OPTIMAL RESOURCE ALLOCATION IN DOWNLINK CDMA WIRELESS NETWORKS

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DISSERTATION

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the doctor's degree at the University of Twente,
on the authority of the rector magnificus,
prof. dr. H. Brinksma,
on account of the decision of the graduation committee,
to be publicly defended
on Thursday 30 May 2013 at 14.45

by

Irwan Endrayanto Aluicius
born on 28 October 1972
in Klaten, Central Java, Indonesia

Dit proefschrift is goedgekeurd door de promotor,
prof. dr. R. J. Boucherie
prof. dr. J.L van den Berg

en de assistent-promotor,
dr. A.F. Gabor

To my parents
To my wife Ina
To my daughters Venda & Dinda

Remember how for forty years now the LORD, your God,
has directed all your journeying in the desert,
so as to test you by affliction and find out
whether or not it was your intention
to keep his commandments.
(The Bible - Deuteronomy 8:2)

Sakèhing prekara daksangga srana kekuwatan
sing diparingaké déning Sang Kristus marang aku.
(I have the strength for everything through HIM who empowers me.)
(The Bible - Philippians 4:13)

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> Science has in fact two aspects. Day science involves reasoning as articulated as gears, results that have the strength of certainty. Aware of its style, proud of its past, sure of its future, the science of days advances in the light. *Night science, on the contrary, wanders in the dark. It hesitates, stumbles, falls.* Questioning everything, it is searching itself endlessly, combining, associating myriads of hypothesis, assumptions still in the form of vague hunches, projects barely taken shape. Nothing guarantees its successes, its ability to survive the tests of logic and experiments, but sometimes thanks to intuition, instinct and the will to discover, as a lightning it illuminates more than a thousand suns....-**François Jacob**, *The Statue Within.*

The long and winding road finally comes to an end. I've been wanders in the dark and hesitated in writing the thesis for years. Luckily, during that years I have met so many good people who have given me more of their time, professional and personal help, and above all: patience over indefinitely deadline for finishing this thesis. Without them, I could hardly imagine that I will have a Ph.D thesis. Therefore I would like to thank all people who help me to finish this thesis.

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Above all, I thank to the Almighty God, who works constantly in mysterious and miraculous ways in my life —*Deus Meus et Omnia* —.

Enschede *Irwan Endrayanto Aluicius*
May 2013

Contents

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List of Symbols & Abbreviations

α	the non-orthogonality factor, *page 5.*
ϵ_i^*	the required energy per bit to interference ratio, *page 5.*
$\lambda(\mathbf{T})$	the Perron-Frobenius (PF) eigenvalue of matrix $\mathbf{T}$, *page 18.*
$(E_b/I_0)_i$	the energy per bit to interference ratio for a user i, *page 4.*
$\mathbf{R}_X$	$(r_1, r_2, \cdots, r_I)$, the rates assigned to users in cell X, *page 43.*
$\mathbf{R}_Y$	$(r_1, r_2, \cdots, r_{L-I})$, the rates assigned to users in cell Y, *page 43.*
$\mathcal{B}$	the set of N base transmitter stations (BTS)., *page 75.*
$\mathcal{F}_1(\mathbf{r})$	the set of feasible power assignments with rate assignment $\mathbf{r}$, *page 77.*
$\mathcal{R}_1$	the set of rates within the allowed range for which a feasible power assignment exists, *page 77.*
$\prec_{\mathbf{P}}$	the received interference ordering, *page 80.*
$\widehat{P^X}$	the uplink received signal of BTS X, *page 8.*
$\widehat{P^Y}$	the uplink received signal of BTS Y, *page 8.*
$l_{i,X}$	the path loss of a user i located at distance d_i from BTS X, *page 4.*
N_0	the thermal noise, *page 4.*
N_0^i	the thermal noise received by mobile i, *page 75.*
P_i	the transmission power towards user i, *page 4.*
r_i	the data rate for a user i, *page 4.*

$V(r_i)$	$\frac{\epsilon_i^* r_i}{W+\epsilon_i^* r_i}$, *page 8.*
x	$\sum\limits_{i \in U_X} P_{iX}$, the total transmitted power in BTS X, *page 65.*
y	$\sum\limits_{i \in U_Y} P_{iY}$, the total transmitted power in BTS Y, *page 65.*
CDMA	Code Division Multiple Access, *page 1.*
FPTAS	Fully Polynomial Time Approximation Scheme, *page 42.*
UMTS	Universal Mobile Telecommunications System, *page 1.*
W	the system chip rate, *page 4.*

Chapter 1

Introduction

1.1 Background - problem description

In the past 10-15 years we have witnessed an enormous growth in the demand for mobile communications ranging from speech only and simple mobile data applications in the early years to full mobile Internet with multimedia applications via smart phones nowadays. To handle the mobile traffic growth and meet the increasing service requirements (higher speeds, etc.) new radio access technologies are deployed. In addition, network operators face the challenge to use the capacity of their installed networks as efficiently as possible.

