Capacity calculation for CDMA network planning

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ABSTRACT OF THE
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This work contains a link and network level analysis of a CDMA based system done from the network planning point of view. As a result of the analysis we outline the requirements and possible methods for network planning.

First we analyse the CDMA system by using a very simple model. This model allows us to determine the nature of the system outage in case of overload. We are able to explain how the capacity depends on the location of users in the cell, the speed of users, and the target CIR value. These results give us conditions and parameters which should be considered in the network planning.

The link level analysis gives us the dependency between the users speed and the target signal-to-interference ratio. The equations are derived for both up- and downlink. In order to derive this dependency we develop models for optimal power control and signal to interference ratio. The analysis shows that the simple relay type of power control performs quite near to the optimal limit. The model of interference indicates that in the downlink the interference depends on the channel response and as such impacts directly the capacity.

The capacity of a CDMA system is estimated usually by simulations. We propose a method for calculating the average system capacity. Compared to simulations the calculation allows to speed up the capacity estimation process. By comparing with the simulations results we show that the proposed method approximates well the cases when users or base stations are nonuniformly distributed.

At the end of the thesis we show how the proposed method can be integrated into planning of a power controlled CDMA system. The developed method can be used for estimating outage areas and blocking probabilities.

Keywords: CDMA, capacity, network planning, interference, power control

Preface

I wish to express my gratitude to Prof. Sven-Gustav Häggman, supervisor of this work, and to Prof Seppo J. Halme, the head of the laboratory, for their interest and patience during this project.

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Contents

List of Symbols

a_i	estimate of the signal amplitude at the i-th finger
$a^{k_n}\left[t-\tau_{l_{k_n}}\right]$	spreading sequence
$b^{k_n}\left[t-\tau_{l_{k_n}}\right]$	information signal of the k-th user from n-th BS
$b_{-1}^{k_n}$, $b_0^{k_n}$	value of the bit
$\cos\left[\omega_c t+\varphi_{l_{k_n}}\right]$	cosinus of carrier frequency ω_c and phase difference φ between the signal for k-th user from n-th BS and reference signal
C	cross correlation function
CIR_t	target CIR value
$CIR_t(r,\theta)$	target CIR value, required to communicate with location indicated by r, θ in the cell
$d_{1_{r,\theta},n}$	distance from the BS n to the location r, θ in the service area of BS 1
E_b	energy per bit
$E_{b,ref}$	energy per bit of reference datarate
$E\{..\}$	average
$f(r)$	function of the attenuation in the channel
$h[n-j]$	filter response
I	total interference
I_{1_1}	interference density for the user 1 in BS 1 service area
I_{mai}^i	multiple access interference

$I_{mai,1}$,$I^i_{mai,1}$	intracell interference
$I_{mai,n}$,$I^i_{mai,n}$	intercell interference
I^i_{ni}	interference due to the thermal noise
I^i_{si}	signal self interference due to the multipath
J	number of filter coefficients
$J_0\left(2\pi vn/\lambda_c\right)$	Bessel function of speed v, moment n, and wavelength λ_c
k_n	index of user k from the BS n
$k_{R_{1_1}}$	relation coefficient between data rate of user and reference datarate
K_n	number of users in the cell n
$K_{1,ref}$	number of users with the reference data rate in the cell 1
L	average attenuation in the channel
L, L_r, L_{k_n}	number of RAKE fingers
m_{CIR}, m_{CIR_i}	the mean amplitude of the received signal after PC
M	number of channels in the system
$n(t)$	noise amplitude
N	number of interfering BS, or neighboring cells
$N\left(0, P_{I_n}\right)$	normal distribution with mean 0 and variance P_{I_n}
m	attenuation law
p_m	probability of m users being in the system
p^k_m	probability that from m users in the system k are active
p^k_{out}	probailiby of the system being in the outage with k users in the system
$\mathcal{P}_k$	probaility of k active users being in the system
$\mathcal{P}_{out}$	total outage probability
P_{I_n}	signal power to other users at the transmitter, variance of the amplitude of the interfering singal at the BS

P_{k_n}	transmitted signal power for user k at the BS n
$P_{k_n}^r$	received signal power of user k from the BS n
$P_{mai,n}$	in downlink total transmitted power to all other users before transmission at BS n
$P_{\max}$	maximal allowed transmission power
P_{ref}	transmission power for reference datarate
$P_1(r,\theta)$	transmitted signal power required to communicate with location indicated by r, θ in the cell
$P_{mai,n}(d_{1_{r,\theta},n})$	Interference from BS n to location indicated by r, θ
$r_{k_n,m}$	distance between the BS m and user k in BS n
$r_{(r,\theta)_n,m}$	distance between the location of the (r,θ) in service are of BS n, and BS m
$r(t)$	received signal
R_{k_n}	datarate
R_{ref}	reference datarate
$R_{l_{k_n}1}\left(\tau_{l_{k_n}i}\right)$, $\hat{R}_{l_{k_n}1}\left(\tau_{l_{k_n}i}\right)$	continuous time partial cross correlation functions between the reference and received bit
$s_{\beta_i}^2$	mean of power after PC
S^i	information signal
$u[n]$	Dirac delta function
U	received signal
v	users speed
$w[n]$, $w_i[n+1]$	samples of white gaussian noise
W	spread bandwith
α	orthogonality factor
$\beta_{l_{k_n}}$	amplitude of the l-th path for user k from n-th BS

$\beta_l^{'}$	signal amplitude at the finger
$\beta\left[n\right]$	sampled amplitude of the channel response
$\beta_i\left[n+1\right]$	is sampled amplitude at the finger i
$\triangle P$	PC step
$\varphi_{l_{k_n}i}$	phase difference between received and reference signal
λ	call arrival rate
λ_c	wavelength
η	power of the thermal noise
μ	mean call holding time
θ	angle from the BS
ρ	density of users
ρ_n	sampled channel correlation function
σ^2	total noise variance
σ_i^2	variance of the interference at different fingers i
$\sigma_{\beta_i^2}$	standard deviation of the channel amplitude
$\sigma_{\beta_i}^2$	variance of the channel amplitude
σ_w^2	total variance of the WGN
$\sigma_{w_i}^2$	variance of the white Gaussian noise
$\sigma_{w_{out}}^2, \sigma_{w_{in}}^2$	output input variance of the white gaussian noise
τ_i	delay at the channel tap
$\tau_{l_{k_n}i}$	delay in the multipath l_{k_n} with respecting tap i
ω_c	carrier frequency

List of Abbreviations

AR	Auto Regressive
BER	Bit Error Ratio
BS	Base Station
cdf	cumulative probability distribution function
CIR	Carrier to Interference Ratio
CDMA	Code Division Multiple Access
FDMA	Frequency Division Multiple Access
FER	Frame Error Ratio
pdf	probability density function
PC	Power Control
QoS	Quality of Service
SIR	Signal to Interference Ratio
TDMA	Time Division Multiple Access
WGN	White Gaussian Noise

Chapter 1

Introduction

In this work we treat the issues related to the capacity of a CDMA based mobile communication system.

In contrast to TDMA and FDMA systems the amount of users that can be served in CDMA with frequency reuse 1 is only interference limited. Interference together with power control create an environment that is difficult to predict and control. In such environment the capacity can be defined statistically by using definition of outage. [OP98].

Outage could be system outage or signal outage. Signal outage is mainly due to deep fade when the system occasionally can not support connections on some link. System outage occurs when too high interference from other sources does not allow anybody to communicate. The level of interference where this outage occurs can be defined as the limit that determines the system capacity and which should not be exceeded.

The capacity can be identified as instantaneous and average capacity. Such separation is not important in FDMA and TDMA based systems. In these systems the limiting factor is the number of channels and therefore both type of capacities are equal. In CDMA the number of users that can be served in the system is a function of interference and the two capacities can be different. The instantaneous capacity is the maximum number of satisfied users under a given quality constraint that at the given moment can be served in the system. Correspondingly the mean over all these different instantaneous capacities give us the average capacity.

In the network these different capacities have different applications. The instantaneous capacity is required by the run time operations for maximizing the system utilization and it is estimated continously. Good examples of such operations are admission and congestion control. Admission control requires capacity for allocating the resources for connections. When the system is in outage this situation should be detected in order to apply a congestion control algorithm.

In network planning it is difficult to consider the system capacity at every moment. Therefore, often the network planning deals only with the average capacity provided by the resources. The average capacity can be calculated by averaging over all possible instantaneous capacities.

The difference between TDMA and CDMA becomes very essential in the next generation mobile networks. The methods well developed and justified in practice for TDMA and FDMA can not directly be applied in design of new CDMA based networks.

1.1 Modeling the system capacity

Regardless the type of capacity considered, the study of the CDMA capacity is mainly related to investigation of the interference in the system. Among the interference studies two trends can be recognized. Network level analysis of the system capacity and investigation of the sources of interference.

An early study of the relationship between the CDMA average capacity and the interference level is given in [CN78]. An extension to this theory which includes shadowing and voice activity monitoring is given in [Gil91].

The approach in the latter reference is to model the statistical distribution of the interference for spatially uniformly distributed users and BS distribution, without analyzing the actual behaviour of the sources of the interference. The capacity is calculated as the probability that interference exceeds some preset limit.

The driving force behind the derivation is the intention to compare TDMA and CDMA systems. For that purpose many simplifications are made. In later papers it was shown that small differences in interference sources reduce the system capacity significantly and therefore it is dangerous to look only at the ideal conditions [NH94].

The type of approach taken in [Gil91] is a good example of hiding all the difficulties in the network under a statistical model. This paper has paved the way for many studies on statistical modeling of the interference for system capacity [VV93] or admission control [EE99].

An alternative view to the capacity is taken for power control purposes. In that context the capacity is defined as system ability to provide the solution to the matrix equation relating attenuations and transmitted powers to all users [Zan92]. The system can support all connections when this matrix equation has solution for positive powers for all users. The more precise view, compared to statistical modeling, provides a tool for analyzing the impact of the channel and behaviour of every particular user. The benefit here is achieved at the expense of complexity. An exhaustive analysis should consider all possible combinations of number of users and their channels.

The investigation of the sources of interference is going in two directions: study of the system performance due to the users distributions and data rates, and study of the receiver performance.

The user distribution is reported to reduce the system capacity affecting in this way directly the network planning process. Studies in that area are mainly simulation based [Fea94] [RK] [WX94].

The simulation has also been the tool for investigating the orthogonality in the CDMA downlink [Hea97] and handover [WL97], both of which affect the capacity due to the impact of the interference.

The allowed interference level in the receiver depends on the modem, coding, and channel parameters. These are the factors in the receiver that have an impact on the network level. In order to reduce the study field the general approach is to separate these factors into link level study.[OP98] The results of link level study provide the information to the network level for capacity calculations.

The link level study is mainly evaluation of the receiver performance. For CDMA capacity the performance is evaluated as BER that is a function of the interference from other users and multipath propagation. The propagation model contains also the impact of the channel variations [Eng95] [Eft97] [Cha94].

1.2 Aim of this work

It is much easier to calculate the capacity for CDMA system with uniform spatial distribution of users and constant bit rate for all the users. The more difficult task is to get a method for capacity calculation applicable in practical networks. An easy way to tackle the problem is to simulate the system. However, the multitude of details makes such simulations very time consuming and not suitable for large networks. To develop a model for calculations is also not easy. The model should incorporate on one hand the issues related to the receiver and channel, on the other hand it has to fit to different distributions and mixes of the demand.

The purpose of this work is to derive a method for calculating the CDMA network capacity. The central issue is applicability of the method to practical network design.

The investigation goes into two directions: suitability of the method for different network level conditions, and receiver and channel impact on the capacity.

In order to develop the model for calculations there is a need to understand the underlying principles of a CDMA system. The previous studies concentrate directly on receiver performance estimation [Pur77] or capacity estimation [VV93] but do not explain the dependencies on the network level. As a result there is reported but not analyzed phenomenon, cell breathing, that make the system planning extremely difficult [Tit97]. In order to avoid such reefs we start our journey by investigating the behaviour of the system as a function of various parameters: location, speed, data rate of users.

We examine separately the link and network level. The former has been thoroughly investigated. However, the studies have not been made in the context of the CDMA network capacity. For that reason the studies of receiver performance do not incorporate the impact of power control and interference variation due to the power change of other users.

On the other hand the community dealing with power control has been busy in deriving the algorithms and studying their stability. There have been very few reports on the impact of power control dynamics on capacity.

Our study of the link concentrates on the derivation of the signal-to-interference ratio as a function of receiver parameters.

The interference level in CDMA depends on the location of users in the network. These dependencies have been studied and reported based on simulation results. The methods for capacity calculation deal mainly with uniform spatial distribution of users. In the future network there is foreseen a demand for many different data rates. This together with nonuniform user distribution creates an environment for capacity study that has not been explored much. We position our study to extend the existing methods to fit into this situation.

1.3 Original contributions

The main target of this work is to provide the requirements and methods for practical network planning. For that purpose we use material reported in the literature. However in some areas the reported methods should be augmented.

In Chapter 2 we investigate the system behaviour. Although such study is quite simple, we have not come accross with it in the literature.

Based on the extension of the capacity from the matrix equation a novel method for calculating the average capacity is proposed. The main benefit of the method is the possibility to separate the estimation of the available channel capacity and multiplexing users into the channel.

In order to support the planning process we give a detailed description of the receiver [Chapter 3]. Similar models have been described for the CDMA systems in the literature [Pur77]. In our analysis we go further and incorporate into the study the impact of power control (PC) and tailor the model to be more suitable for the study of total capacity.

The receiver model allows us to do a novel study of the orthogonality factor in the CDMA downlink.

The power control studies are elaborated with an optimal limit for PC performance.

The models of PC and CIR are used to study the CIR dependency on the speed of users. Such dependency has been reported in the literature before [SMG98] however, there is missing such a thorough analysis that is given here.

A new method for CDMA network planning is proposed in Chapter 4. The method allows also to provide a novel look on the multiservice CDMA network.

1.4 Outline of the thesis

In order to reveal all the problems in CDMA network planning we divide the analysis into different levels by adopting the top-down approach. Accordingly to that, first we look at the network level behaviour and dependencies. Armed with information from there we proceed to analyze the lower level system properties and dependencies. Finally the results of all these preparing studies are combined together into a network planning method.

The initial network level study is made in Chapter 2. This is a necessary starting point for the evaluation of more complex methods. It starts with a description of the system behaviour. We look at the network level impact of users distribution, speed of user and different data rates. The results are verified with simulations. The chapter contains also a model for capacity estimation.

From the simple system model we derive the conditions under which the more precise models should operate.

The link level study in Chapter 3 provides the parameters that are used in calculation of capacity at the network level. The study results in a function of dependency of interferences on speed of users. For that function the power control and interference in a CDMA system is analyzed. The interference is considered separately in up and downlink. We simulate the functional dependency of CIR on speed.

The thesis culminates in Chapter 4 where the issues related to the network planning are treated. The discussion is illustrated with simulations for different situations in the network.

Finally, Chapter 5 summarizes the thesis and discusses some directions for further studies.

Chapter 2

CDMA analysis with a simple system model

In this chapter we analyze the dependencies in a CDMA system by using a simple system model. The purpose of the study is to derive the input for link level investigations and rules for the network planning.

The study is made from the capacity point of view. We look at the network level impact of the users distribution, speed of users and multiservice data rates. After a short introduction and description of the system model a verbal description of the behaviour of the system is given [Section 2.3]. The description is illustrated with results from numerical calculations.

In Section 2.4 we give a definition of the channel capacity of a CDMA system and a method for calculating this measure.

2.1 Introduction

The accurate estimation of CDMA system capacity is a complex process. In order to avoid computational difficulties the complexity is often hidden into a probabilistic model of the system. While simplifying the treatment, the statistical model does not reveal the underlying dependencies in the system and thus prevents the development of more precise solutions. This chapter analyses the dependencies and behaviour of the system as seen at the network level. The study is made by adopting a simple model, similar to the one used by Viterbi [Vit95] or Rappaport [Rap96], and analysing the system behaviour when some parameters are changed.

The aim of the analysis is to determine the conditions where a more precise study at the link level should be carried out. Together, the results of this chapter and the link level study in the next chapter generate an input for the capacity estimation for network planning.

In order to be able to track the impact of one single user we use the instantaneous capacity definition given for power control analysis, see for example [Zan92]. We are looking at different conditions generated by changing spatial distributions, data rates, and speeds of users.

Early investigations of cell capacity considered only uniform spatial distribution of users [Gil91]. It was soon realized that in CDMA the distribution of users affects the system capacity [NH94]. This finding has stimulated many simulations where the spatial distribution of users is nonuniform. In such simulations the nonuniformity is usually studied at the network scale, not within one cell.

The impact of the multirate data users is mainly studied by simulations [AS97] [MHB95]. In this chapter we use a simple equation, binding carrier-to-interference ratio, data rate of users, and available channel capacity, to explain the behaviour shown by simulations.

Impact of users movements on the network capacity can be viewed in two different contexts: link level or network level. At the link level it reveals itself as higher CIR requirement for rapidly moving users. At the network level the movements are related to the changes of the available channel capacity over time. However, the dynamics of these changes have received little attention in the literature.

