} : 7.74$	$UE_{42} : 0$	$UE_{43} : 0$	$UE_{44} : 16.53$	$UE_{45} : 25.73$
$UE_{46} : 14.16$	$UE_{47} : 0$	$UE_{48} : 12.74$	$UE_{49} : 7.70$	$UE_{50} : 15.39$

Table 7.1: The results of power allocation using the decentralized iterative scheme.

interference, while UE_{40} is far away from all base stations presented in the system.

Fig. 7.16 shows the level of total spectral efficiency in all ten cells during the iterative process of power allocation. The step number denotes the points when a power is allocated to each user. Further, the iteration cycle represents the points when a full cycle of power allocation to all users in the system is done. The spectral efficiency corresponding to step 1 denotes the efficiency achieved when all users are allocated with no power, $P_{k,i}^{(DL)} = 0$. Further, step 2 denotes the case when just one cell has reallocated its transmit powers, considering that all other cell operate with transmit powers determined in previous step. Because this case actually means not considering real influence of interference, the speed of increasing the allocated powers is limited as explained in Section 5.2.3. We notice that the spectral efficiency is increasing very fast during the first cycle, as the transmit powers are increased from zero but still on relatively low level to cause high interference. On the other side at iteration cycle 2 ($n = 2$) we can see that the function is not constantly increasing any more. The reason for such a behaviour is that at the each step powers are determined within the cell, locally, not calculating the effect on the spectral efficiency in the whole system. As the allocated powers increase, the inter-channel interference also increases and can cause fall in the total spectral efficiency.

We notice that during each iteration cycle the spectral efficiency is in-

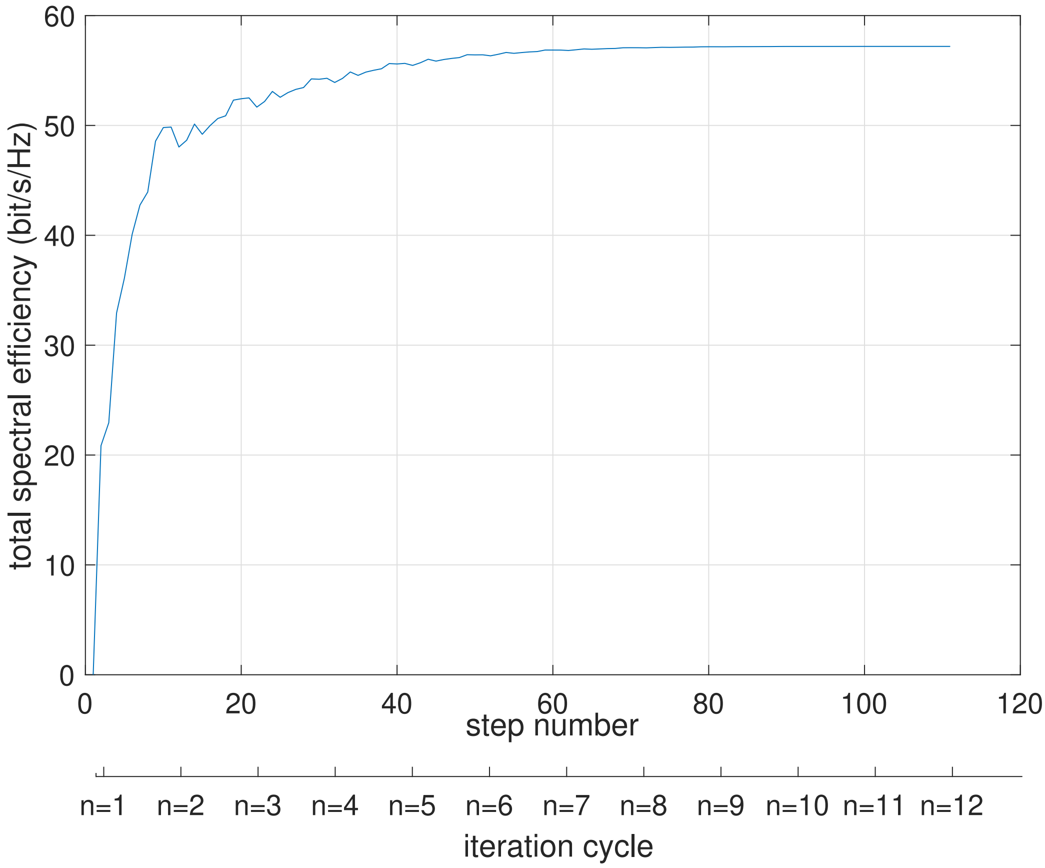

Figure 7.16: Total spectral efficiency during the process of allocation of transmit powers.