The third generation Universal Mobile Telecommunications System (UMTS) employes Code Division Multiple Access (CDMA) as the technique of sharing the network capacity among users. In a CDMA system, calls share a common spectrum, their transmissions are separated using (pseudo) orthogonal codes. The impact of multiple calls is an increase in the interference level, that limits the capacity of the system. Therefore, variation of load over space and time, and the inherit capacity restrictions due to scarce resources are fundamental issues in the operation of a wireless CDMA system. Load variation may occur at different time scales that require different solutions. At the operational level (time scale of minutes), load fluctuations occur due to randomness in call generation, call location and call lengths. At this time scale, load balancing is carried out via power and rate assignment as well as a reconfiguration of calls over cells. Managing the scarce resources via power and rate assignment requires an underlying algorithm that is fast enough to adapt to variations at this time scale. This thesis develops mathematical models for characterizing and optimizing capacity of CDMA-based wireless network via power and rate allocation.

1.2 Related work

The joint rate and power assignment problem for CDMA systems has received considerable attention over the past 10-15 years. Due to the complexity of the problem, several restrictions have been made, in order to obtain mathematically tractable models. The most common simplifications are considering a cell in isolation, thus neglecting the interference effects, or assuming some extra properties of rates/powers, like unlimited rates or powers. For a simplified model of a single cell in isolation, downlink power assignment schemes for maximizing the throughput (sum of rates) or minimizing the total power in the cell are proposed in [LMS05, DNZ02, YX03]. In [DNZ02], Duan et al. present a procedure for finding the power and rate allocations that minimizes the total transmit power in one cell. For the downlink most studies are based on pole capacity [Sip02] or based on discrete event or Monte-Carlo simulation leading to time consuming evaluation of feasibility and/or capacity [Sta02]. Resource assignment in a multicell environment is more complex than in a single cell, due to the interference caused by users in adjacent cells. It has been studied in the framework of cell-breathing for fixed data rates, see e.g. the pioneering work of [Han95, Yat95] that consider the uplink, that in the early days of CDMA was considered to be the bottle-neck. In this thesis, we aim for developing analytically tractable models for the joint rate and power assignment problem in the downlink of CDMA systems.

First, we review some related work of Chapter 2 where we develop a model for two cell linear model. We consider the joint rate and power assignment problem under the assumption that all users are using the same known rate. This leads to a model for characterizing downlink and uplink power assignment feasibility. For this, we will make use of the Perron Frobenius theory (see [Sen73]). A similar successful work using Perron Frobenius theory on the uplink was presented in [EE99, Han99, BCP00]. Effective interference models such as developed in [EE99] allow for a characterization of feasibility based on the total number of users only. However, the analysis in [EE99] requires a homogeneous distribution of the users over the network cells. In [Han99], feasibility is characterised via the Perron-Frobenius eigenvalue of an interference matrix of the network state. Unfortunately, for the uplink the PF eigenvalue is not available in closed-form so that it provides only a semi analytical evaluation of the uplink capacity. In Chapter 2, the analytical expression of the Perron-Frobenius eigenvalue is available in closed-form. As in [EvdBB05], we derive a condition for the existence of a feasible power allocation for the downlink when the rates allocated to users are known. The discretized downlink two cell model enables a characterization of downlink power feasibility via the Perron-Frobenius eigenvalue of a suitably chosen matrix.

Next, we review some related works of Chapter 3. The model in Chapter 3 is based on Perron-Frobenius theory. Another approach for joint optimal rate and power allocation, based on the Perron-Frobenius theory, is proposed by Berggren [Ber01] and by O'Neill et al. [OJB03]. Berggren [Ber01] describes a distributed algorithm for assigning base transmitter station (BTS) powers such that the common rate of the users is maximized. In [OJB03], Perron-Frobenius theory is used to design an approximation algorithm for a model with multiple rates, which permits the use of techniques from convex optimization. Both papers assume continuous rates for users. The models in [Ber01, OJB03, EvdBB05] have lead us into the model extension with the rates chosen from a discrete set. The goal is to allocate rates from a discrete and finite set $R = \{R_1, ..., R_K\}$ to the users such that the total utility, i.e., the sum of the utilities of all users, is maximized.