In order to concentrate only on the system behaviour at the network level the model is very simple. The analysis ignores the fast fading and advanced methods for interference cancellation. The model includes only the power control and average attenuation in the channel. The environment is simple and does not pretend to give exhaustive results on the capacity but rather information about the behaviour of the system. Though such a model might not be usable in practice, it preserves the general properties of a CDMA system.

As a result we end up with requirements and conditions that should be taken into account in the CDMA capacity estimation. It provides also the conditions for the study of a more precise model.

2.2 System model

In this section we describe CDMA in a form that allows an easy analysis of the system behaviour in later sections.

Consider a CDMA system where the received signal quality is described by the bit energy per noise ratio $\frac{E_b}{I_{1_1}}$. The energy per bit is the received signal power divided by the data rate, $E_b = \frac{P_{1_1}}{R_{1_1}}$. The noise density is total received noise power divided by the spread signal bandwidth $I_{1_1} = \frac{I}{W}$.

We derive the equations for the first user in the first base station (BS). The parameters describing BS are noted by subscript and users with subsubscript. For example, the index $_{1_2}$ refers to the second user in the first BS.

The noise in a CDMA system is composed from interference due to the multiple access and thermal noise. Interference, I, contains two factors: interference from the users in the same cell, intracell interference $I_{mai,1}$, and from other cells, intercell interference $I_{mai,n}$.

The relation $\frac{E_b}{I_{1_1}}$ is called signal-to-interference ratio - SIR. The carrier to interference ratio, $CIR = \frac{P_{1_1}}{I}$, is related to SIR by the so called spreading gain $\frac{W}{R_{1_1}}$.

$$\frac{E_b}{I_{1_1}} = SIR = \frac{W}{R_{1_1}} CIR \leq \frac{W}{R_{1_1}} \frac{P^r_{1_1}}{I_{mai,1} + \sum\limits_{n=2}^{N} I_{mai,n} + \eta}, \tag{2.1}$$

where N is the number of neighboring cells and η is the power of the thermal noise. A similar description of a CDMA system is used by Viterbi [Vit95] and Rappaport [Rap96].

For reliable communication the bit error ratio (BER) at the receiver should not exceed some preset limit. BER is inversely proportional to $\frac{E_b}{I_{1_1}}$, consequently, when BER is set also $\frac{E_b}{I_{1_1}}$ is fixed. In our analysis we assume that the required BER is the same for all the services. That means also $\frac{E_b}{I_{1_1}}$ is the same for all the services and in further analysis we set it to be constant.

The CIR values for which this BER level is satisfied is called *target* CIR, CIR_t. Because there is no need to have higher CIR_t value the power control (PC) attempts to keep the CIR in the receiver at the level of CIR_t value. For achieving that the PC change the transmitted power - P_{1_1}.

An ideal power control keeps the received signal power CIR_t times above the interference. This dependence can be maintained only until the maximum allowed transmission power is reached. That is a limit above which the transmission power can not be increased and, consequently, the required CIR_t level cannot be reached. The transmitted power can be expressed as minimum from the function following the interference and maximum allowed transmission power. $P_{1_1} = \min\left(P_{1_1} \cdot CIR_t \cdot r^m_{1_1,1}, P_{\max}\right)$.

Through this chapter we consider only ideal PC. There is no transition time to reach the optimal transmitted power value. At every moment the transmitted power to the user gives optimal solution to Eq. 2.1 for all users or is maximum allowed. That allows us directly to see if the system can support the demanded load.

We manipulate Eq. 2.1 only for downlink. In downlink all signals from the same BS propagate along the same path allowing us to simplify the analysis.

Eq. 2.1 expresses communication quality in terms of data rate and signal powers but it does not explicitly reveal the impact of power control and users locations. In the equation $P^r_{1_1}$ describes the power received by the first user at the first BS. The same can be expressed also due to transmitted power P_{1_1} and attenuation in a channel $f(r)$ giving us: $P^r_{1_1} = P_{1_1} \cdot f(r)$. For further simplicity we ignore the complexity of the channel and describe it only as a power function of distance r^{-m}, where m is the path loss exponent. By broadening this view to the total power from the BS the interference can be expressed as function of total transmitted power to all other users from the BS n and attenuation $P_{mai,n} r^{-m}_{1_n,n}$. With this changes the Eq. 2.1 takes the form:

$$\begin{aligned} \frac{E_b}{I_{1_1}} \leq \frac{W}{R_{1_1}} & \frac{P_{1_1} r^{-m}_{1_1,1}}{P_{mai,1} r^{-m}_{1_1,1} + \sum_{n=2}^{N} P_{mai,n} r^{-m}_{1_1,n} + \eta} \\ & = \frac{W}{R_{1_1}} \frac{P_{1_1}}{P_{mai,1} + \sum_{n=2}^{N} P_{mai,n} \left(\frac{r_{1_1,1}}{r_{1_1,n}} \right)^m + \eta r^m_{1_1,1}}. \end{aligned} \tag{2.2}$$

In Eq. 2.2 $r_{1_1,1}$ and $r_{1_1,n}$ are distances from host BS and neighboring BS, respectively. Interference is described not by the signal power at the mobile receiver but by the power at BS and attenuation in the channel.

In order to better understand system behavior depending on these parameters we rewrite Eq. 2.2 into the form

$$\frac{\frac{W}{R_{1_1}}}{\frac{E_b}{I_{1_1}}} + 1 \geq \frac{P_{mai,1}}{P_{1_1}} + \sum_{n=2}^{N} \frac{P_{mai,n}}{P_{1_1}} \left(\frac{r_{1_1,1}}{r_{1_1,n}} \right)^m + \frac{\eta r^m_{1_1,1}}{P_{1_1}}. \tag{2.3}$$

As can be seen from Eq. 2.3 the number of users that can be served (N) or in other words the system capacity depends on: intracell interference, intercell interference, noise. By reducing any of these terms the capacity of the system is increased.

2.3 Behavior and capacity of a CDMA system

We start our analysis by looking at Eq. 2.3 and verbally describing the behaviour of the system. The statements are later illustrated by simulations.

The equations 2.2 or 2.3 are sufficient to depict a general behaviour of a CDMA network. Eq. 2.3 directly describes the limit of the capacity due to the interference. The left part of Eq. 2.3 is a constant and the equation can be satisfied for different combinations of the parameters at the right. These parameters may be constant or changing over a time of observation, representing correspondingly a static or dynamic characteristics.

As static cases we scrutinize impact of spatial distribution of user and multiservice data rates of users. In this context static means that location, data rate, *target CIR*, and communication channel are assumed to be constant during the observation.

Dynamic behaviour is considered when we track the capacity dependency on movements of users.

2.3.1 Description of the system behaviour

The equation 2.3 should be written for every user. A CDMA system can provide service to all the users when this set of inequalities holds.

When this set of inequalities is considered together with the limit for maximal power one can conclude that:

- the amount of users the CDMA system can serve is not constant but depends on the interference level in the system,
- interference in the system is related to powers of all users,
- when load in the system is higher than available transmission capacity the service quality is first deteriorated for the users to which is highest attenuation in the channel.

These statements can be justified verbally as following.

The signal power of one user contributes to interference of other users. This circular dependency is hidden in Eq. 2.3 into the first two terms at right hand. These two terms show the relationship among the signals in the same cell, the first term, as well among the signals from other cells, the second term.

When signal power to one user is increased also the interference to other users is increased. Because of higher interference other users have to increase the transmitted signal power that in turn increase the interference and the user, considered firstly, has to increase its signal power even more. Such process continues attempting to reach the *target* CIR value for all users.

The relationship among users powers is not limited to one cell, the signal in one cell generates interference to other cells. The change of power in one cell change the interference in neighboring cells making the power change to propagate from cell to cell over the whole network.

For the network planning it is important to know when this iterative power change is ending. The increase of power is intended to satisfy Eq. 2.3, that was violated by increasing the interference, valid again. Because of the circular relationship the signal power and interference are changed in the same tact. The inequality can be satisfied only if in Eq.2.3 the third term at the right can be scaled down correspondingly to increase of the first two terms. The noise level in the system is constant and therefore the increase of the signal power decreases the third term. However, as one can see for high power value the term is close to zero and additional increase of power does not provide the wanted effect. The user just continues to increase the signal power without any hope to satisfy the inequality any more. The system is overloaded.

The power increase stops when the inequalities can be satisfied and all the users have required CIR value. The maximum number of users, for which the *target* CIR level can be reached, define the channel capacity of the system.

The behaviour of the system in overload conditions is set by physical limitations.

The CIR_t can not be reached for some users. They increase the signal power and due that interference to other users. The interference increase violates the inequality 2.3 for all the users and everybody has to increase its transmission power. The chain reaction ends only when some users reach the maximal allowed power. Because these users can not increase their power any more, they can not increase interference, other users are capable to achieve satisfactory CIR level. It should be noted that the satisfactory CIR level is achieved at expenses of the users who have reached the maximal allowed power. For these users CIR is less than required.

The transmission power has to compensate the interference and attenuation in the channel. Due to the attenuation the highest transmitted power is required for the users at the cell border. The users there are also the first for whom the CIR will be violated and who, because of that, are not able to maintain communication link. In that way the users at the cell border will not have connection and the effective cell size shrinks. This relationship is called cell breathing [Tit97].

In this context the system capacity can be seen as maximal number of users for whom Eq. 2.1 is satisfied. When to sum together data rates to each of users we get the available channel capacity of the system.

There are various reasons for increase of power. Obvious culprits are new users entering the system. However it is easy to block a new user and during system operation we are more concerned about power change due to users movements. When users move the attenuation in channel changes and with that the signal power required to compensate it.

As we see the capacity depends on the signal powers of each users. That directly projects to the capacity dependency on users location in the cell - the spatial distribution of users. Users near to the BS generate little interference to the neighboring cells. When most of users are not affected by interference from neighboring cells more users can be admitted. Contrary to that the users at the cell border reduce the total amount of available channels.

2.3.2 Simulation model for numerical examples

These conclusions can be illustrated with simulations. As a test case we set up a network with a cell in the center and one surrounding tier of six cells. The cell diameter is 1000 m, and attenuation parameter is 4. Spread bandwidth W is 4.096 MHz, and data rate R is 10 kbit/s for every user. The required SIR value is set to be 5 dB, that gives for the CIR_t 0.0077. We make calculations only for the downlink.

In that configuration we study the interference as function of the number of users and their spatial distribution in the cell. Because we assume circular symmetry the results are given as function of required signal power depending on distance from BS.

For numerical study we replace the sum of users in the cell with the integral over cell area. In this way we do not consider the location of any particular user but distribution of users, user density. That allows us to integrate over user's density and for users in the the first BS service area Eq. 2.2 takes the form:

$$CIR_t(r,\theta) \leq \frac{P_1(r,\theta)}{\int\limits_0^D \int\limits_0^{2\pi} r\rho P_1(r,\theta)\, dr\, d\theta + \sum\limits_{n=2}^{N} P_{mai,n}(d_{1_{r,\theta,n}}) + \eta r^m_{(r,\theta)_1}}, \tag{2.4}$$

where the arguments (r,θ) indicates values of the function at the location defined by radius r and angle θ. For calculations we cover the service area with a grid and calculate the interference as sum of the elements of the grid. The transmitted power to one point of grid at location (r,θ) can be noted as $P_1(r,\theta)$. Interference in the host cell is evaluated as integral over the whole service area - from 0 to D by radius and from 0 to 2π by angle. ρ describes user density per area.

The attenuation to the one point is calculated by a simple power law, r^m. The transmission power from the other BSs is scaled with the distance relation $\left(\frac{r_{(r,\theta)_1,1}}{r_{(r,\theta)_1,n}}\right)^m$

During the summation the power to each point of the grid, $P_1(r,\theta)$, is weighted with users density at the given point ρ. Eq. 2.4 is written for each point in the grid and solved for all of them together. The interference power from other cells is calculated as the total transmitted power from given BS

$$CIR_t(r,\theta) \leq \frac{P_1(r,\theta)}{\sum_{r}\sum_{\theta} \rho P_1(r,\theta) + \sum_{n=2}^{N} P_{mai,n}\left(\frac{r_{(r,\theta)_1,1}}{r_{(r,\theta)_1,n}}\right)^m + \eta r^m_{(r,\theta)_1,1}}. \tag{2.5}$$

We use Eq. 2.5 for studieng the system with uniform and nonuniform distribution of users.

2.3.3 Uniform spatial distribution of users

The interference is increased when users are added to the network. Also we predicted that the power for the users at the cell border is higher than near to BS. This situation is represented in Fig. 2.1. There on the x - axis is distance from BS and on y - axis is transmitted power required for communication. The number of users in the system is given as parameter.

Even in highly loaded cells the farther located users require higher power compared to nearer located users. This is because interference from other cells is higher at the cell border, interfering signals from neighboring BS have attenuated less compared to the locations nearer to the BS.

The increase of the signal power due to addition of a new user is not very significant when only few users are in the system. That is because in Eq. 2.3 the term due to the noise can be scaled down with smaller increase of power.

The simulated system is not capable to support 110 users in the system. As predicted the transmission power for users at the cell border is driven to the maximum and the CIR requirement for these users is violated [Fig. 2.3]. The effective cell size has shrunk because users at the cell border are not able to maintain their communication links. The CIR is minimum for users at the cell border and increases gradually when users are

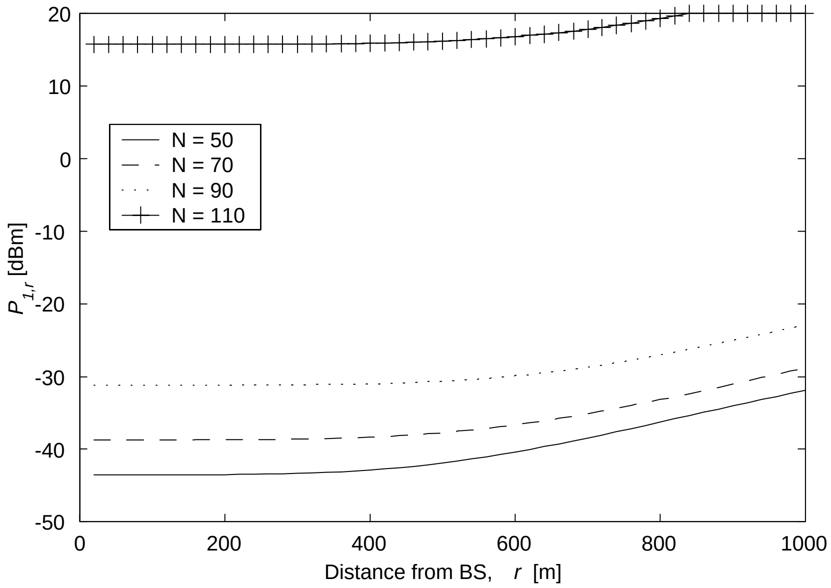

Figure 2.1: Signal power to different locations in a cell as function of number of users (N) in the cell

located nearer to the BS.

For better understanding the contribution of each terms in the right side of Eq. 2.3 they are evaluated separately [Fig. 2.2].

Near to the BS the intracell interference is dominant. Neither the intercell interference or noise do not contribute much to the total interference. The small portion of the intercell interference can be explained by attenuation in the channel - the signals from other BS have attenuated and are very small near to the host BS.

The share of noise is small because of the distance. Users at the cell border require high signal power. In order to compensate the interference generated by the users at the cell border also the near located users have to increase their signal power. When signal is received this high power has not attenuated much in the channel and it is significantly higher than the noise floor. The term due to the noise is scaled down very much. The main source of interference for those users is intracell interference.

On the contrary, for the users at the cell border all three types of interference generate significant share of total interference. The attenuation from the other BS can be in the same order as attenuation from the host BS. In result the total interference pool is shared nearly equally among of these two types of interferences. For small amount of users also the term due to the noise is significant. This can be explained by a desire of power control to maintain only *target CIR*. When the target level of CIR is reached the power increase is not needed any more and there remains the term due to the noise.

2.3.4 Non-uniform spatial distribution of users

The purpose for exploring non-uniform distributions of users in not to reveal the system capacity for particular density of demand, but rather to study the behaviour and limits of the system. For that reason we only look at two extreme cases: all the users are at the cell border and they are all near to the host BS. In practice both of these cases are very rare and usually a system operates somewhere between this two limits.

We compare these two cases with the uniform distribution of users. Fig. 2.4 describes the total transmitted power from the BS when one user is located at the distance given on the x-axes. For example for "minimum distance" all other users are near the BS and one user is located at distances 1...1000 with step 1. The total transmitted power is calculated separately for all these 1000 different locations of one user. In the first configuration, for example, all users are near to BS and one user at the distance 1 m. A point on the graph is as power for that one users as solution for that configuration. Next point is calculated when one user is located at distance 2 m. Similar procedure is made for the case when all the users are at the cell border.

For uniformly distributed users the total transmitted power is calculated in the same way. All other users now, however, are not located near to BS or cell border but the uniform spatial distribution of users is used.