creasing slower and slower as it reaches the optimal point. As the optimal allocation is found, spectral efficiency tends to a constant value meaning that the transmit powers have not changed though whole iteration cycle. Even though no change grater than the constant δ has been made, this cycle is still of crucial significance to the process because it denotes that the function has converged and the optimal values of the transmit powers are set.

7.3 Performance of centralized vs. decentralized TDD

Finally we can compare performance of the proposed algorithms. The simulated model consists of four cells. Each cell is modeled as an equilateral triangle, with a base off 1000 m. Within each cell four users are distributed uniformly.

Because of time consumption problem of running proposed algorithm for centralized TDD, an optimal solution is found by extensive search. Finding a solution in decentralized manner is done by the approach 3, which has shown the best performance.

After running the simulations, we have obtained the following mean values of total spectral efficiency:

- centralized TDD: 29.0
- decentralized TDD: 23.0.

It is obvious that centralized solution outperforms distributed approach by approximately 20%. Moreover, it is important to emphasize that in the future work, further simulations should be conducted, using more realistic data and bigger cellular systems. We assume that by running simulations where pre-saved data used for optimizing decentralized system is calculated on a big number of probes, algorithm for decentralized TDD would perform better.

Chapter 8

Conclusion and future work

This thesis examined possibility of increasing the capacity of a cellular system by applying dynamic TDD, where each cell operates in DL or UL based on traffic requirements. Since this can lead to a scenario where neighboring base stations are transiting in opposite directions, high inter-channel interference is expected. To solve this issue we have addressed two questions

1. scheduling and

2. power allocation

so the spectral efficiency is maximized.

In this thesis we have proposed two approaches to calculate parameters of a cellular system, which optimize dynamic TDD in centralized and decentralized manner. In centralized TDD, differently to decentralized, a central unit is present which oversees the whole system and optimizes it. On the one hand it is a reason for having higher computational cost. On the other hand it enables the system to reach the optimal solution, i.e., maximize total spectral efficiency for all users.

Power allocation by centralized approach consists of an optimization problem with constraints. It includes MK variables. To solve this problem we have used Lagrange multipliers method. Further, scheduling is done by observing performance of all possible scheduling combinations in the system.

The same problem, has as well been approached in a decentralized manner. The process of scheduling is done as a partially cooperative game, where BSs are the players. Each sub-frame is continuously divided by timing markers, representing a desire of a cell to transmit in DL or UL. Scheduling is determined gradually until the values of the timing markers converge to one extreme. Secondly, powers are allocated in each BS by solving Lagrange multipliers method.

In Chapter 6 we have discussed computational effort for each of the algorithm. We have concluded that centralized TDD requires way higher computational cost. It is especially significant as the size of the observed cellular system, number of cells and number of users per cell, increases. Calculated computation cost of each algorithm is:

- Centralized TDD: $\mathcal{O}(2^M(5MK)^3)$.
- Decentralized TDD: $\mathcal{O}(M(5K)^3)$.

On the other side centralized TDD provides better performance by approximately 20%. We assume that the number becomes smaller if the more realistic data set has been used to run the simulation. However, decentralized approach would still show significant performance downgrade compared to centralized TDD.

About future work, the proposed algorithms should be simulated on a more realistic model. It is to emphasize that the proposed algorithms as well as created MATLAB codes support model of any size, M cells and K users.

Further, it is to investigate if the proposed centralized method can be combined with the decentralized in order to use benefits of both approaches. It could be done through clustering of neighboring cells, or cells which show similar traffic profile. Further, it would be useful to determine on real case scenarios, to which extent the combination of the two approaches increases spectral efficiency.

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Wien, Juli 2019

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