Moreover, in Chapter 3 we develop a model with cell decomposition, which leads to a distributed algorithm for downlink rate allocation. In [LMS06], a distributed algorithm, without considering the status of the other cells, was developed via a dynamic pricing algorithm. In Chapter 3, we include the rate allocation of other cells.

Next, in Chapter 4, we extend the model under a continuous rate assumption. The goal is to assign rates to users, such that the utility of the system is maximized. For this purpose, we do a dimension reduction of the power control matrix, as was done for the uplink (see [Han99, MH01, ZBG03]). Due to the complexity of interference-limited systems, analytical solutions for optimal joint power and rate assignments are scarce. In a game theoretic approach, [ST11] optimize power allocation for a single cell. For continuous rates, for a single cell uplink model [KO09] allows a rate dependent energy per bit to interference ratio. For a multiple cell uplink model, in [DYX09] the maximum minimum-rate under quality of service constraints is considered via a power assignment search method. This is a combinatorial optimization method that is similar to that used in [BSW06] for minimizing the total power in a two cell downlink model with fixed data rates.

In Chapter 5, the last part of this thesis, we address the joint downlink rate and power assignment for maximal total system throughput in a multi-cell CDMA network in an analytical setting. It generalizes the results of [BEG07, LMS05, Mus10, ZOB07] to multiple cells to obtain a full analytical characterization of the optimal power and rate assignment in the downlink of a multi-cell CDMA network. [MKT06] shows that in the optimal rate assignment some mobiles operate at maximum rate while others operate at the minimum rate, and only one mobile operates at an intermediate rate, and [ZOB07] shows that the optimal power assignment in the uplink can be obtained by a greedy procedure, where fairness is guaranteed via interference constraints. Optimizing network performance requires performance measures. In this thesis, the satisfaction of a user in segment $i, i \in \{1, ..., L\}$ is measured by means of a positive utility function $u_i(R_i)$. For a presentation of the utility functions commonly used in the literature see [TAG02]. For the uplink, optimal rate and power assignment strategies to maximize total throughput are considered in [HA07, ZMG11, Mus10, OW99, OZW03, VRM11, SS10] and to maximize the minimum rate to achieve fairness in [DYX09, PJ06]. For the downlink, [LMS05] propose a distributed algorithm for rate and power assignment that maximizes total utility. In [Jav06], Javidi analyzes several rate assignments in the context of the trade-off between fairness and overall throughput. The rates are supposed to be continuous and the algorithms proposed for the rate allocation are based on solving the Lagrangean dual. For a subset of utility functions (i.e. either convex or concave or S-shaped or inverse S-shaped), [LK09, ZMG11] propose a near optimal algorithm for downlink resource assignment problems, where the resource may be the power or the rate of the mobile. The non-convex power allocation problem is solved using particle swarm optimization. Weighted fairness is introduced by assigning weights to each user. A dynamic pricing algorithm to obtain a power assignment that maximizes the total utility of the mobiles for two 1 dimensional cells (mobiles situated e.g. on a highway) is proposed in [ZHJ05]. An iterative linear programming approach for joint power allocation and BTS assignment is considered in [LSM09]. An exact algorithm for rate and power assignment that maximizes total throughput in two cells is presented in [BEG07]. Although it may lead to significant imbalance among the mobiles [SSB10], see e.g., [Tsi11] for the trade-off between fairness and throughput, it is argued in [Lit03] that maximal throughput also results in minimal mean sojourn time (time to handle the call).

1.3 Basic models

Effective interference

CDMA is an interference limited system, therefore the capacity of the system is directly related to the interference level. A common measure of the quality of the transmission is the energy per bit to interference ratio, $(E_b/I_0)_i$, that for a user i is defined as (see e.g. [HT07])

$$\left(\frac{E_b}{I_0}\right)_i = \frac{W}{r_i}\frac{\text{useful signal power of user i}}{\text{interference + thermal noise}}, \tag{1.1}$$

where W is the system chip rate, N_0 is the thermal noise and r_i is the data rate for a user i.

First, let us consider the numerator. The received signal power of user i depends on the transmitted power and the user location. In this thesis, for simplification of the mathematical model, we assume deterministic path loss propagation between a transmitter X and a receiver in segment i of the following form

$$P_i^{'} = P_i l_{i,X}, \tag{1.2}$$

where $l_{i,X}$ depends only on the distance d_i between a user i and BTS X, $P_i^{'}$ is the received power of the user i and P_i is the transmission power towards the user i. If $l_{i,X} = d_i^{-\gamma}$, where $\gamma \geq 0$ is independent of the distance, this model performs reasonably well in flat service areas for $d_i \geq 1$ km (see [ARY95, Hat80]).