The lowest curve on the Fig. 2.4 corresponds to the case when the users are near to BS. As can be seen when the user is located farther from the BS the power starts to increase sharply. This is because the farther located user needs more power to compensate

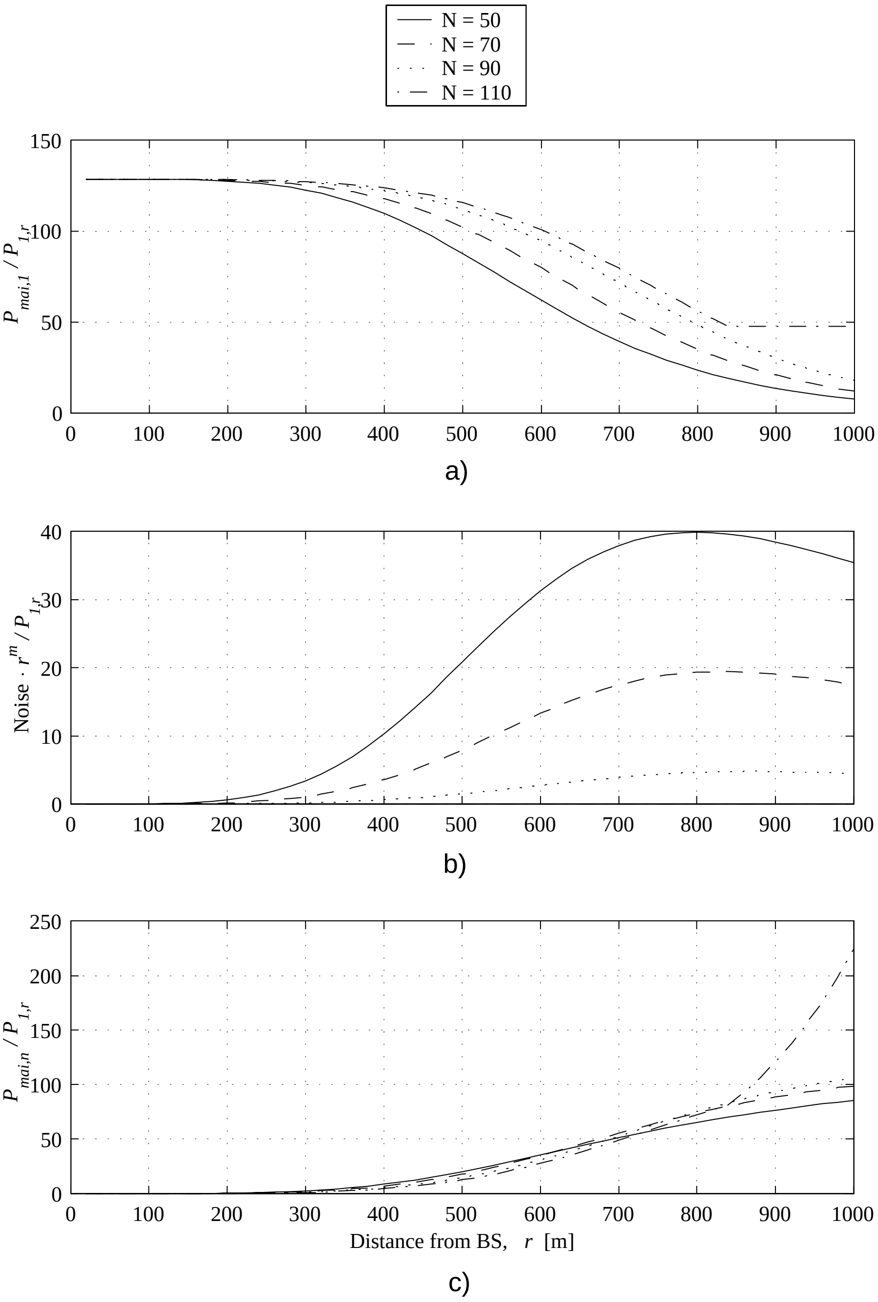

Figure 2.2: Contribution of different type of interferences to total interference. All interferences are normalised with the transmitted signal power. a) intracell interference b) intercell interference c) noise

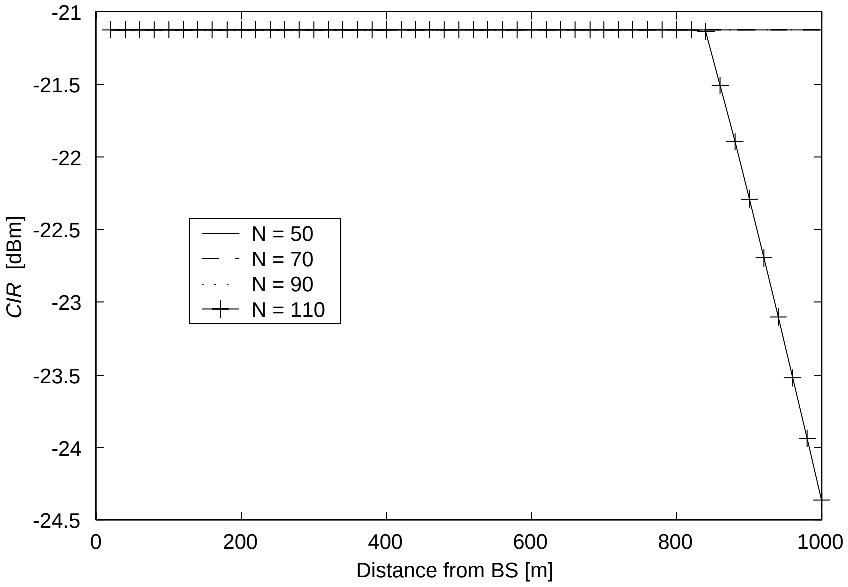

Figure 2.3: CIR at different locations in a cell

the attenuation due to distance. Increase of the power to the users increases interference to other users, who also will increase their power. The power in the system follows the power to the farthest located user. Despite the fact that most users are near to BS, when the user reach the cell border the total power is near to the total power for uniform distribution of users.

When the users are at the cell border the system is in outage despite the location of the one user. The reason for outage is that the users from the neighboring cell generate as much interference as the users from the host cell. By elaborating on that one can conclude that when the possible interference pool is divided between host and neighboring cells equally the system is always capable to provide service to all the users. From Eq. 2.1 one can easily see that the worst case capacity corresponds to the capacity required when all the users are at the cell border. When only one neighboring cell generates the interference and the users are equally divided among the cells this is $CIR_t = \frac{1}{2N-1} \Rightarrow N = \frac{1}{2}\left(\frac{1}{CIR_t} + 1\right)$. However when the assumption on uniform distribution of users holds the cell capacity can be much higher.

Figure 2.4: Transmission power as function of a user distance with different user distributions in the cell.

2.3.5 Variable bit rate services

The data rate may vary accordingly to service. In order to be able to use the results with fixed data rate we compare a multiservice network with a network providing only voice connections. Data rate to a voice user is selected as reference data rate. And the maximum amount of voice users that can be served by the system gives us the reference system capacity.

Also for multiple data rates the target energy per bit to interference ratio should still be satisfied: $\frac{E_b}{I_1} = \frac{W}{R_{1_1}} \frac{P_{1_1}}{I_{mai,1} + \sum_{n=2}^{N} I_{mai,n} + \eta}$. The effect of multiservice is considered by setting the R_{1_1} to correspond the data rate of particular user.

For comparing with constant bit rate we describe the transmission power as function of transmission power for reference data rate. For reference data rate energy per bit is $E_{b,ref} = \frac{P_{ref}}{R_{ref}}$, similarly for general data rate it is $E_b = \frac{P_{1_1}}{R_{1_1}}$. The required bit error ratio is achieved for some constant energy per bit to interference ratio $\frac{E_b}{I_1}$ We assume this to be same for all data rates. We can make this assumption because the target $\frac{E_b}{I_1}$ can always transferred to some constant value by increasing the corresponding datarate. That means that the higher *target SIR* value can be mapped to the higher datarate and constant *target SIR* for all users. This transformation shold be taken accound later when the total transmitted bitrate in the cell is calculated.

When the interference level is same for all services, the energy per bit should is also equal $E_{b,ref} = E_b$. The transmitted power can accordingly expressed in terms of transmitted power for the reference system

$$P_{1_1} \approx \frac{R_{1_1}}{R_{ref}} P_{ref} = k_{R_{1_1}} P_{ref}.$$

For reference data rate $k_{R_{1_1}} = 1$. When to assume that the transmitted power is same for all user with reference datarate and by knowing how many such users the system can support we can write for the total transmitted power in the cell $P_{ref} \sum_{k_1=1}^{K_{1,ref}} k_{R_{1_1}} = P_{ref} K_{1,ref}$. Because all the transmitted power can be presented trough the reference transmitted power we can write:

$$\sum_{k_1=1}^{K_1} P_{k_1} = P_{ref} \sum_{k_1=1}^{K_1} k_{R_{k_1}} \approx P_{ref} K_{1,ref}, \qquad (2.6)$$
$$\sum_{k_1=1}^{K_1} k_{R_{k_1}} \approx K_{1,ref}.$$

Eq. 2.6 is the wellknown stochastic knapsack problem (see for example [Ros95]). By solving Eq. 2.6 for a given $K_{1,ref}$ one gets the service mix that can be supported by the network. In other words services with different rates have all together the same channel capacity (total bit rate) as $K_{1,ref}$ users with a single service.

The capacity for the reference data rate varies depending on attenuations in the channels. Therefore, Eq. 2.6 is not an equality nor an inequality, but is nearly equal. This is because the change of data rates changes the demand distribution in the cell and that in turn affects the interference level.

The high data rate user introduces nonuniformity of demand distribution. The user with k times the data rate of a voice users demands also k times more power. That can be interpreted as k voice users communicating from the same location. Such interpretation makes clear that for high k there can be less voice users in the cell and the load spatial distribution is different when there would be $K_{1,ref}$ voice users only. For example when one user transmits with 300 kbit/s and for voice is required 10 kbit/s the data user corresponds to situation where 30 users communicate at the same location. Because the capacity depends on user spatial distribution the available capacity becomes extremely dependent on location of high data rate user.

Eq. 2.6 dose not give exact capacity but is an easy approximation for estimating the capacity for different service mixes. It is much easier to solve the stochastic knapsack in Eq.2.6 than to study the capacity for every data rate of users. If the capacity for various data rates does not differ much from the capacity for reference data rate, the capacity for latter can used in planning process as the system capacity. We address this issue in Chapter 4.

2.3.6 System capacity with moving users

Above we found that the channel capacity depends on spatial distribution of users. When users moves the spatial distribution and the instantaneously available capacity is changing. In this section we attempt to analyze the impact of the speed, amount of users and cell size on capacity variation. The analysis below is intended to illustrate the CDMA with different cell size and users speed. The analysis only describe the problems that appears in such system and conditons that should be investigated more thoroughly.

For the study we model analytically an extreme situations where the system capacity is maximal and it starts to decrease with the users movements. We describe the call holding time the cell size and users speed as parameters of the equation. That allows to compare and to conclude on the systems with different values for these parameters.

The channel capacity is maximum when users are near to BS. When users start to move away from the BS the available capacity decreases. At the moment when demand exceeds the capacity the system will be in outage. The outage occurs when in the "good" condition, users near to BS, was admitted more users than the system could serve after they have moved to "bad conditions", further from BS. However, when into the cell are admitted K_1 users some of them can close the connection before the system moves into outage. Therefore the probability that the system will be in outage is equal to the probability that moving users reach the outage condition before any of the calls will departure.

We set up a test case where all the users, K_1, are near to BS and they start to move away from BS with constant speed v. We denote with r_R the "capacity limit distance", the distance from BS where K_1 users can not be served anymore. The time required to reach that limit when the initial distance is $r_i = 1$ is $t_r = \frac{r_R - r_i}{v}$.

For exponential call holding time the probability that non of the calls were released during t_r is $P_{b,out}\left(t_r, K_1\right) = \int\limits_{t_r}^{\infty} e^{-K_1 \mu t} dt = \frac{1}{K_1 \mu} e^{-K_1 \mu t_r}$. Where μ is mean call holding time.

The system will be in outage when the interference level does not allow to maintain the *target CIR* ratio. This will happen for all the links at the same time. For calculating at what distance it happens in our test case we rewrite Eq. 2.3 into form

$$K_1 + \sum_{n=1}^{N} K_n \left(\frac{r_1}{r_n}\right)^m + \frac{r_1^m \eta}{P} \leq \frac{1}{CIR_t}. \tag{2.7}$$

When the capacity limit is reached the signal power is so large that the third term is very small and can be left out.

We assume that the interference is generated mainly by three neighboring BS, $N = 3$, and interference depends only on distances between BS. Let the distance between neighboring BS be r_d. Eq. 2.7 can be simplified by taking into account the distance from other BS as $r_j = (r_d - r_1)$. Inserting r_d into Eq. 2.7 and writing it for distance r_1 one gets

$$r_1 \leq \frac{C}{1+C} r_d,$$

where C is a function of attenuation, m, number of users in cell , K_1, and CIR_t

$$C\left(m, K_1, CIR_t\right) = \sqrt[m]{\frac{1}{3K \cdot CIR_t} - \frac{1}{3} - \frac{1}{3K^2}}.$$

Now the system can be analyzed by the set of equations

$$\begin{aligned} P_{b,out}\left(t_r, K_1\right) &= \frac{1}{K_1 \mu} e^{-K_1 \mu t_r} \\ t_r &= \frac{\frac{C}{1+C} r_d - r_i}{v}. \end{aligned}$$

We evaluate the equations for two different cell sizes for 2000 m and 200 m and for different speed rates $v = 2..20 \frac{m}{s}$. For these parameters the interesting number of users is in the range from 50 to 70. That corresponds to amount of users that can not be satisfied in the cell when all of them would be at the cell border.

The outage probability for the small and big cell are given on Fig. 2.5 and 2.6 respectively. Compared to slow users the quickly moving users reach the outage region earlier, there is less time for some users to end the call, and therefore the probability for outage is higher. Similarly for the higher number of users the region where the system will be in outage is reached quicker.

The outage probability is much less for bigger cell. That can be explained by attenuation. In bigger cells it takes much longer to get to the cell border where interference

Figure 2.5: Outage probability in a big cell as function of user speed, calculated for different number of users, N, in the cell.

from other cells is high. By moving the same distance the environment changes less in bigger cell compared to smaller cell.

2.4 Capacity definition of the CDMA system

In previous sections we described the varying environment of CDMA. In this section we concentrate on the capacity of such an environment. First we define the capacity, based on this definition we propose a method for calculating it, and finally we compare the CDMA capacity to the capacity of known systems like TDMA.

By the channel capacity we understand the maximum total bit rate that can be transmitted in one cell. This total bit rate is calculated as sum of bit rates of individual users in the cell. The demanded capacity can be more or less than available channel capacity. When it is more the system is in outage.

The system outage is different from blocking. In case of blocking some arriving users

Figure 2.6: Outage probability in a small cell as function of users speed, calculated for different number of users, N, in the cell.

are not admitted to the system, blocked, and there is no impact on the users already in the system. The system outage affects also the users who are already in the system. Because of the change of environment the channel capacity decreases and the demanded data rate to all the users can not be provided. Of course during the system outage also new arrivals are blocked.

The instantaneous channel capacity can be calculated by solving the equation 2.2 for all the users. It can be done effectively by writing this set into matrix form as it is done in calculations for power control purposes [Zan92].

$$
\begin{gathered}
f\left(r_{1_1}\right)\frac{P_{1_1}}{CIR_t} - f\left(r_{1_1}\right)P_{1_2} - \ldots - f\left(r_{1_1}\right)P_{1_k} - \sum_{n=2}^{N} I_{mai,n} - \eta = 0 \\
f\left(r_{1_1}\right)P_{1_1} - f\left(r_{1_1}\right)\frac{P_{1_2}}{CIR_t} - \ldots - f\left(r_{1_1}\right)P_{1_k} - \sum_{n=2}^{N} I_{mai,n} - \eta = 0 \\
\vdots \\
f\left(r_{1_k}\right)P_{1_1} - f\left(r_{1_k}\right)P_{1_2} - \ldots - f\left(r_{k,1}\right)\frac{P_{1_k}}{CIR_t} - \sum_{n=2}^{N} I_{mai,n} - \eta = 0
\end{gathered}
\tag{2.8}
$$

Where $f\left(r_1\right)$ is attenuation in the channel and P_{1_1} power at transmitter send to the 1-th user in 1 BS.

Because it is a matrix equation it can have a solution where some powers are negative. In practice the negative power is not feasible. It means that the system can not support all the users and some users should be removed from the system. After removal their power is set to zero and the size of the matrix decreases. Accordingly, the channel capacity is reached for the number of users for whom this matrix can be solved for positive powers for all the users.

There are two problems related to the estimation of the capacity from the matrix: how to find the maximum number of users that can be served and because the capacity depends on the parameters describing the users speed, location, and so on. at given moment how to find what is exact capacity. First of them is related to finding out the maximum size of the matrix. Depending on the users locations, channel to users, and speed to users the maximum size of the matrix vary. The second problem express the question that which matrix size should be chosen for the cell capacity.

The first problem can be tackled by solving the matrix equation for different number of users. The maximum number of users where the solution for signal powers has all positive values which are less than $P_{\max}$ is the channel capacity of the system.

The second problem can be solved by using the statistical average of capacity. For given number of users in the system one can test different configurations of user locations.

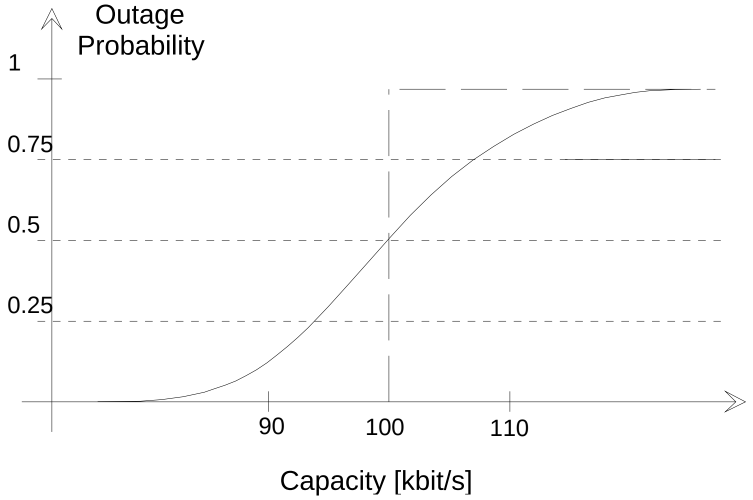

Figure 2.7: Capacity defined as outage probability for given datarate in the system a) CDMA, continuous line b) TDMA, dashed line

Some of these configurations provide the required solution to 2.8 some of these do not. The retio of the configurations where the matrix can not be solved to the total amount of configurations gives the probability that the system will be in outage for given number of users in the system. The resulting capacity is not a fixed number but a vector of outage probability values. [Fig. 2.7].

In order to calculate the average outage for a given number of users in the system one has to solve Eq. 2.8 for all possible configurations of user locations. This is difficult to calculate analytically. However, the retio can be obtained by Monte Carlo simulation: by choosing random configuration of users and assuming that for a sufficiently large number of different combinations the ratio of 'bad' configurations to all possible configurations starts to approach the average outage value.

For a given number k of users the capacity is probability of the system being in the outage for this number of users. By summing the data rate of all users one can also look at the capacity as function of the data rate in the cell [Fig. 2.7]. For example when there are 90 users in a cell with a 10 $kbit/s$ data connection the total data rate will be 900 $kbit/s$. For that channel capacity the outage probability will be about 10 %.

The vector description of capacity can also be applied to TDMA, where the outage probability will be zero when the data rate for connections is less than the channel transmission capacity and it is one when demanded data rate is higher. In Fig. 2.7 the channel transmission capacity is 100 $Kbit/s$ when transmitted data rate is less than that the whole demand can be satisfied. When the required data rate is more than 100 $Kbit/s$ some of the connections can not be supported, there is not enough transmission capacity available.

The description of outage given here is somewhat different from the one used in the conventional studies of CDMA. The traditional approach calculates the outage probability for one user based on the total interference level from the Eq. 2.2. The interference is approximated with the distribution and in calculation are used moments of it. The moments are calculated by numerical integration for uniform spatial distribution of users [Gil91] The approach proposed here provides more flexibility for studying the system behaviour as function of movement or location of users.

2.4.1 Simulation of the system capacity

We illustrate the capacity calculation for the same test network used above in the analysis of CDMA behaviour. We do the calculations only for one type of service.

Monte Carlo simulation requires to solve Eq. 2.8 for each amount of users many times. Solving the matrix equation is very time consuming. However, for our purposes it is enough to find out does the matrix have the required solution or not. That can easily be done by using property of power control (PC). PC attempts to solve Eq. 2.8 by increasing power to each user. When a solution for all positive powers exist the system converges to it, when solution does not exist PC continues to increase the power until some of users reach the maximum allowed power. Consequently when some users have maximum allowed power the system is in outage.

The numerical evaluation becomes very simple: set small initial power to all the users, for the users for whom the CIR requirement is violated increase the transmitted power, end the calculation when the total transmitted power converge to some value or some users reach the maximum allowed power.

For Monte Carlo simulation, for each number of users in the system, the process should be repeated many times.

Solution of Eq. 2.8 gives us two types of information: the total transmitted output power from BS and the outage condition. Because the output power is calculated over many configurations it will be given by a distribution [Fig. 2.8]. In the figure we have shown mean, 10 %, and 90 % level of the output power for given number of users.

The fraction of the configurations where the system was in outage is given in Fig. 2.9. As we see the outage probability starts to increase sharply when the amount of users exceeds some limit.

There is clear relationship between the transmitted power and outage probability. Two separate states of the system can be observed, namely overload and nonoverload. In the overload state the transmitted power to all users is significantly more than in nonoverload case. Though the states have very different power levels inside the state the power change variation is not very significant.

2.5 Results on study based on the simple model

The analysis in this chapter had two targets: to describe the general behaviour of CDMA and based on that to derive requirements for link level studies and network planning.

The behaviour of a CDMA system stems from two facts: the system is interference limited and interference is not constant but varies. Some of the consequences of that are described below.

Because the interference is not constant the signal powers in the cell are changing dynamically. When the demanded bit rate exceeds the available capacity dynamic power change is pulled into continuous growth of the power that in practice is stopped at some preset limit value for power. Although in this case the power in the cell is maximum,

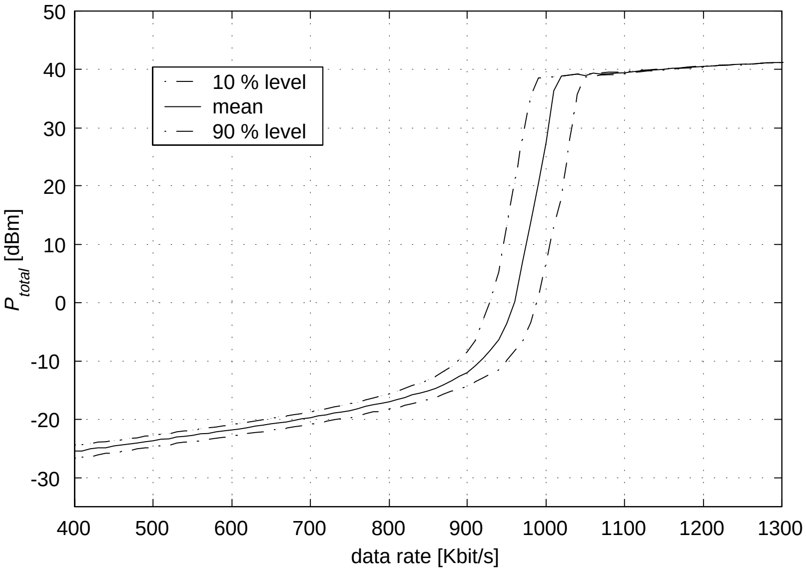

Figure 2.8: Total transmitted power level in a WCDMA cell. Mean, 10 % and 90 % fractions.

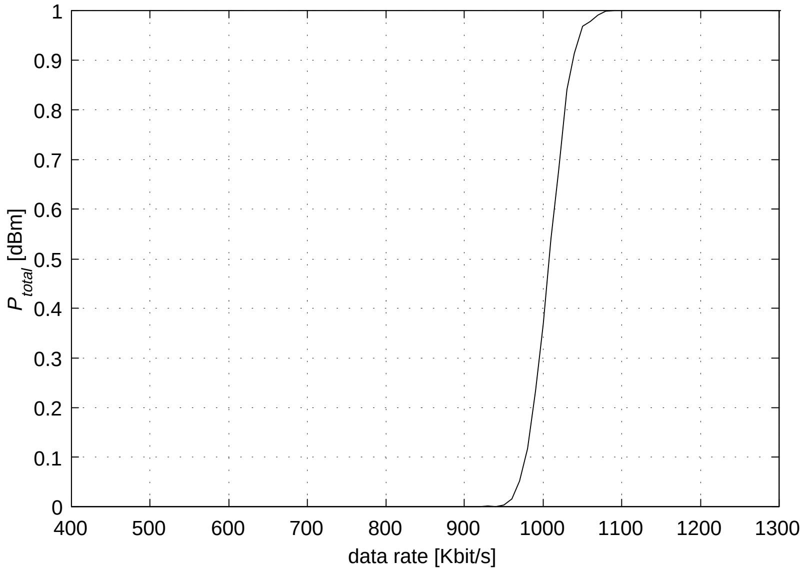

Figure 2.9: Outage probability for different number of users in the cell.

far located users have very high interference and effective cell size has shrink, the cell breaths.

If the system is operating near to the capacity limit, overrunning it sometimes, the transmitted power jumps, oscillates, between the maximum allowed power value and some smaller value. The smaller value is usually a power required to compensate interference to the farthest located user.

The power control has an interesting impact on outage probability. Because of power control the reason for outage is not only attenuation in the channel but also overrunning the available capacity in the cell.

Such problems can be avoided by allowing into cell only as many users as it can handle, unfortunately the available capacity in a CDMA cells is not constant it is changing with users movements. There is a minimum capacity that guarantees service quality for all users in the worst case. However the worst case might happen very seldom. Designing the system for the worst case requires network over dimensioning for other cases.

Higher bit rate for one user corresponds to many conventional users at one location in a cell and the total cell capacity depends where the mobiles are located in the cell. As such a high bit rate service corresponds to nonuniformity of users distribution and brings with itself all the problems related to it.

For a given amount of users in a cell there are only some configurations of users locations where demanded data rate to each user can be satisfied. "Good" configuration of user locations allows to accept an arriving call. These configurations are alternating when users move in the cell.

For quickly moving users the conditions in the cell change rapidly and it is highly probable that before any call is released, demanded capacity is reduced, users have moved to locations where demanded capacity exceeds available capacity. Therefore for quickly moving users the calls cannot be accepted even when users are in a "good" location. In case of slowly moving users the probability of that the environment changes, system reach the "bad" configuration, is much less. In result, average capacity in the cell with higher users speed is less compared with slowly moving users.

For the same speed conditions total capacity of the bigger cell will be more than for smaller cell. This is because in the bigger cell it takes more time for users to move from "good" positions to "bad" positions.

As conclusion we may sum the above: The system capacity in CDMA is a function of many variables like speed of the users, their location, cell size, targeted CIR.

This functional dependency shapes also the peculiarities of the CDMA network planning. Conventional cellular network planning process relies on estimation of the cell coverage and capacity. In CDMA based network these two parameters are very vague and more dynamic functions than constants. Therefore in CDMA systems operational algorithms such as admission control, power control, and dealing with overload conditions become more important. The planning process can deal only with estimated values. Discrepancies from those should be taken care by real time operations.

The estimation of the coverage in CDMA is related to estimation of the capacity. Outage occurs only when the network is fully loaded and some users have reached the maximum allowed power. Because the outage occurs due to the interference the exact study should embrace the whole fully loaded network at the same time. We target issues related to that in Chapter 4. Before that we improve our simple system model by investigating the link level.

The link level study has to provide a better model for calculating CIR and also the more realistic value of *target* CIR. The network can operate in overload and nonoverload conditions. The overload is an special system state. Because the *target* CIR values are violated for some users, the real time control methods in the system attempt to move out from that state as quickly as possible. Therefore we study the link level only in nonoutage conditions. From simulations we see that in this case the interference does not change much and can be assumed to be stationary.

Chapter 3

Study of the CIR dependency on user speed

In this chapter impact of the modem and channel on the CDMA capacity is studied. The capacity is a function of required BER or FER and these in turn are dependent on user speed. The BER or FER in turn are monotonic functions of CIR. That allows us to characterise the channel by CIR dependency of user speed, calculated in Section 3.6. Calculation of CIR requires development of the interference model (Section 3.5) and channel response after power control - PC (Section 3.4)

The chapter starts with a short introduction (Section 3.1) and description of the system (Section 3.2) and channel model (Section 3.3).

The interference model is derived separately for down- and uplink. By using the interference model we are able to analyze the orthogonality factor in downlink.

The results are illustrated with simulation and numerical examples.

3.1 Introduction

CDMA capacity is interference limited. The amount of interference in the system depends on the channel characteristics and implementation of the modem. The modem impact on the capacity is usually considered by separating the link level and network level studies [OP98]. The network level determines the parameters that link level should provide and the conditions under which link level should be studied. In such framework the link level considers all the details related to the modulation, coding, decoding and channel.

The receiver performance is described by the bit or frame error rate (BER, FER). Calculation of these rates requires information about coder, decoder, and channel. These are generally difficult to evaluate analytically and therefore are usually calculated numerically. However, for calculation of the system capacity we are interested in the interference the users generate. The amount of interference the user generate depends on the *target* CIR for the user. BER and FER are monotonic functions of CIR which makes it possible to describe the receiver performance only by CIR. Therefore it is sufficient to provide the capacity calculation at the network level with the CIR as function of link level parameters.

The analysis of the simple system model clearly separates the overload and nonoverload operation modes. We study the link level in the nonoverload condition. The capacity can be calculated as limit when the nonoverload conditions changes to overload.

The nonoverload is a normal condition where the system is expected to operate most of the time. In normal condition interference from other users generates the noise floor. We assume for a given number this floor to be stationary and constant in average. The required channel quality is achieved when the received signal power is *target* CIR times over this noise floor. When the power is higher the received CIR is higher, the channel has less errors, but the user generates also more interference to the network, the total capacity of the CDMA network is decreasing. In order to keep the signal power exactly to satisfy the required CIR the system uses power control (PC).

As seen in Fig. 3.1 the PC introduces a feedback loop that alters the distribution of the signal in the receiver input. The analysis of the receiver performance has to look at the whole control loop. This can be done by first modeling the channel without PC and then applying the impact of the feedback due to the PC.

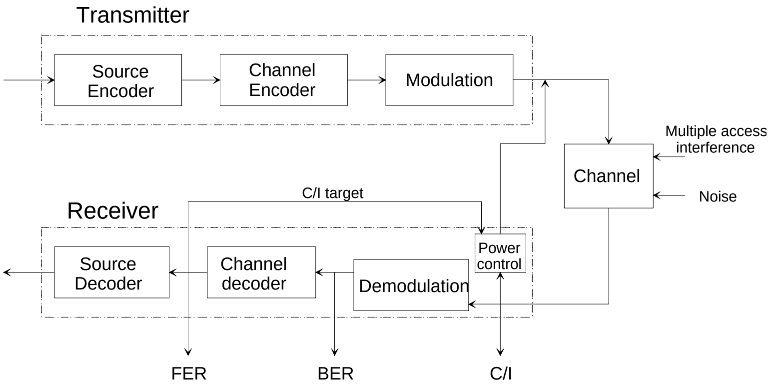

Figure 3.1: Communicaiton channel with PC

The PC operates on different levels: closed loop and open loop power control.

The purpose of the closed loop PC is to keep the received CIR at a constant level, set by the outer loop PC. The outer loop PC sets for *target* CIR value that satisfies the required channel quality.

The open loop PC has to set the target CIR because the coding gain and due to that BER (or FER) is different for different signal distributions.

Although closed loop PC attempts to keep the signal level constant due to the slow update interval and finite PC step it is not capable to do it. As a result for high speed users there remains significant variation of the signal.

The closed loop power control has been extensively studied. Main target of the investigations has been to develop algorithms for PC [BG98] or to identify the stability criteria [Zan92]. Our study here is done for a different purpose - to identify the signal distribution after applying PC and from there to calculate the FER. We do it by deriving the optimal limit for the variation of interference that PC can reach.

Due to the spreading code nonorthogonality the CDMA channel contains interference from other users arriving along multiple paths. Such channel without coding is evaluated in several papers [Pur77] [Eft97]. In this chapter the model described in these papers is developed further by tailoring it accordingly to environment characteristics for CDMA down and uplink.

By having the signal distribution after the PC and also the interference model the coded system is simulated. The result is given as relation between the CIR and the BER. This gives us the function required for network planning with users with different speed.

3.2 System model

In this section we describe how the receiver handles the signal. This is done by giving a parametric model of the signal after the RAKE receiver. In later section we calculate the distribution of parameters and that allows to use the model for calculating the CIR.

Consider a CDMA system with multiple cells and K users in a cell. Each user is assigned a pseudo random spreading code sequence. Information is coded with QPSK modulation i.e. binary signals on a I and Q axes. In downlink signals from one BS are synchronized. In uplink signals and propagation paths are independent and due to power control the power of the received signals are assumed in average to be equal. The system operates in multipath environment where different paths are assumed to be uncorrelated.

Description of the channel depends on the way the system sees it i.e. it is a function of type of the receiver and signal bandwidth. We assume that the system under study has a RAKE receiver.

In simple form a RAKE receiver can be understood as a set of synchronous receivers tuned to different channel taps. A functional description of RAKE for a two tap channel is given in Fig. 3.2. The signal at the receiver input is the sum of the signals arriving along different paths. Each finger of RAKE is synchronised to one of the paths. The RAKE finger is synchronous receiver - the received signal is multiplied with the local copy of the signal that has the same phase as the signal from the path to which the finger is synchronised. The signals at output are maximum ratio combined, weighted with the amplitude and conjugate phase of the corresponding path and summed.