Next, let us consider the interference term in the denominator. In a multicell environment, since all users are using the same frequency, interference either comes from users in the same cell, called the intracell interference, $I_{\text{intracell}}$, or comes from users in the neighboring cells, called the intercell interference, $I_{\text{intercell}}$. For downlink intracell interference, non-orthogonality factor α represents how much interference can be reduced by the system within the cell. The value of α is between zero and one, i.e., $0 \leq \alpha \leq 1$, where $\alpha = 0$ means the system is completely non-orthogonal and $\alpha = 1$ means the system is completely orthogonal. The higher the value of non-orthogonality factor α, the lower the intracell interference. For uplink intracell interference, it is generally assumed (see e.g. [EE99, HT07]) that the signals are perfectly orthogonal.

Quality of service

In order to ensure a certain quality of service, the energy per bit to interference ratio of a user i has to be above a prespecified value ϵ_i^*, $(E_b/I_0)_i \geqslant \epsilon_i^*$ (see [EE99]). In the presence of perfect power control, we assume that the energy per bit to interference ratio of a terminal in segment i equals the threshold ϵ_i^*, i.e.,

$$\left(\frac{E_b}{I_0}\right)_i = \epsilon_i^*, \text{ for all users } i. \tag{1.3}$$

For the rest of this thesis, we develop models under the perfect power control assumption.

Next, we discuss the downlink transmit power and the uplink received power model separately. Although these problems are similar in nature, that is power and rate assignment is based on maximising a utility function and is subject to energy per bit to interference ratio constraints, the actual power and rate assignment problems differ. In the downlink a few BTSs transmit to many mobiles, whereas in the uplink many mobiles transmit to a few BTSs. The corresponding sources (locations) for interference are different, resulting in similar but different power and rate assignment problems. As a consequence, some insight from the uplink power and rate assignment are of interest for the downlink problem, but a solution for the uplink does not yield a direct solution for the downlink.

Downlink transmit power

Consider a CDMA wireless system with two BTSs, say cell X and cell Y. Assume that the number of users in the systems is L, where I users are assigned to BTS X and $(L - I)$ users are assigned to BTS Y. Let $l_{i,X}$, respectively $l_{i,Y}$, be the path loss of user i from BTS X, respectively from BTS Y. Let us assume that the location of users in cell X is ordered such that $l_{1,X} < l_{2,X} < ... < l_{I,X}$. Thus, the user 1 with path loss $l_{1,X}$ is located the closest to BTS X, and the user I with path loss $l_{I,X}$ is the furthest to BTS X. And from users in cell Y, let us assume that the location of users is ordered such that $l_{I+1,Y} > l_{I+2,Y} > ... > l_{L,Y}$. Thus, the user L with path loss $l_{L,Y}$ is located closest to BTS Y. Hence, the users path loss from BTS X is $l_{1,X} < l_{2,X} < ... < l_{I,X} < l_{I+1,X} < l_{I+2,X} < ... < l_{L,X}$.

Let r_i be the assigned downlink rate to user i that requires a transmit power P_i from the BTS. Under the described path loss model and a constant thermal noise N_0, the energy per bit to interference ratio of user i assigned to BTS X is

$$\left(\frac{E_b}{I_0}\right)_i^{down} = \frac{W}{r_i}\frac{P_i l_{i,X}}{\alpha l_{i,X}(\sum\limits_{j=1}^{I} P_j - P_i) + l_{i,Y}\sum\limits_{j=I+1}^{L} P_j + N_0}, \tag{1.4}$$

for $i \in \{1, ..., I\}$, where $l_{i,X}$ the path loss from the BTS X to user i and P_i is the transmitted power from the BTS to the user in the cell. Similarly, the energy per bit to interference ratio of a user i assigned to BTS Y is

$$\left(\frac{E_b}{I_0}\right)_i^{down} = \frac{W}{r_i}\frac{P_i l_{i,Y}}{\alpha l_{i,Y}(\sum\limits_{j=I+1}^{L} P_j - P_i) + l_{i,X}\sum\limits_{j=1}^{I} P_j + N_0}, \tag{1.5}$$

for $i \in \{I+1, ..., L\}$, where α is the non-orthogonality factor, $l_{i,Y}$ the path loss from the BTS Y to user i and P_i is the transmitted power from the BTS to the user in the cell. Next, we will derive an explicit formulation of the total transmit power of a BTS given that the user i in the cell is assigned a downlink rate $r_{i.}$