The important fact is that the signal arriving at a different path than the one where

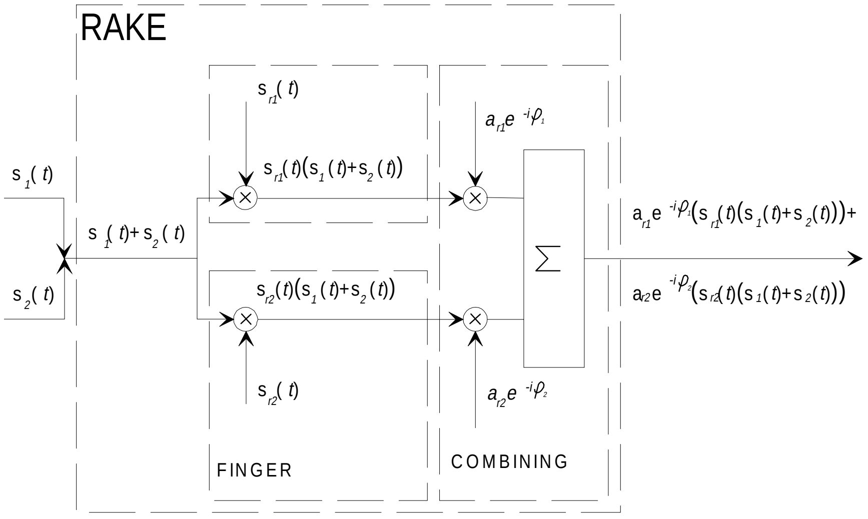

Figure 3.2: Functional model of a RAKE receiver.

RAKE is synchronised contribute to the interference. In result the performance of the receiver will be function of the channel response. We analyze this dependency more deeply in later sections, now we give only more precise description of the signal at the RAKE output.

For simplicity we can assume that there are as many channel taps as fingers and note the number of them with L. This allows to reduce the burden of indexes required in equations.

The signal at the receiver input can be described as a sum of white Gaussian noise $n(t)$ and information signals from N cells each with K_n user and L_{k_n} multipath components for each user [Pur77].

$$r(t) = n(t) + \sqrt{2} \sum_{n=1}^{N} \sum_{k_n=1}^{K_n} \sum_{l_{k_n}=1}^{L_{k_n}} \beta_{l_{k_n}} a^{k_n}[t-\tau_{l_{k_n}}] b^{k_n}[t-\tau_{l_{k_n}}] \cos\left[\omega_c t + \varphi_{l_{k_n}}\right] \tag{3.1}$$

where

$\beta_{l_{k_n}}$ amplitude of the l-th path for user k from n-th BS,

$a^{k_n}\left[t-\tau_{l_{k_n}}\right]$ spreading sequence

$b^{k_n}\left[t-\tau_{l_{k_n}}\right]$ information signal of the k-th user from n-th BS

$\cos\left[\omega_c t+\varphi_{l_{k_n}}\right]$ cosinus of carrier frequency ω_c and phase difference φ between the signal for k-th user from n-th BS and reference signal

Each RAKE finger is a coherent receiver tuned to one multipath component. After correlation the signals at each finger consists of four different types of components: information signal (S^i) , the self interference due to multipath (I^i_{si}), Gaussian random variable due to thermal noise (I^i_{ni}), and multiple access noise (I^i_{mai}). The last one can be split into intracell interference $\left(I^i_{mai,1}\right)$, due to the signals in the same cell and intercell interference $\left(I^i_{mai,n}\right)$ from the signals in other cells. Maximal ratio combining weights and sums this mix from each finger. When it is assumed that RAKE has L_r fingers the sinal at the receiver output for the user $k_n=1_1$, first user in the first BS, is:

$$U=\sum_{i=1}^{L_r}\beta_i\left\{S^i+I^i_{mai,1}+I^i_{mai,n}+I^i_{si}+I^i_{ni}\right\} \tag{3.2}$$

Where the components are expressed as

$S^i=\sqrt{\frac{1}{2}}a_i\beta_{i_{1_1}}R_{1_{1_1}1}\left(\tau_{1_1 1}\right)\cos\left(\phi_{1_1 1}\right)=\sqrt{\frac{1}{2}}a_i\beta_{i_{1_1}}Tb^{1_1}_1$

$I^i_{si}=\int\limits_{nT_c}^{T+nT_c}n\left(t\right)a_i a^{1_1}\left(t-nT_c\right)\cos\left(w_c t+\varphi_{i_{1_1}}\right)dt$

$I^i_{mai,n}=\sum\limits_{n=2}^{N}\sum\limits_{k_n=1}^{K_n}\sum\limits_{l_{k_n}=2}^{L_{k_n}}\sqrt{\frac{1}{2}}a_i\beta_{l_{k_n}}\left\{b^{k_n}_{-1}\cdot R_{l_{k_n}1}\left[\tau_{l_{k_n}i}\right]+b^{k_n}_0\cdot\hat{R}_{l_{k_n}1}\left[\tau_{l_{k_n}i}\right]\right\}\cos\left(\phi_{l_{k_n}i}\right)$

$I^i_{mai,0}=\sum\limits_{k_1=1}^{K_1}\sum\limits_{l_{k_1}=1}^{L_{k_1}}\sqrt{\frac{1}{2}}a_i\beta_{l_{k_1}}\left\{b^{k_1}_{-1}\cdot R_{l_{k_1}1}\left[\tau_{l_{k_1}i}\right]+b^{k_1}_0\cdot\hat{R}_{l_{k_n}1}\left[\tau_{l_{k_1}i}\right]\right\}\cos\left(\phi_{l_{k_n}i}\right)$

$I^i_{ni}=\sum\limits_{l_i=1 l\neq i}^{L_{1_1}}\sqrt{\frac{1}{2}}a_i\beta_{l_{1_1}}\left\{b^{1_1}_{-1}\cdot R_{l_{1_1}1}\left[\tau_{l_{1_1}i}\right]+b^{1_1}_0\cdot\hat{R}_{l_{1_1}1}\left[\tau_{l_{1_1}i}\right]\right\}\cos\left(\phi_{l_{1_1}i}\right)$

where

a_i is estimate of the signal amplitude at the i-th finger,

$b^{k_n}_{-1}$, $b^{k_n}_0$ are the values of the previous and current bit,

$\varphi_{l_{k_n}i}$ phase difference between received and reference signal.

$R_{l_{k_n}1}\left(\tau_{l_{k_n}i}\right)$, $\hat{R}_{l_{k_n}1}\left(\tau_{l_{k_n}i}\right)$ are continuous time partial cross correlation functions between the current and previous bit. Overlapping is due to the different delays τ in a channel. The index l_{k_n} note the path l, for the user k, from the BS n. These cross correlation functions are defined similarly as in [Eng95].

Because we do not evaluate the exact interfernce from nonsyncronous copies we assume that the delay is spread only over one symbol. This delay is sufficient to illustrate the reason of the interference and how the interference can be calculated.

The cross correlation function is the main culprit for the interference in the system. The spreading codes are usually designed to be orthogonal. The orthogonality is guaranteed when the codes are synchronous, i.e. start at the same moment. Unfortunately signals arriving along different paths are nonsynchronous they can start from whatever moment compared to signals from other paths.

The cross correlation is illustrated in Fig. 3.3. On the figure we have described the signal from two different paths. The reference signal at the finger is synchronised to the signal from the path 1. After the correlation with the signal from the synchronised path the output will be 1 or 0.

The signal from the other path is not synchronised. The previous bit b_{-1} overlap the bit of the reference signal during the time interval $t_{2,-1}$. As a result at the correlator output is cross correlation part from the previous bit b_{-1}, $R_1(t_{2,-1})$, and from the current bit b_0, $\hat{R}_1(t_{2,0})$.

In Fig. 3.3 the correlation is shown only among the signals from different paths. In CDMA we have similar cross correlation among the signals from different users and that is the main reason of interference in the system. In Eq. 3.2 this cross correlation is noted by $\left\{b_{-1}^{1_1} \cdot R_{l_{1_1}1}\left[\tau_{l_{1_1}i}\right] + b_0^{1_1} \cdot \hat{R}_{l_{1_1}1}\left[\tau_{l_{1_1}i}\right]\right\}$. The equation describes only the correlation correlation among previous and current bit in practice it can also be among the current and next bit. However, this does not change the way how the correlation is calculated and for sake of simplicity we describe it only for previous and current bit.

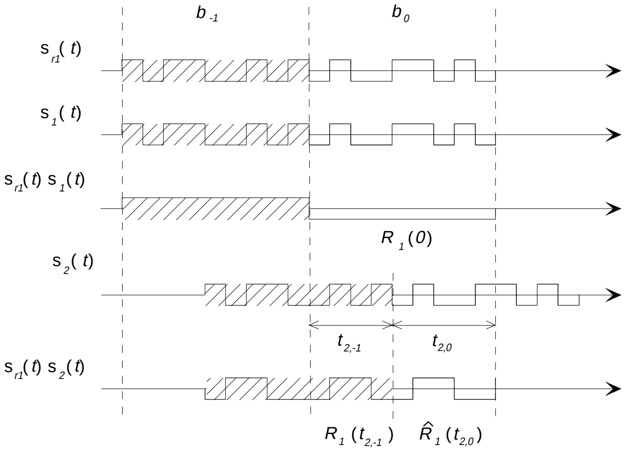

Figure 3.3: Decription of the calculation of the cross correlation function when the RAKE finger is syncronised to the signal from path $s_1(t)$.

The cross correlation function depends on the codes overlapping time given in the figure as $t_{2,-1}$ and $t_{2,0}$. In Eq. 3.2 the overlapping time is labeled as $\tau_{l_{k_n}i}$. Where the indexes stand for the path where finger is synchronised i and for every path l, from every user k, from each BS n.

The amount of interference generated by the nonsynchronous copies depends on the spreading codes. For the sake of generality we note it by constant C that should be selected for every particular type of spreading code separately. In other words we replace into Eq. 3.2 $C = \left\{ b_{-1}^{k_n} \cdot R_{l_{k_n}1}\left(\tau_{l_{k_n}i}\right) + b_0^{k_n} \cdot \hat{R}_{l_{k_n}1}\left(\tau_{l_{k_n}i}\right) \right\}$. For example in [Pur77] [Rap96] code cross correlation is assigned value $\frac{T^2}{6G}$ where T stands for a symbol length and G for a period of the code sequence.

For calculating the CIR we need moments of U. In order to calculate these moments we have to describe the amplitude distribution at each channel tap β_i and interference from every transmitter. We do that in the next chapters.

3.3 Distribution of the received signal amplitudes

In this section we describe the channel model used in the further analysis. In order to be consistent with network level analysis we factor the channel response into attenuation and fast fading. This is done by normalizing the received signal with average received power. At the end of the section we describe the distribution of the normalized signal amplitudes.

3.3.1 Normalisation of the signal amplitude

In network level study the average received power was assumed to be constant and variation due to fast fading and imperfect PC was neglected. Power of the received signal is gathered as sum of signal powers from each RAKE finger. For smooth transition from network to system level we separate the average path loss and fast fading. For that we normalize the average received signal power in a way that the sum of average signal powers from each finger will be one.

When the signal amplitude at each finger is noted as $\beta_l^{'}$. the average signal power from finger l is

$$E\{\left(\beta_l^{'}\right)^2\}. \tag{3.3}$$

Total average received power is sum of received powers from each finger

$$E\{\sum_{l=1}^{L}\left(\beta_l^{'}\right)^2\}. \tag{3.4}$$

When the signals from different fingers are assumed to be uncorrelated one can rewrite the total average power as

$$\sum_{l=1}^{L} E\{\left(\beta_l^{'}\right)^2\}. \tag{3.5}$$

This average power at each finger contains the channel attenuation, L, and variation due to fast fading. We separate the attenuation by normalization.

$$\sum_{l=1}^{L} E\{\left(\beta_l^{'}\right)^2\} = \sum_{l=1}^{L} E\{\frac{\left(\beta_l^{'}\right)^2}{\mathsf{L}}\mathsf{L}\} = \sum_{l=1}^{L} E\{\frac{\left(\beta_l^{'}\right)^2}{\mathsf{L}}\}\mathsf{L} = \mathsf{L}\sum_{l=1}^{L} E\{(\beta_l)^2\} \tag{3.6}$$

Where β_l is normalized amplitude. L can be interpreted as average path loss. It is also normalisation constant selected so that the sum of the average normalized power from each finger is one.

$$\sum_{l=1}^{L} E\{\frac{\left(\beta_l^{'}\right)^2}{\mathsf{L}}\} = \sum_{l=1}^{L} E\{(\beta_l)^2\} = 1 \tag{3.7}$$

The instantaneous signal amplitude is given by

$$\sqrt{\mathsf{L}}\sum_{l=1}^{L} \beta_l. \tag{3.8}$$

We are able to distinguish between average path loss and fast variations in the channel. The network level analysis took into account only the average path loss L. This corresponds to the channel without fast variation i.e. the term $\sum_{l=1}^{L} \beta_l$ is constant. For link level studies this simplification is not appropriate any more and therefore we consider the amplitude at each RAKE finger to be given by a random distribution.

3.3.2 Distribution of the channel response

For analysis we are interested in two cases: when receiver is and is not synchronized to the signal. The first of them corresponds to the distribution of the informational signal and second describes the distribution of interference.

Information signal

The information signal is described by the first and second order statistics: distribution and correlation function. Signal distribution is used in calculation of CIR. The correlation helps us model the dynamic behaviour of the PC.

We assume that incoming information signal at one channel tap has complex Gaussian distributed amplitude with mean zero and the same variance on I and Q axes. It can be described in polar form by uniformly distributed argument, between $0 \div 2\pi$, and Rayleigh distributed modulus.

The RAKE receiver contains a set of coherent receivers. A coherent receiver generates a local copy of the spreading signal and synchronise it to the informational signal. When receiver is locked to the phase of the transmitted signal the phase becomes known to the receiver. After the uncertainty related to the phase is removed only the amplitude of the signal remains undefined and should be given by distribution.

When the signal phase is known the signal amplitude at the RAKE output will be same as amplitude distribution of the random signal in input. The Rayleigh distributed amplitude is given as $p_r(r) = \frac{r}{\sigma_{\beta_i}^2} \exp\left(-\frac{r^2}{2\sigma_{\beta_i}^2}\right)$, with the mean $\sigma_{\beta_i}\sqrt{\frac{\pi}{2}}$and variance $\sigma_{\beta_i}^2\left(\frac{4-\pi}{2}\right)$.Where σ_{β_i} is standard deviation of the corresponding Gaussian distribution at finger i. Amplitude on the real and imaginary branches can be calculated as projection on corresponding axes. In practice it means multiplication the amplitude of the received signal with $\sin\frac{\pi}{4}$ and $\cos\frac{\pi}{4}$ respectively.

Power of the received signal is given by chi-square distribution $p\left(y\right) = \frac{1}{\sqrt{2\pi y}\sigma_{\beta_i}} e^{-y/2\sigma_{\beta_i}^2}$ with mean $E\{y\} = 2\sigma_{\beta_i}^2$ and variance $\sigma_y^2 = 4\sigma_{\beta_i}^2$.

The complex Gaussian process that builds up the Rayleigh distribution can be generated by filtering the White Gaussian Noise (WGN) with a Doppler filter. Filtering the WGN introduces into resulting signal a correlation that corresponds to the filter response. The correlation due to the Doppler shift can be approximated by a zeroth order Bessel functions.[Par92].

For simulations or analysis it is often convenient to describe the system at discrete time moments. When the Doppler filter is described as FIR filter the Bessel function gives directly the impulse response of the filter.

Let describe the channel in discrete form. Then the amplitude distribution $\beta[n]$ after the Doppler filter is convolution of the WGN $w[n]$, and the filter response $h[n]$ [See Fig. 3.4]

$$\beta\left[n\right] = \sum_{j=0}^{J} h[n-j]w[n]. \tag{3.9}$$

Where n stands for the time moment where samples are taken.

The filter coefficients corresponds to sampled channel correlation function ρ_n at moments n

$$h[n] = \rho_n u[n]. \tag{3.10}$$

Where $u[n]$ is unit function.

The correlation function is sampled Bessel function at the time moments n

$$\rho_n = J_0\left(2\pi v n/\lambda_c\right).$$

Where the correlation is function of the wavelength λ_c, and speed v of the user.

From the theory of statistical digital signal processing [The92] it is known that the

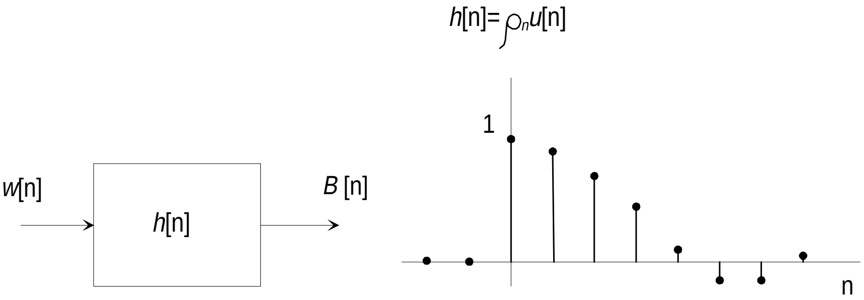

Figure 3.4: Generating the channel response β by filtering the white Gaussian noise with a Doppler filter. The filter coefficients are calculated as sampled zeroth order Bessel function.

variance of the filtered signal can be calculated from the variance of the input signal as:

$$\sigma_{\beta_i}^2 = \sigma_{w_i}^2 \sum_{j=0}^{J} \left|\rho_j\right|^2 . \tag{3.11}$$

Because the Bessel function has domain from 0 to ∞, we need infinite amount of filter coefficients, $J \to \infty$. In practice we limit that with some number.

The variance of the input WGN can be calculated from the variance of the output process

$$\sigma_{w_i}^2 = \frac{\sigma_{\beta_i}^2}{\sum\limits_{j=0}^{J} \left|\rho_j\right|^2} . \tag{3.12}$$

By substituting into the equation the zeroth order Bessel function for correlations

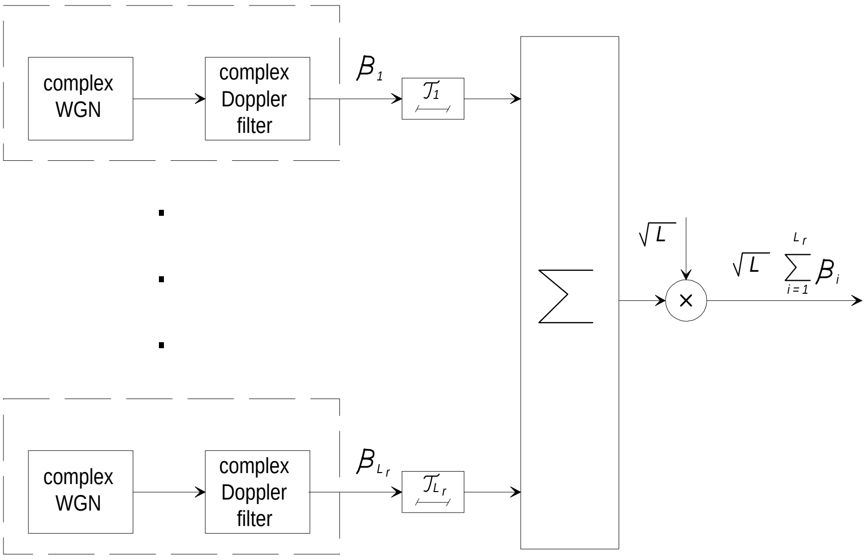

Figure 3.5: The channel amplitude generated by filtering the white Gaussian noise

$$\sigma_{w_i}^2 = \frac{\sigma_{\beta_i}^2}{\sum_{j=0}^{J} \left|J_0\left(2\pi v j/\lambda_c\right)\right|^2}. \tag{3.13}$$

Normalisation of channel taps gave us the variation at each tap i - $\sigma_{\beta_i}^2$ and allows to calculate the variation $\sigma_{w_i}^2$ of the corresponding WGN process. Because we approximate the correlation with FIR filter the value of the $\sigma_{w_i}^2$ becomes a function of the amount filter taps J. However when for when J increase the value converge.

The channel model is summarised in Fig. 3.5. The channel has L_r taps. Signal amplitude at each tap β_i is given by Gaussian distribution with variance $\sigma_{\beta_i}^2$ corresponding to average signal power from the tap. The Gaussian distribution is generated by filtering the White Gaussian Noise with variation $\sigma_{w_i}^2$ calculated from Eq. 3.13. The Doppler filter defines the correlation in the channel. Each tap has its own delay τ_i. Amplitudes of delayed taps are summed together and the resulting amplitude is scaled with average attenuation $\sqrt{\mathsf{L}}$. The output of the channel model is correlated Gaussian process $\sqrt{\mathsf{L}}\sum_{l=1}^{L}\beta_l$.

The discussion above can be summarised for the channel model. The amplitude variation at one channel tap can be calculated by filtering the WGN process and scaling the output with factor $\sqrt{\mathsf{L}}$.[Fig. 3.5] The variance of the WGN process is calculated from Eq. 3.13, by using the variance of the corresponding tap $\sigma^2_{\beta_i}$, speed of user, and wavelength.

Interfering signal

Signals arriving to the RAKE receiver along different paths are not coherent to the reference signal at the finger. As a result the phases of these signals are unknown and can take whatever value between $0 \div 2\pi$. It is known that signal with Rayleigh distributed amplitude and such uniformly distributed phase has complex gaussian distribution. Its projection to I and Q branches is normally distributed with mean zero and standard deviation equal to σ. Subsequently the interference that would be generated on one axis has power density σ^2.

3.4 Distribution of the information signal power after PC

In this section we analyze the power control impact on the received signal distribution. After the verbal description of the PC working environment follows an analytical study of the signal power distribution after PC. The section ends with results from calculation and simulation.

Without PC the received signal distribution would be same as the distribution of the channel taps. The PC attempts to maintain CIR constant. Depending on user speed and resolution of PC this objective is only partially reached and only the distribution of

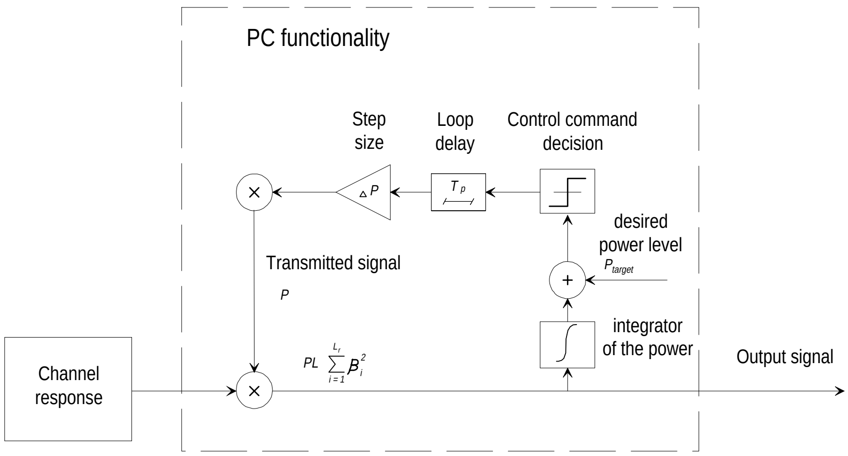

Figure 3.6: Power control loop. Functionality in the dashed box is replaced by the model.

the received signal power is changed. In order to calculate this changed distribution one has to look at the whole PC loop.

In normal conditions the power control loop attempts to smooth out the fast fading. Fast fading in a mobile channel is generated due to the Doppler shift in the channel. The width of the Doppler spectrum specifies also duration of fades, variation speed of the channel [Pro89]. The purpose of the fast power control is to compensate the signal variation by changing the transmission power inversely to the fading in the channel.

A simplified model of PC loop is given on Fig. 3.6. The received signal power averaged over some time period and compared with desired power level. The desired power level is set to satisfy the *target* CIR. Based on the comparison the decision is made to increase or to decrease the transmitted power. The power control command takes effect when the decision arrives at the transmitter. Before the transmitted signal is received it attenuates in the channel.

In feedback channel the PC commands are send only at certain time moments. The interval between this moments introduces delay and determines the speed of the PC, the PC bandwidth.

In feedback channel can be send only finite amount of information and therefore the transmitted power can be changed only by the finite step $\triangle P$.

There are two main reasons why the PC can not compensate the attenuation in the channel: the control loop bandwidth is less than the speed of channel variation, loop delay is high, and the precision of PC step $\triangle P$ does not allow to select appropriate power level.

When the frequency at which the PC commands are generated is less than the variation speed of the channel, the channel changes quicker than the PC is capable to handle and control decisions are based on the random noncorrelated events.

Even when the decision process for PC is capable to estimate attenuation of the channel at the next moment the precision of control does not allow to tune the transmitted power to the optimal value. This does not allow precisely to compensate the attenuation and the received signal can not be kept constant. This can be characterised as insufficient resolution of PC, or in other words to the quantization error of the PC. The situation is comparable to slope overload of differential encoding - the signals amplitude at next moment varies more that the system is capable to react [JN84].

Also the quantization error of the finite steps of PC behaves similarly to differential encoding. For slow users the channel is varying less than the PC step and quantization error is dominant source for the error. For quickly moving users the channel variation is larger that the PC step, the control system becomes "overloaded" and the main error is due to amplitude variation of the channel.

The precise model of the PC should cover both of these cases. Because of the nonlinear nature of PC this, however, is difficult to achieve. Unfortunately, no good analytical treatment of the overload conditions of described systems is known. On the other hand if to recall that we are only interested in the signal distribution at the receiver output, the exact implementation is not so important. We can describe it as optimal level that any PC algorithm can reach. For that we develop a new model of PC based on the correlation of the channel.

3.4.1 Analytical model for signal distribution after PC

We describe the signal level at the receiver output by the optimal level that PC can reach. In order to do that it is sufficient to look only at operations that PC is intended to execute and not on any particular implementations. In this context the PC loop can be treated as black box for which only input and output are given. We do that by replacing the whole power control loop with a model that describes the optimal limits of the output parameters.

Because the PC is not capable to keep the constant signal level at the receiver output its functions can be separated into two procedures: reducing the signal variation and keeping the mean power at the required level.

The optimal power control maintains mean amplitude of the received signal, m_{CIR}, such that the mean power is at required level.

PC is capable to compensate only part of the channel variation. We modeled the channel as filtered WGN process. Filtering introduced correlation that allows to predict the next signal value and compensate it. After removing the correlation in the signal the output will be WGN process. The optimal PC is whitening filter.

From the statistical signal processing it is known that the optimal whitening filter is inverse of the coloring filter, the Doppler filter in our model. Therefore the optimal PC can be modeled as an inverse Doppler filter. Convolution of the filter and its inverse, or multiplication in the frequency domain, results in removal of the impact of the filtering. When the Doppler filter is generated by auto regressive (AR) filter, the inverse filter is linear prediction error filter (Fig. 3.7). The filter coefficients of the prediction error filter are obtained by inverting the AR filter [The92]

Variation $\sigma^2_{w_{out}}$ of the WGN at the PC output will be same as the variation $\sigma^2_{w_{in}}$ of the WGN that generates the channel response. We note it simply σ^2_w for the whole signal and $\sigma^2_{w_i}$ for channel tap i.

We modeled each channel tap as a filtered Gaussian noise. In order to do the correct prediction each channel tap should be predicted separately. In other words the optimal

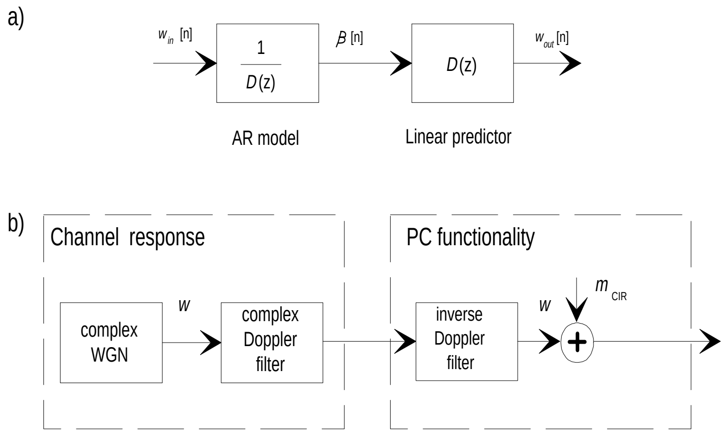

Figure 3.7: a) Linear prediction applied to an autoregressive process, b) channel and the model of PC.

power control should be modeled as set of inverse filters for each channel tap. However, in output of a RAKE receiver signals from these different channel taps are summed inphase. Because of the linearity and inphase summation we can replace this separate filters with one. [Fig. 3.7]. The scaling constant of the attenuation $\sqrt{\mathsf{L}}$ is absent in the figure since it was assumed that the PC is capable to compensate the average attenuation.

We can conclude that the power control can be modeled as a black box that includes the inverse Doppler filter and addition of the required mean value which compensates average attenuation and guarantees the CIR. In order to describe the signal amplitude after PC we have to find the variation of the remaining WGN and the added mean.

We assumed that we know the average signal power at each channel tap. Each tap was modeled with Rayleigh distribution generated by filtering the WGN process. In order to find the variation of the initial WGN process we describe the amplitude at one tap in autoregressive form

$$\beta_i\,[n+1] = \sum_{j=0}^{J} \rho_j^* \beta_i[n-j] + w[n+1]. \tag{3.14}$$

As we described the PC implements the inverse filtering and addition of the required mean value m_{CIR} to the signal. The inverse filtering is essentially subtraction from the signal value the part due to the correlation $\sum_i \rho_i^* \beta[n-i]$. The PC functionality can be described as

$$\beta_i\,[n+1] - \sum_{j=0}^{J} \rho_j^* \beta_i[n-j] + m_{CIR} = w_i[n+1] + m_{CIR_i}. \tag{3.15}$$

The delay of PC loop is considered by selecting the filter coefficients with the same frequency as the PC commands are send in the feedback channel. That means we sample the channel with the PC frequency.

The variation of the WGN was calculated above by Eq. 3.13. We described the received signal with complex Gaussian distribution. At the I and Q branches the signal is normally distributed with mean 0 and standard deviation σ_w.

When PC is modeled as in Fig. 3.7 the signal at the receiver output for each RAKE finger will have nonzero mean Gaussian distribution with variance $\sigma_{w_i}^2$ and mean m_{CIR_i}. The power distribution of such process is known to have noncentral chi-square pdf. and amplitude will have the Rice pdf [Pro89]. In order to fully describe this pdf we need the value of m_{CIR_i}.

For calculating the mean m_{CIR_i} we use the relationships between the nonzero mean Gaussian distribution and chi-square distribution. [Pro89] The mean value at all fingers can be calculated by using the relationships for mean power at one finger

$$E\left\{\beta_i^2\right\} = 2\sigma_{w_i}^2 + s_{\beta_i}^2 = 2\sigma_{w_i}^2 + 2m_{CIR_i}^2. \tag{3.16}$$

$$\sigma_{\beta_i}^2 = 4\sigma_{w_i}^4 + 4\sigma_{w_i}^2 s_{\beta_i}^2 \tag{3.17}$$

Where m_{CIR_i} and σ_{w_i} are mean and standard deviation of the gaussian distribution on one axis. $E\left\{\beta^2\right\}$ and $\sigma_{\beta^2}^2$ are mean and variation of the resulting power distribution (chi-square distribution) on the given finger. $s_{\beta_i}^2$ is called the noncentrality parameter of the distribution.

This relationships should hold for power of one finger and as well for total received power.

$$\sum_i E\left\{\beta_i^2\right\} = \sum_i \left(2\sigma_{w_i}^2 + 2m_{CIR_i}^2\right) = \sum_i 2\sigma_{w_i}^2 + \sum_i s_{\beta_i}^2 = 2\sigma^2 + 2m_{CIR_i}^2 = P \tag{3.18}$$

For one finger we get the average power received at the finger is $E\left\{\beta_i^2\right\} = 2\sigma_{w_i}^2 + 2m_{CIR_i}^2$, and because of the normalization the total received signal is $1 = \sum_i E\left\{\beta_i^2\right\} = 2\sigma_{w_i}^2 + 2m_{CIR_i}^2$ Subsequently we can calculate the deviation on each finger and from there the new mean amplitude for each finger.

The fact that for Rayleigh distributed signal at each channel tap after applying the PC the signal power has chi-square pdf and amplitude has Rice distribution can be interpreted as following. The fading channel contains correlation that allows to predict the next value of the signal amplitude. The coherent receiver adjust to the predicted phase and power control attempts to match the amplitude. In order to obtain the required CIR the amplitude is set accordingly to the attenuation and interference in the channel. By following the phase of the correlation component the receiver generates a specular component. Higher the correlation is stronger the component is. The mean kept by PC can be interpreted as strong sinusoidal component that is introduced to the signal and followed at the receiver.

For calculating the signal distribution after PC we need some input parameters. For calculating the filter coefficients we need the PC frequency, that gives the time moments where the Bessel function is sampled. The amount of filter coefficients is defined by correlation time in the channel, for how long time we calculate the Bessel function values. For calculating the Bessel function values we need the speed of the user and the wavelength. In order to calculate the remaining deviation in the channel is required the amount of channel taps and mean power at each of them.

The algorithm itself contains following steps.

- By using the development in section 3.3.2 normalize the channel and calculate the standard deviation of the complex gaussian signal at each RAKE finger before the PC is applied.
- Accordingly to Eq. 3.13 calculate the variance in the channel after PC is applied. This will be function of the user speed, wavelength, and length of the Doppler filter.
- By using the mean power value at each finger calculate the mean m_{CIR_i} introduced by the optimal PC.
- Accordingly to Eq. 3.17 calculate the deviation in of the signal at the receiver output when PC is applied.

3.4.2 Numerical evaluation of the signal distribution after PC

We compare the optimal PC with simulation results of the relay type PC implementations. Before we go to this comparison we give an numerical example of calculation the signal distribution with optimal PC.

Example of calculation of the distribution parameters

Consider a system with PC frequency 0.00064 s and correlation time in the system $t_{int} = 0.01$. The Doppler filter will have $\frac{0.01}{0.00064} = 15$ samples. We assume the user speed 10 $\frac{m}{s}$ and communication frequency 2 GHz. The normalized mean power at each finger is $E\left\{\beta_i^2\right\}$ =[0.5 0.3 0.2].

Without PC on one axis the variation of the signal amplitude is [0.25 0.15 0.2].

Inserting these values into Eq 3.13 we get for the white gaussian noise after the PC σ_{w_i} =[0.22 0.17 0.14].

Eq. 3.16 provides us with the added mean values for each finger $m_{CIR_i} = \sqrt{\frac{E\{\beta_i^2\}-2\sigma_{w_i}^2}{2}} =$ [0.45 0.35 0.29].

From Eq. 3.17 the standard deviation at each finger will be $\sigma_{\beta_i^2}$ =[0.29 0.17 0.12].