From Eq.(1.3) and Eq.(1.4), the downlink transmit power of BTS X to the user i in cell X, for $i \in \{1, ..., I\}$, is

$$P_i = \alpha \sum_{j=1}^{I} V(r_j) P_j + l_i \sum_{j=I+1}^{L} V(r_j) P_j + V(r_i) l_{i,X}^{-1} N_0, \tag{1.6}$$

where

$$V(r_i) = \frac{\epsilon_i^* r_i}{W + \alpha \epsilon_i^* r_i}, \text{ for } i \in \{1, ..., L\}, \tag{1.7}$$

and

$$l_i = \begin{cases} \frac{l_{i,Y}}{l_{i,X}}, \text{ for } i \in \{1, ..., I\}, \\ \frac{l_{i,X}}{l_{i,Y}}, \text{ for } i \in \{I+1, ..., L\}. \end{cases} \tag{1.8}$$

Similarly, from Eq.(1.3) and Eq.(1.5), we can also express the required transmit powers of BTS Y to the user i in cell Y, for $i \in \{I+1, \cdots, L\}$,

$$P_i = l_i \sum_{j=1}^{I} V(r_j) P_j + \alpha \sum_{j=I+1}^{L} V(r_j) P_j + V(r_i) l_{i,Y}^{-1} N_0. \tag{1.9}$$

Uplink received power

The interference model for the uplink differs from that for the downlink, as a for the uplink many terminals transmit to a few BTSs. In the uplink, the interference is measured by the BTS, hence, it is more appropriate in the uplink to measure the received power in the BTS. Let the received power of a user i in BTS X with pathloss $l_{i,X}$ be P_i^X, then

$$P_i^X = P_i l_{i,X}. \tag{1.10}$$

Moreover, the uplink transmit power of a user is limited, say $P_i \le P_{\max}$.

Let r_i be the uplink rate for user i in cell X. From (1.3), the uplink energy per bit to interference ratio for the user i assigned to BTS X is

$$\left(\frac{E_b}{I_0}\right)_i = \frac{W}{r_i}\frac{P_i^X}{\left(\sum\limits_{j=1}^{I} P_j^X - P_i^X\right) + \sum\limits_{j=I+1}^{L} l_j P_j^Y + N_0}, \tag{1.11}$$

for $i \in \{1, ..., I\}$.

Similarly for BTS Y, the uplink energy per bit to interference ratio for the user i assigned to BTS Y, given that the uplink rate r_i, is

$$\left(\frac{E_b}{I_0}\right)_i = \frac{W}{r_i}\frac{P_i^Y}{\sum\limits_{j=1}^{I} l_j P_j^X + \left(\sum\limits_{j=I+1}^{L} P_j^Y - P_i^Y\right) + N_0}, \tag{1.12}$$

for $i \in \{I+1, ..., L\}$.

For a user i, $i \in \{1, 2, \cdots, L\}$, under the assumption of perfect power control, in the uplink, the user's terminal is required by the BTS to transmit enough power such that $(E_b/I_0)_i = \epsilon_i^*$, for all users i, $i \in \{1, 2, \cdots, L\}$. Moreover, under the assumption of uplink perfect power control, each BTS requires all terminals in the cell to transmit enough power such that the received signal is the same, i.e., $P_i^X = \widehat{P^X}$ and $P_j^Y = \widehat{P^Y}$ (see e.g. [EE99, HT07]). Hence, from (1.11) and (1.12), we have

$$\epsilon_i^* = \frac{W}{r_i}\frac{\widehat{P^X}}{\widehat{P^X}(I-1) + \widehat{P^Y}\sum\limits_{j=I+1}^{L} l_j + N_0}, \tag{1.13}$$

$$\epsilon_i^* = \frac{W}{r_i}\frac{\widehat{P^Y}}{\widehat{P^X}\sum\limits_{j=1}^{I} l_j + \widehat{P^Y}(L-I-1) + N_0}. \tag{1.14}$$

Then, the uplink received signal, $\widehat{P^X}$, at the BTS X should satisfy

$$\widehat{P^X} = V(r_i)\left(I\widehat{P^X} + \left(\sum_{j=I+1}^{L} l_j\right)\widehat{P^Y} + N_0\right), \tag{1.15}$$

and the uplink received signal, $\widehat{P^Y}$, at the BTS Y should satisfy

$$\widehat{P^Y} = V(r_i)\left(\left(\sum_{j=1}^{I} l_j\right)\widehat{P^X} + (L-I)\widehat{P^Y} + N_0\right), \tag{1.16}$$