The total added mean is simply sum of the individual added means $m = \sqrt{\sum_i (m_{CIR_i})^2} =$ 0.64. The total remaining variation can be calculated by setting into the 3.17 the total added mean and the total noise variance, that calculated as sum of variances of individual WGN processes. $\sigma_w^2 = \sum_i \sigma_{w_i}^2$. The total variance is $\sigma_{\beta_i^2} = 0.58$.

Comparison of simulation and calculations of the signal distribution after PC

The power control attempts to remove signal variation in the channel. Its performance can be described as variance difference of a PC and non PC systems. As reference system we select the Raylaigh fading signal with average power 1. From this signal we calculate the remaining variance with PC depending on user speed. In other words we generate the Rayleigh fading signal with average power 1, apply to it the PC and compare the remaining variance with initial variance. We compare the optimal PC with the performance of the relay type PC.

Eq. 3.13 shows that the amount of the variation in the channel that can be compensated depends on the correlation time in the channel. We approximate the correlation in the channel with the Bessel function. The Bessel function has domain from zero to infinity and for some parameters it decays very slowly.

In practical calculation we can handle only finite amount of filter taps and therefore the Bessel function should be cut somewhere. In example above we assumed the correlation time to be $t_{int} = 0.01$. With sampling at every 0.00064 s the FIR filter has only 15 taps. Because the variance of the WGN process that can not be predicted is inverse of the sum of filter taps the longer correlation time results smaller variance.

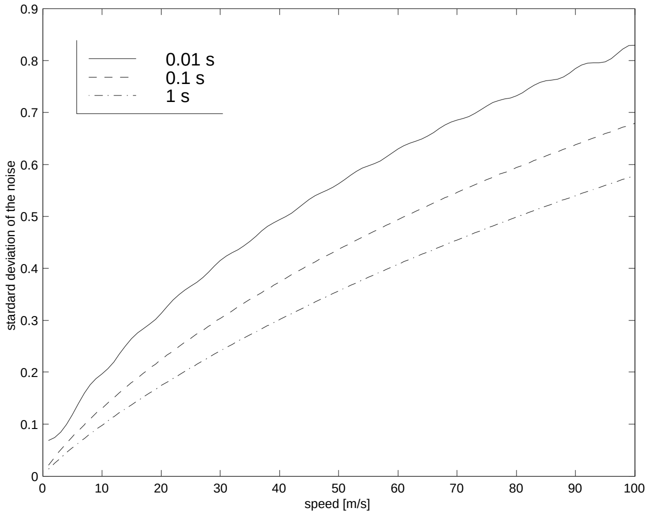

Figure 3.8: Standard deviation of the gaussian noise in linear singal model as function of speed of users. Prediction is made based on different time intervals 0.01 0.1 and 1 second.

On the other hand Bessel function is only approximation of the real correlation function in the channel. The real channel is not stationary and samples far apart in time or space are not correlated as would be predicted by Bessel function. Therefore the long correlation time does not describe the actual situation in the channel. In practical calculations the value for correlation time should be taken based on measurements.

Fig. 3.8 shows the calculated remaining variance after PC for different user speed and correlation time in the channel as parameter. All other parameters were same as in numerical example above.

Unfortunately, the longer correlation time increases complexity of the system. The simplest PC algorithm, relay type algorithm, does not predict the signal value at next moments. Also it does not consider signal history but only the current value. It simply compares the received power in one measurement interval with target threshold and if it is less decides to increase and otherwise to decrease the transmission power. Performance of such an algorithm is dependent on the chosen power step. We evaluate the algorithm for 1, 2, and 3 dB power control steps and compare it with optimal PC (Fig. 3.9).

We simulate the relay type power control by first generating the correlated channel response. The PC that can be described by Fig. 3.6 is applied to this channel response. The received power is compared to the preset target level. If it is less the command is to increase the transmitted power by PC step otherwise to decrease. The transmission power for next moment is generated by multiplying the power at the given moment accordingly to the PC decision. The new input signal is generated by multiplying the transmitted power with the attenuation in channel.

The PC frequency is 0.00064 the same as the time the received signal is averaged over.

The relay policy is highly dependent on PC step (Fig. 3.9). For higher user speed the channel changes quicker that the system is capable to perform and regardless of PC step the results are nearly similar.

When the PC is not capable to follow the changes in the channel PC introduce additional noise that increase the channel variance over the reference value.

PC analysis here considers only variation due to the fast fading. In the longer intervals also the average attenuation is changing and is followed by the PC. This phenomena is disregarded here by the assumption that the network behaves in non overloaded conditions in which case system outage does not occur.

3.5 Interference in CDMA

Eq. 3.2 can directly be used for simulating the receiver. In following we analyze the statistical distribution of the interference with intention to simplify Eq. 3.2. The resulting equation allows us to conclude on the orthogonality factor in downlink and to analyze the soft handover. In order to be used in the network level studies the model contains description of the attenuation in the channel, multipath nature of propagation and number of users.

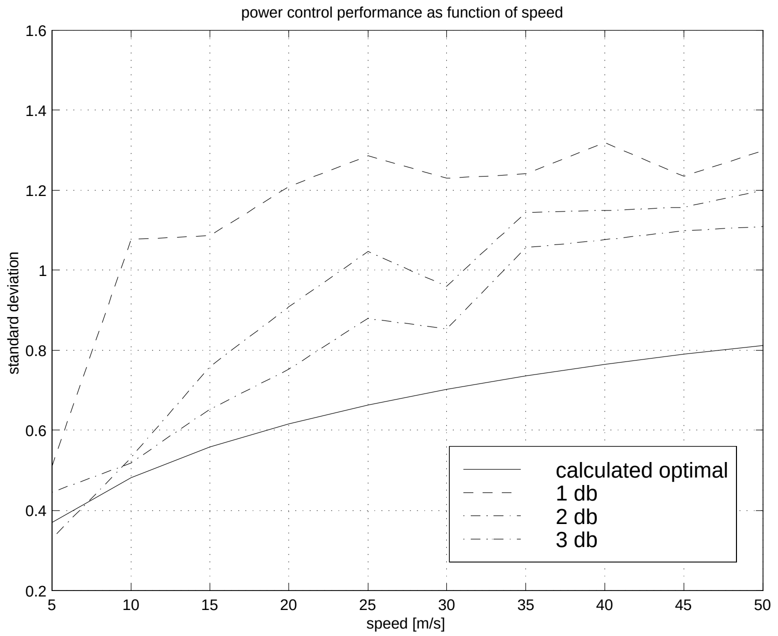

Figure 3.9: Relay based power control. Decision is made based on comparison of the current value with target value. The simulation is made for 1, 2, 3 db PC step. The result is compared with theoretical optimal result calculated for 0.1 s correlation interval.

The analysis made her can be used in various ways. In studies in the first chapter we used a simple system model. The more precise equation, that is evaluated in this section, allows to check the correctness of this simple model. Also, we are capable to look how different factors in physical layer affect the system capacity. Finally the simplified Eq. 3.2 is used in simulation of CIR dependency on speed in next section.

The received signal in Gaussian channel is traditionally described by the first two moments of its distributions. For the constant signal amplitude and zero mean gaussian noise the signal power is equal to the square of the mean of the received signal and the noise power is equal to the variance of the signal i.e. we get directly CIR [Pro89]. In fading channel the signal amplitude can take different values described by probability distribution of the amplitude. The CIR is described as conditional probability, conditioned with amplitude. The analysis where such conditional probability is used assume that noise and interference are not correlated with the information signal. In CDMA the interference depends on channel response and therefore it is correlated with informational signal. We calculate the mean and variation of the received signal and interference by accounting this correlation.

The orthogonality of the spreading codes guarantees that the interfering signals with the same phase as reference signal at the finger are cancelled. Therefore in CDMA the interference is produced only by signals with different channel delay. In other words because of the multipath nature of the channel orthogonality between delayed copies of the spread signals is not preserved and cross correlation gives not zero but an interference component. The signals arriving from other transmitters, other BS in downlink or other users in uplink, have nearly always different code phase than the information signal and can be assumed to be nonsynchronous - generate the interference.

3.5.1 Interference in downlink

The CDMA downlink is characterized by the fact that signals from the same BS propagate along the identical path. In that environment distribution of the received signal can be calculated by first estimating the distribution of the transmitted signals at BS and then scaling it with the distribution of the channel response and attenuation.

Interference at the receiver is transmitted signal to the other users. By considering that we can calculated the distribution of the total signal transmitted to the other users and that gives directly distribution of the interference. As we mentioned this can be made by first calculating the distribution of the amplitude of the signals transmitted to other users at BS and scaling it with the attenuation in the channel.

We approximate distribution of the sum of transmitted signals to other users at BS with normal distribution. Parameters for that distribution can be calculated by noting that in binary channels an information signal is stream of equally probable plus minus ones. Summation of such streams to all the users, K, gives a symbol with binomially distributed amplitude. Due to the distance differences the amplitude of the binary streams are scaled with corresponding transmission powers. For many users sum of such signals can be approximated by normal distribution. Contrary to the exact binomial distribution, that for constant number of users K takes values between $\pm K$, normal distribution can have any real value and therefore this approximation only underestimates the quality of the channel. The variance of the interference calculated accordingly to these rules is

$$P_{I_n} = \sum_{k_n=1}^{K_n} P_{k_n}. \tag{3.19}$$

Normally distributed signal at BS transmitter is scaled with channel response. The channel impact can be thought as creation of multiple copies of the signal. Because the signal propagates along multiple paths at the receiver we will have multiple copies of the signal, arriving at different time moment and having amplitude scaled with the amplitude of the corresponding path. Above we described the channel amplitude as $\sqrt{\mathsf{L}}\beta$. Accordingly the interference amplitude along one path i from the BS n can be calculated as $\sqrt{P_{I_n}\mathsf{L}_n}\beta_{i_n}$.

As we mentioned the signals arriving from the same BS at the same moment have same phase and ideally produce no interference. Interference in downlink is created by copies arriving along different paths and signals from other BS. The interfering signal distribution at BS is scaled with channel response $\sqrt{\mathsf{L}}\beta$ and correlation component that we noted as C.

Now we have all the pieces for evaluating an analytical form of mean and standard deviation of the received signal. The square of the mean gives us the received signal power and variance is related to the power of interference.

By averaging Eq. 3.2 we get for the mean

$$E\{U\} = E\left\{\sum_{i=1}^{L_r}\beta_i\left(S^i + I^i_{mai,0} + I^i_{mai,n} + I^i_{si} + I^i_{ni}\right)\right\} = E\left\{\sum_{i=1}^{L_r}\beta_i S^i\right\}. \tag{3.20}$$

The interference components there have mean 0. The interference is not synchronised to the reference signal at the receiver. Above the channel for such signal was described by the complex Gaussian noise with zero mean and constant mean attenuation L_n from BS n. The interference at BS has also zero mean normal distribution, $N\left(0, P_{I_n}\right)$. The product of two distributions with zero mean has also zero mean.

The mean of U will be only the mean of the information signal from each finger i weighted with the amplitude of the corresponding finger β_i.

$$E\left\{\sqrt{P_s\mathsf{L}_1}\sum_{i=1}^{L_r}\beta_i\beta_i\right\} \tag{3.21}$$

The second moment of U is

$$E\left\{U^2\right\} = E\left\{\left(\sum_{i=1}^{L_r}\beta_i\left(S^i + I^i_{mai,0} + I^i_{mai,n} + I^i_{si} + I^i_{ni}\right)\right)^2\right\} \tag{3.22}$$

$$= E\left\{\left(\sum_{i=1}^{L_r}\beta_i\left(S^i + \sum_{l=1,l\neq i}^{L_r}\left(I^l_{si} + I^l_{mai,1}\right) + \sum_{l=1}^{L_r}\left\{\left(\sum_{n=1}^{N} I^l_{mai,n}\right) + I^i_{ni}\right\}\right)\right)^2\right\}$$

At this point we can apply the assumption of statistical independence among the terms in Eq. 3.22. This can be justified because different interfering components arrive along different channels and different channels can be assumed to be uncorrelated. When user moves the phase and amplitude of the channel change. For different paths these changes are different, and that destroys the correlation among the paths.

$$E\left\{U^2\right\} = E\left\{\left(\sum_{i=1}^{L_r}\beta_i S^i\right)^2\right\} + E\left\{\left(\sum_{i=1}^{L_r}\beta_i\left(\sum_{l=1,l\neq i}^{L_r}\left(I_{si}^l + I_{mai,0}^l\right) + \sum_{l=1}^{L_r}\left\{\left(\sum_{n=1}^{N} I_{mai,n}^l\right) + I_{ni}^i\right\}\right)\right.\right. \tag{3.23}$$

The second moment contains two components: part due to the interference and due to the information signal. In the analysis below we look at the interference. Because the interference has zero mean its second moment is equal to the variance and the variance is equal to the interference power. The orthogonality assumption of different paths for each finger allows us to calculate it as a sum of variances of individual fingers. In other words the interference generated to different RAKE fingers have independent phases.

$$\begin{aligned}\sum_{i=1}^{L_r}\sigma_i^2 &= \sum_{i=1}^{L_r} E\left\{\left(\beta_i\left\{\sum_{l=1,l\neq i}^{L_r}\left(I_{si}^l + I_{mai,0}^l\right) + \sum_{l=1}^{L_r}\left\{\left(\sum_{n=1}^{N} I_{mai,n}^l\right) + I_{nl}^l\right\}\right\}\right)^2\right\} \\ &\leq \sum_{i=1}^{L_r} E\{\beta_i^2\}\left(\sum_{l=1,l\neq i}^{L_r} E\left\{\left(I_{si}^l + I_{mai,0}^l\right)^2\right\} + \sum_{n=1}^{N}\sum_{l=1}^{L_r} E\left\{\left(I_{mai,n}^l\right)^2\right\} + \sum_{l=1}^{L_r} E\left\{\left(I_{ni}^l\right)^2\right\}\right)\end{aligned} \tag{3.24}$$

Where we use the Swartz inequality and the fact that average of sum of uncorrelated variables is equal to sum of averages of these variables.

The total variance of the interference, σ_i^2, is weighted sum of interference from different fingers. At every finger we can separate intracell, intercell interference and noise. The orthogonality assumption of different paths allows us to calculate the total interference power as a sum of variances of individual components.

At one RAKE finger intercell interference is a power from the host BS received from other paths than the path where the finger is synchronised, $l \neq i$.

$$E\left\{\left(I^l_{si} + I^l_{mai,1}\right)^2\right\} \leq C\mathsf{L}_1 \left(\sum_{k_1=1}^{K_1} P_{k_1}\right)\left(\sum_{l=1,l\neq i}^{L_r} E\{\left(\beta^l_1\right)^2\}\right) \tag{3.25}$$

The phase of the path l is not synchronized with the signal. After normalization the power from path l is σ_l^2. Because the paths are normalised by separating the mean L and varying component so that $\sum\limits_{l=1}^{L_r} E\{\left(\beta^l_n\right)^2\} = 1$, one can write

$$\sum_{l=1,l\neq i}^{L_r} E\{\left(\beta^l_1\right)^2\} = \sum_{l=1,l\neq i}^{L_r} \sigma_l^2 = \left(1 - \sigma_i^2\right) = \left(1 - E\{\left(\beta^i_1\right)^2\}\right). \tag{3.26}$$

The signals from other BS are not synchronized with the information signal, all the paths between neighboring BS and receiver contribute to interference. Therefore one has to sum over all the paths l form the other BS.

$$E\left\{\left(I^j_{mai,n}\right)^2\right\} \leq \sum_{n=2}^{N}\left(C\mathsf{L}_n \left(\sum_{k_n=1}^{K_n} P_{k_n}\right)\left(\sum_{l=1}^{L_r} E\{\left(\beta^l_n\right)^2\}\right)\right) \tag{3.27}$$

Again we can use the fact that the power at each finger was normalised to 1, allowing to simplify the above.

$$E\left\{\left(I^j_{mai,n}\right)^2\right\} \leq \sum_{n=2}^{N}\left(C\mathsf{L}_n \sum_{k_n=1}^{K_n} P_{k_n}\right) \tag{3.28}$$

Finally the $E\left\{\left(I^i_{ni}\right)^2\right\}$ stands for average noise power η.