where

$$V(r_i) = \frac{\epsilon_i^* r_i}{W + \epsilon_i^* r_i}. \tag{1.17}$$

1.4 Overview and contribution

Chapter 2

In Chapter 2, we develop a model for downlink power assignment in a CDMA-based wireless system. We analyze feasibility of the downlink power assignment in a linear model of two CDMA cells, under the assumption that all downlink users in the system receive the same rate. This is done by discretizing the area between two BTSs into small segments. The model considers the number of users and the users' location in each segment. Then, the power requirements are characterized via a matrix representation. We obtain a closed-form analytical expression of the so-called Perron-Frobenius eigenvalue of that matrix. Based on the Perron-Frobenius eigenvalue, we obtain an explicit decomposition of system and user characteristics. Although the obtained relation is non-linear, it basically provides an effective interference characterisation of downlink feasibility for a fast evaluation of outage and blocking probabilities, and enables a quick evaluation of feasibility. We have numerically investigated blocking probabilities and have found for the downlink that it is best to allocate all calls to a single cell. Moreover, this chapter has also provided a model for determining an optimal cell border in CDMA networks. We have combined the downlink and uplink feasibility models to determine cell borders for which the system throughput, expressed in terms of downlink rates, is maximized.

This chapter is based on the papers:

- [EvB03] A.I. Endrayanto, J.L. van den Berg and R.J. Boucherie. Characterizing CDMA downlink feasibility via effective interference, in *Proceedings 1st International Working Conference on Heteregeneous Networks* - HetNetsÕ03, pp. 62/1-62/10, Ilkley, United Kingdom, 21-23 July 2003.

- [EvdBB05] A.I. Endrayanto, J.L van den Berg, R.J Boucherie, An analytical model for CDMA downlink rate optimization taking into account uplink coverage restrictions, *Performance Evaluation* 59, ISSN: 0166-5316 , February 2005.

Chapter 3

In Chapter 3, we extend the model from Chapter 2. This chapter still considers the two cells linear model where the coverage area is divided into small segments. Previously, we have assumed that all users in the cells are using the same rate, regardless users' location. In this chapter, we differentiate rate allocation based on their location. We assume users in the same segment receive the same rate. The rates are chosen from a discrete set. The goal is to assign rates to users in each segment, such that the utility of the system is maximized.

For each segment the transmit power requirements are characterized via a matrix representation that separates user and system characteristics. Based on the Perron-Frobenius eigenvalue of the matrix, we reduce the downlink rate allocation problem to a set of multiple-choice knapsack problems. The solution of these problems provides an approximation of the optimal downlink rate allocation and cell borders for which the system throughput, expressed in terms of utility functions of the users, is maximized. We have reduced the downlink rate allocation problem into a set of multiple-choice knapsack problems. Thus the rate allocation problem is NP-hard. Thus it is very unlikely that polynomial time algorithms exist (unless P=NP). In this chapter, we design an algorithm that is actually a fully polynomial time approximation scheme (FPTAS) for the rate optimization problem. We have derived a combinatorial algorithm for finding a downlink rate allocation in a CDMA network, that, for $\epsilon > 0$, achieves a throughput of value at least $(1 - \epsilon)$ times the optimum.

The approach in this chapter has several advantages. First, the discrete optimization approach has eliminated the rounding errors due to continuity assumptions of the downlink rates. Using our model, the exact rate that should be allocated to each user can be indicated. Second, the rate allocation approximation we have proposed guarantees that the solution obtained is close to the optimum. Moreover, the algorithm works for very general utility functions. Furthermore, the model in this chapter indicates that the optimal downlink rate allocation can be obtained in a distributed way: the allocation in each cell can be optimized independently, interference being incorporated in a single parameter t.

This chapter is based on the papers:

- [EBB04] A.I. Endrayanto, A.F. Bumb, R.J. Boucherie, A multiple-choice knapsack based algorithm for CDMA downlink rate differentiation under uplink coverage restrictions, in *Proceedings 16th ITC Specialist Seminar*, Antwerp, Belgium, 31 August- 2 September 2004.

- [EBBW04] R.J. Boucherie, A.F. Bumb, A.I. Endrayanto, G.J. Woeginger,A combinatorial approximation for CDMA downlink rate allocation, in *Proceedings 7th INFORMS Telecommunications Conference*, Boca Raton, Florida, United States, March 7-10, 2004.
- [BBEW06] R.J. Boucherie, A.F. Bumb, A.I. Endrayanto, G.J. Woeginger, A combinatorial approximation for CDMA downlink rate allocation, in Ch.14 of *Telecommunications Planning: Innovation in Pricing, Network Design and Management*, ISBN: 978-0-387-29222-5 , Springer, 2006.

Chapter 4

In Chapter 4, we propose a fast and exact joint rate and power allocation algorithm in the downlink of a telecommunication network formed by two cells, where the base stations transmit at limited powers. Thus, we incorporate in our model two important aspects of a CDMA network, namely interference and limited powers. We assume that the rates are continuous and may be chosen from a given interval. Thus, it is a different model than that of the previous chapters. The assumption in this chapter seems realistic, since in a CDMA system data rates may be rapidly modified in accordance with channel conditions, resulting in an average rate that lies in an interval.

First, we have developed a model for the joint rate and power allocation problem. Due to the impact of the interference between users in different cells, this problem is much more difficult then that of the previous chapters, where the model was analysed under unlimited powers. Despite its non-convexity, the optimal solutions can be very well characterized. Second, we have analyzed several properties of the optimal solutions. We proved that the optimal rate allocations are monotonic in a function of the path loss. Based on this property, we show that in the optimal rate allocation, only 3 rates are given to users. Finally, we propose a polynomial time algorithm in the number of users that solves optimally the joint rate and power allocation problem. The results can be extended to non-decreasing utility functions. Moreover, the algorithm can be extended to iteratively solve the rate/power allocation problem in a small number of cells.

This chapter is based on the following paper

- [BEG07] R.J. Boucherie, A.F. Gabor, A.I. Endrayanto, Optimal joint rate and power assignment in CDMA networks, presented in *The 3rd International Conference on Algorithmic Aspects in Information and Management* (AAIM'07), Portland, USA, 6-8 June 2007.

- [BGE07] R.J. Boucherie, A.F. Gabor, A.I. Endrayanto, Optimal joint rate and power assignment in CDMA networks, in *Lecture Notes in Computer Science* , ISBN: 978-3-540-72868-9, Springer-Verlag, 2007, pages 201-210.

Chapter 5

In Chapter 5, we extend the continuous rate model to the multi cell case. We present a full analytical characterization of the optimal joint downlink rate and power assignment for maximal total system throughput in a multi cell CDMA network. The cell model is a planar model, where the cell coverage has a hexagonal shape.

Chapter 5 has three main contributions. First, we provide an explicit and exact characterization of the structure of the optimal rate and power assignment. Second, we give a characterization of the optimal rate assignment in each cell. We prove that in a network with N base transmitter stations (BTSs) either all mobiles have maximum rate, or in k BTSs all mobiles have maximum rate and the other BTSs transmit at maximum power, or $N-1$ stations transmit at maximum power. In the latter case, finding the optimal power for the remaining BTS can be reduced to a discrete problem in which only a discrete set of powers must be considered in the optimization procedure. Third, based on these results, we give an exact algorithm for solving the rate and power assignment problem and a fast and accurate heuristic algorithm for power and rate assignment to achieve maximal downlink throughput in a multi cell CDMA system. Under this heuristic, for a cell with the total transmit power less than the maximum, the intermediate rate is neglected, i.e., the heuristic assigns maximum and minimum rates only. Moreover, the heuristic orders the cells according to a certain criterion and assigns maximum power and rates in this order. It is shown that the heuristic is fast and accurate up to high load.

This chapter is based on the paper:

- [EGB12] R.J. Boucherie, A.F. Gabor, A.I. Endrayanto, Exact and Heuristic Algorithm for Throughput Maximization in MultiCell CDMA (submitted).

The relation between chapters is illustrated in Figure 1.1.

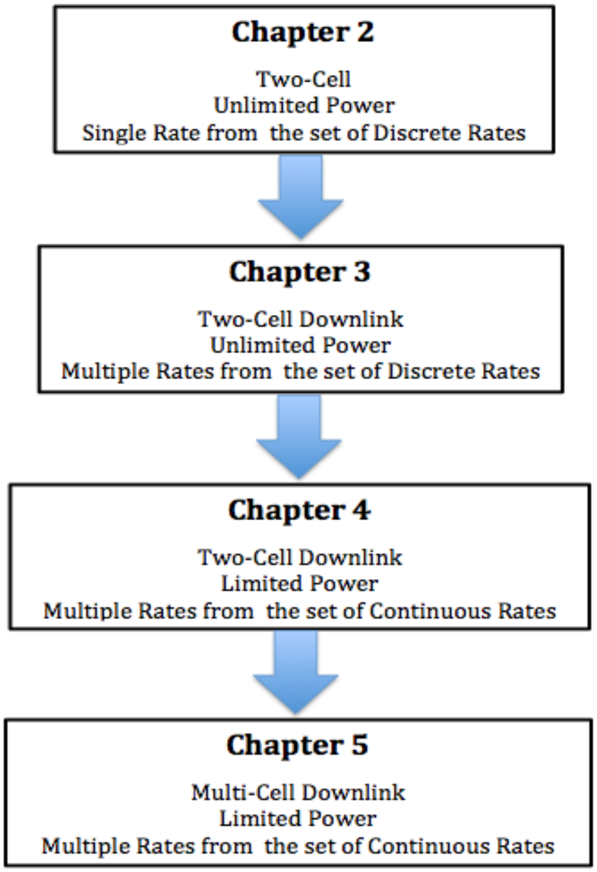

Figure 1.1: *The relation between chapters*

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Summary

This thesis presents a full analytical characterization of the optimal joint downlink rate and power assignment for maximal total system throughput in a multi cell CDMA network.

In Chapter 2, we analyze the feasibility of downlink power assignment in a linear model of two CDMA cell, under the assumption that all downlink users in the system receive the same rate. We have obtained an explicit decomposition of system and user characteristics. Although the obtained relation is non-linear, it basically provides an effective interference characterisation of downlink feasibility for a fast evaluation of outage and blocking probabilities, and enable a quick evaluation of feasibility. We have numerically investigated blocking probabilities and have found for the downlink that it is best to allocate all calls to a single cell. Moreover, this chapter has also provided a model for determining an optimal cell border in CDMA networks. We have combined downlink and uplink feasibility model to determine cell borders for which the system throughput, expressed in terms of downlink rates, is maximized.

In Chapter 3, we have considered the two cell linear model where the coverage area was divided into small segments. Previously, we have assumed that all users in the cell are using the same rate, regardless their location. In this chapter, we have differentiated rate allocation based on their location. We have assumed that users in the same segment receive the same rate which is chosen from a discrete set. The goal is to assign rates to users in each segment, such that the utility of the system is maximized. In this chapter, we design an algorithm that is actually a fully polynomial time approximation scheme (FPTAS) for the rate optimization problem. The model in this chapter indicates that the optimal downlink rate allocation can be obtained in a distributed way: the allocation in each cell can be optimized independently, interference being incorporated in a single parameter t.

In Chapter 4, we have analyzed the two cell model under the assumption that the rates are continuous and may be chosen from a given interval. Moreover, we also taken into account the downlink limited transmit power. First, we developed a model for the joint rate and power allocation problem. Despite its non-convexity, the optimal solution in this chapter can be very well characterized. Second, we analyzed several properties of the optimal solutions. We have proved that the optimal rate allocations are monotonic as a function of the path loss. Based on this property, we have showed that in the optimal rate allocation, in each cell, only three rates are given to users. Finally, we have proposed a polynomial time algorithm in the number of users that solves optimally the joint rate and power allocation problem. The results can be extended to non-decreasing utility functions.

In Chapter 5, we have extended the model of the previous chapter to a multi-cell setting. We have presented a full analytical characterization of the optimal joint downlink rate and power assignment for maximal total system throughput in a multi cell CDMA network. Moreover, the cell model is a planar model. Chapter 5 has three main contributions. First, we provide an explicit and exact characterization of the structure of the optimal rate and power assignment. Second, we give a characterization of the optimal rate assignment in each cell. Third, based on these results, we give an exact algorithm for solving the rate and power assignment problem and a fast and accurate heuristic algorithm for power and rate assignment to achieve maximal downlink throughput in a multi cell CDMA system.

Irwan Endrayanto Aluicius

Curriculum Vitae

Irwan Endrayanto Aluicius was born in Klaten, Indonesia on October 28, 1972. He received his Bachelors degree in Mathematics at Gadjah Mada University, Indonesia in 1996. Afterwards, he became a staff member at the same department.

In 1998, via a bridging programe conducted by University of Twente in Institut Teknologi Bandung (ITB) Indonesia, he was awarded full scheme scholarship called TALIS (Talented Indonesian Students) from Netherlands Education Centre (NEC). From August 1998 until May 2000, he was a Master student at the Faculty of Applied Mathematics. Under supervision of Dr. Erik A. van Doorn (from Universiteit Twente) and Ir. Bart Sanders (from Libertel/Vodafone), he wrote a thesis with the title ”Performance Modeling of CDMA Systems”. He graduated in June 23, 2000 and obtained the title of Master of Science in Engineering Mathematics.

After returning home for one year, he went on September 2001 to became a PhD student (in Dutch: *Assistent in Opleiding* or AIO) at Stochastic Operation Research Group, Department of Applied Mathematics, University of Twente, under the supervision of prof. dr.Richard J Boucherie, prof. dr. J.L. van den Berg and Dr. Adriana F Gabor.

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Colophon

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