The interference at one finger is sum of these components.

$$\sigma_i^2 = C\left(\mathsf{L}_1\left(1 - E\{\left(\beta_1^i\right)^2\}\right)\sum_{k_1=1}^{K_1} P_{k_1} + \sum_{n=1}^{N}\left(\mathsf{L}_n \sum_{k_n=1}^{K_n} P_{k_n}\right)\right) + \eta \tag{3.29}$$

From this the total interference after maximal ratio combining will be

$$\sigma^2 = \sum_{i}^{L_r} E\{\left(\beta_1^i\right)^2\}\left(C\left(\mathsf{L}_1\left(1 - E\{\left(\beta_1^i\right)^2\}\right)\sum_{k_1=1}^{K_1} P_{k_1} + \sum_{n=2}^{N}\left(\mathsf{L}_n \sum_{k_n=1}^{K_n} P_{k_n}\right)\right) + \eta\right) \tag{3.30}$$

This can be regrouped by noting that the interference from host BS contains similar component as in the interference from other BS:

$$\begin{aligned} \sum_{i}^{L_r} E\{\left(\beta_1^i\right)^2\}\left(C\left(\sum_{n=1}^{N}\left(\mathsf{L}_n \sum_{k_n=1}^{K_n} P_{k_n}\right) - E\{\left(\beta_1^i\right)^2\}\mathsf{L}_1 \sum_{k_1=1}^{K_1} P_{k_1}\right) + \eta\right) &= \\ \left(C\sum_{n=2}^{N}\left(\mathsf{L}_n \sum_{k_n=1}^{K_n} P_{k_n}\right) + \eta\right)\left(\sum_{i}^{L_r} E\{\left(\beta_1^i\right)^2\}\right) & \\ -C\mathsf{L}_1 \sum_{k_1=1}^{K_1} P_{k_1} \sum_{i}^{L_r} E\{\left(\beta_1^i\right)^2\}\left(1 - E\{\left(\beta_1^i\right)^2\}\right) & \end{aligned} \tag{3.31}$$

Normalisation of average powers allows us to simplify the expression further

$$\sigma^2 = \left(C\sum_{n=1}^{N}\left(\mathsf{L}_n \sum_{k_n=1}^{K_n} P_{k_n}\right) + \eta\right) - C\mathsf{L}_1 \sum_{k_1=1}^{K_1} P_{k_1} \sum_{i}^{L_r}\left(E\{\left(\beta_1^i\right)^2\}\right)^2. \tag{3.32}$$

Now we have all the parameters to describe the channel quality by CIR.

$$\begin{aligned}
&\frac{P_s \mathsf{L}_1 E\{\sum\limits_{i=1}^{L_r} \left(\beta_1^i\right)^2\}^2}{\sum_i^{L_r} E\{\left(\beta_1^i\right)^2\} \left(C \left(\sum\limits_{n=1}^{N} \left(\mathsf{L}_n \sum\limits_{k_n=1}^{K_n} P_{k_n} \right) - E\{\left(\beta_1^i\right)^2\} \mathsf{L}_1 \sum\limits_{k_1=1}^{K_n} P_{k_1} \right) + \eta \right)} \\
&\leq \frac{P_s \mathsf{L}_1 \left(\sum\limits_{i=1}^{L_r} E\{\left(\beta_1^i\right)^2\} \right)^2}{\sum\limits_{i}^{L_r} E\{\left(\beta_1^i\right)^2\} \left(C \left(\sum\limits_{n=1}^{N} \left(\mathsf{L}_n \sum\limits_{k_n=1}^{K_n - 1} P_{k_n} \right) - E\{\left(\beta_1^i\right)^2\} \mathsf{L}_1 \sum\limits_{k_1=1}^{K_1} P_{k_1} \right) + \eta \right)} \\
&\leq \frac{P_s L_1}{C \left(\sum\limits_{n=1}^{N} \left(\mathsf{L}_n \sum\limits_{k_n=1}^{K_n} P_{k_n} \right) - \mathsf{L}_1 \sum\limits_{k_1=1}^{K_1} P_{k_1} \sum\limits_{i}^{L_r} \left(E\{\left(\beta_1^i\right)^2\} \right)^2 \right) + \eta}
\end{aligned} \tag{3.33}$$

The analysis in this section provide us with the equation describing the interference (Eq. 3.32) and CIR 3.33.

The Eq. 3.32 allows to calculate the interference when the cross correlation function C, attenuation from each BS L_n, number of users in each cell, K_n, and average channel response are known. The main difference between Eq. 3.33 and the simple model used in previous chapter is the fact that CIR depends on channel response. From the total interfering power transmitted from the host BS a factor $E\{\left(\beta_1^i\right)^2\}\mathsf{L}_1 \sum\limits_{k_1=1}^{K_n} P_{k_1}$ is subtracted. That factor is due to the nonorthogonality of the signals arriving along different paths and is called orthogonality factor

The interference from other BS is well described by the mean attenuation and total power transmitted from BS. If C is equal to coding gain in Eq. 2.1 and Eq.3.33 the interference from other BS will be same.

By C we note the cross correlation function, as it was described above it depends on the spreading code used in the system. Eq. 3.33 is fit to the particular system by selecting the value for C. Such tailoring is not possible when the simple Eq. 2.1 is used.

Orthogonality factor in downlink As we see the orthogonality factor is function of channel response. Because the network capacity depends on CIR that means the channel response at each location should be included into capacity estimation. In this section we analyze how the orthogonality factor affects the total interference depending on user location in the cell.

Analytical description of the orhogonality factor in Eq. 3.32 shows that its impact depends on the channel response and interference from other BS.

The orthogonality factor was introduces as the rate the intercell interference in downlink is reduced due to code orthogonality. [Hea97]. The factor is defined as amount of the interference decreased compared with the total power that arrives to the receiver from other users $1-\alpha$.

In [Hea97] the value for the orthogonality factor is suggested to be around 0.4-0.6. This result is achieved from simulations. The transmitted power for the user with only noise in the system is compared with the transmitted power when also other users are considered.

By having Eq. 3.32 we are well positioned to calculate the value for orthogonality factor.

For the interference from the host BS we can write

$$1-\alpha = E\{\left(\beta_1^i\right)^2\}\left(1-\sum_i^{L_r} E\{\left(\beta_1^i\right)^2\}\right) = \left(1-\sum_i^{L_r}\left(E\{\left(\beta_1^i\right)^2\}\right)^2\right). \tag{3.34}$$

From there can be concluded that the orthogonality parameter is $\alpha = \sum_i^{L_r}\left(E\{\left(\beta_1^i\right)^2\}\right)^2$.

It also shows that the orhogonality in downlink is not constant but function of channel response. The impact of a channel distribution on the interference can be illustrated by analysing signal at the RAKE.

Other users signals generate interference only when they are not orthogonal to the reference signal. Signals from the path where the finger is synchronised are orthogonal and can be assumed to contribute no interference. The interference generated by the copies of the signals arriving along the paths that are out of the selection area of the RAKE finger.

For example when the channel response has average normalised power $E\{\beta_i^2\} = [0.5$ $0.3\ 0.2]$ the interference at the first finger is equal to the power received from the other paths [0.3+0.2]. Similar calculation should be made for each finger resulting for second finger [0.5 + 0.2] and for third [0.5 + 0.3]. In case of maximal ratio combining when the signals are weighted with the amplitude at given path and summed after that one will get the resulting total interference as $(0.5(0.3{+}0.2){+}0.3(0.5{+}0.2){+}0.2(0.5{+}0.3)) = 0.62$. In this way in downlink the intercell interference is dependent on total energy arriving along different paths.

Similar calculation can be done also by using Eq. 3.34. For given channel response the orthogonality parameter is $\alpha = 0.5^2 + 0.3^2 + 0.2^2 = 0.38$. The intracell interference from this is $(1 - \alpha) = 0.62$.

The interference reduction is due to orthogonality of signals from the same BS propagating along the same path. Because $\sum_{i}^{L_r-1} E\{\left(\beta^i\right)^2\} = 1$, α is always less than 1 and one has always some gain due to orthogonality of the synchronized signals in downlink.

It can be seen that α is minimum when all the powers arriving along different paths are equal. Interference from the same cell will be 0 when there is only one path. When the power along all multipaths are equal and the number of multipaths increase α decreases.

The benefit due to the orthogonality factor depends also on the interference from other BS. Transmitted interfering power from each BS is summed together after weighting with average attenuation from given BS L_n. Near to the host BS, where the signal from the host BS has attenuated little, the intercell interference is relatively small. The intracell interference is dominant type of interference and because it is affected by the orthogonality factor we get quite significant gain from orthogonality. Near to the cell border the average attenuation L_n from neighboring BS is in the same order as attenuation from the host BS. The relative amount of the intercell interference from total interference decreases. The orthogonality factor impacts the smaller amount of total interference. This can be understood as sum of two components where one component is scaled. $(1 - \alpha)\, I_{mai,1} + I_{mai,n}$ and the sum is kept constant. The increase of $I_{mai,n}$ reduces the impact of $I_{mai,1}$ and due to that also the impact of scaling the later is reduced, we get less gain from orthogonality.

One can conclude that the gain due to the orthogonality depends on the channel response, the length and power distribution in it, and location of the user in the cell.

3.5.2 Interference in uplink

The received signal in uplink can also be described by simplifying Eq. 3.2 and calculating the mean and variance of the received signal U. Uplink, however, has different environment and not all the simplifications made for downlink can be used there. In uplink the signals are emitted from different locations and received by the same receiver. In such environment signals from different users are generally not synchronized and we can not assume them to be ideally orthogonal as we could do in case of downlink. The signals from different sources can be assumed statistically independent and that allows us to treat them separately.

Above was approximated the interference generated by one other users by the complex Gaussian distribution. The mean of this distribution is zero and variance equal to the attenuation L and cross correlation component C multiplied with the variance of the normalised channel response.

Because the interference terms have zero mean the averaging Eq. 3.2 gives for the mean of the received signal to be sum of the means of the information signal at each finger. In other words the information signal amplitude gathered from each RAKE finger gives the mean of the received signal

$$E\left\{\sqrt{P_s\mathsf{L}_1}\sum_{i=1}^{L_r}\beta_i\beta_i\right\} = \sqrt{P_{1_1}\mathsf{L}_{1_1}}\sum_{i=1}^{L_r}E\left\{\left(\beta^i_{1_1}\right)^2\right\} = \sqrt{P_{1_1}\mathsf{L}_{1_1}}. \tag{3.35}$$

Again we used the normalisation of the power at each finger $\sum_{i=1}^{L_r}E\left\{\left(\beta^i_{1_1}\right)^2\right\} = 1$

Similarly to the downlink the interference power is equal to the sum of powers of individual interferences. Statistical independence of interference sources allows to study them separately.

The variance of U in Eq. 3.2 contains the variance of the information signal and interference. We look only at the interference. Because the interference has zero mean the second moment and variance are the same

$$\sigma^2 = E\{\left(\sum_i \beta^i_{1_1}\left(I^i_{si} + I^i_{mai,1} + I^i_{mai,n} + I^i_{ni}\right)\right)^2\}. \tag{3.36}$$

The statistical independency between different terms allows to write it as:

$$\sigma^2 \leq \sum_i E\{\left(\beta^i_{1_1}\right)^2\}\left(E\{\left(I^i_{si}\right)^2\} + E\{\left(I^i_{mai,1}\right)^2\} + E\{\left(I^i_{mai,n}\right)^2\} + E\{\left(I^i_{ni}\right)^2\}\right). \tag{3.37}$$

I_{si} is interference generated by the signal copies arriving not by the path where the finger is synchronised,

$$E\{\left(I^i_{si}\right)^2\} = \sum_{l=1, l\neq i}^{L_1} CP_{1_1}\mathsf{L}_{1_1}E\{\left(\beta^l_{1_1}\right)^2\}. \tag{3.38}$$

The normalization of the sum of average powers from different paths to 1. The interference due other copies of the information signal can be written as $\sum\limits_{l=1,l\neq i}^{L_1} E\{\left(\beta^l_{1_1}\right)^2\} = 1 - E\{\left(\beta^i_{1_1}\right)^2\}$ and that simplifies the equation into form

$$E\{\left(I^i_{si}\right)^2\} = CP_{1_1}L_{1_1}\left(1 - E\{\left(\beta^i_{1_1}\right)^2\}\right). \tag{3.39}$$

$I_{mai,1}$ is intercell interference generated by other users. Because the user signals are not synchronized the orthogonality assumptions can not applied and the interference is proportional to the energy of the signals of all the other users.

$$\begin{aligned} E\{(I_{mai,1})^2\} &= \sum_{k_1=2}^{K_1}\sum_{l=1}^{L_{k_1}} CP_{k_1}\mathsf{L}_{k_1}E\{\left(\beta^l_{k_1}\right)^2\} = \\ &= \sum_{k_1=2}^{K_1} CP_{k_1}\mathsf{L}_{k_1}\sum_{l=1}^{L_1} E\{\left(\beta^l_{k_1}\right)^2\} = \sum_{k_1=2}^{K_1} CP_{k_1}\mathsf{L}_{k_1}. \end{aligned} \tag{3.40}$$

$I_{mai,n}$ is interference generated by the users from all neighboring cells

$$E\{(I_{mai,n})^2\} = \sum_{n=2}^{N}\sum_{k_n=1}^{K_1}\sum_{l=1}^{L_{k_n}} CP_{k_n}\mathsf{L}_{k_n}E\{\left(\beta^j_{k_n}\right)^2\} = \sum_{n=2}^{N}\sum_{k_n=1}^{K_n} CP_{k_n}\mathsf{L}_{k_n}. \tag{3.41}$$

There L_{k_n} normalises the path for user n in cell k, and therefore the sum $\sum_{l=1}^{L_{k_n}} E\{\left(\beta^j_{k_n}\right)^2\} = 1$

I_{ni} is interference due to the noise with power spectral density η.

$$\begin{gathered} \sum_{i=1}^{L_1} E\{\left(\beta^i_{1_1}\right)^2\}\left(C\left(P_{1_1}\mathsf{L}_{1_1}\left(1 - E\{\left(\beta^i_{1_1}\right)^2\}\right) + \sum_{k_1=2}^{K_1} P_{k_1}\mathsf{L}_{k_1} + \sum_{n=2}^{N}\sum_{k_n=1}^{K_1} P_{k_n}\mathsf{L}_{k_n}\right) + \eta\right) \\ \sum_{i=1}^{L_1} E\{\left(\beta^i_{1_1}\right)^2\}\left(C\left(\sum_{k_1=1}^{K_1} P_{k_1}\mathsf{L}_{k_1} - P_{1_1}\mathsf{L}_{1_1}E\{\left(\beta^i_{1_1}\right)^2\} + \sum_{n=2}^{N}\sum_{k_n=1}^{K_1} P_{k_n}\mathsf{L}_{k_n}\right) + \eta\right) \\ \sum_{i=1}^{L_1} E\{\left(\beta^i_{1_1}\right)^2\}\left(C\left(\sum_{n=1}^{N}\sum_{k_n=1}^{K_1} P_{k_n}\mathsf{L}_{k_n} - P_{1_1}\mathsf{L}_{1_1}E\{\left(\beta^i_{1_1}\right)^2\}\right) + \eta\right) \end{gathered} \tag{3.42}$$

And because of the normalization of the channel response we can write:

$$\left(C\left(\sum_{n=1}^{N}\sum_{k_n=1}^{K_1} P_{k_n}\mathsf{L}_{k_n} - P_{1_1}\mathsf{L}_{1_1}\left(E\{\left(\beta^i_{1_1}\right)^2\}\right)^2\right) + \eta\right) \tag{3.43}$$

By combining the Eq. 3.35 and Eq. 3.43 for CIR can be written

$$\frac{P_{1_1}\mathsf{L}_{1_1}}{\left(C\left(\sum_{n=1}^{N}\sum_{k_n=1}^{K_1}P_{k_n}\mathsf{L}_{k_n}-P_{1_1}\mathsf{L}_{1_1}\left(E\{(\beta^i_{1_1})^2\}\right)^2\right)+\eta\right)} \tag{3.44}$$

Compared to the downlink we have the orthogonality component only for information signal but not for the other users in the cell. The more precise case points out the fact that due to multipath the signal generates interference to itself.

3.6 Study of the target CIR with the outer loop PC

It is reasonable to assume that all the users with the same service have same service quality. In the studies in Chapter 2 we guaranteed that by setting the *target* CIR equal for all the users. The equal CIR_t means that the average signal powers are equal. In this Chapter we show that the signal distribution at the receiver depends on user speed. From the theory is known [Pro89] that for different channel response the BER is different. However, the coding gain is higher for the worse channel. Unfortunately coding is not capable to equalise the BER for different type of channels. Therefore for keeping the service quality same for all the users the *target* CIR has to be changed. Higher CIR_t means higher power and more interference and because of that also decrease of the capacity. In order to study this decrease at the network level we need the function of *target* CIR dependency on user speed. That is analyzed in this section.

The investigation of BER or FER contains also coding and makes the analytical treatment very difficult. We overcome this problem by simulating the system. We do the study only for downlink by combining the Eq. 3.32 and method for calculating the signal distribution after the PC.

Simulation is carried out in two stages: first we found the average power to each user to satisfy the initial interference and then we find the *target* CIR for one user depending on the user speed.

The first stage is similar to the simulation made in the Chapter 2. We set initially the same *target CIR* to all the users, locate the users and solve the required transmission power for each user. The transmission power defines the background interference density that during the simulation is assumed to be stationary.

In the second stage we calculate CIR level for one user for given interference floor. For that we generate a random bit stream, code it, scale it with channel response and add to it random noise that is calculated accordingly to the interference density.

Distribution of the channel response depends on the user speed and is calculated accordingly to the algorithm in Section 3.4.

After decoding the bit stream we compare the error rate with the target error rate. If it not satisfying our requirement we increase the *target CIR* value for the user we are looking at and return to the first state to calculate new transmission power for all the users. For new iteration locations of the users are not changed.

The *target CIR* is increased until the error rate for the user we are looking at is less than target error rate.

More precise description of the algorithm with flowchart and source code is given in Appendix. C.

The simulation we use the algorithm for capacity calculation with simple channel model. Most of the parameters are same. Now, however, we have introduced the orthogonality factor $\alpha = 0.4$, and fixed the number of users $K = 60$. The signal distribution after channel is calculated accordingly to algorithm in Section 3.4. For the coding we use a 1/3 rate convolutional code with constrain length 6. The generation polynome is [52 66 76].

The *target CIR* as function of user speed is plot on figure 3.10. As was expected the higher speed requires higher *target CIR* ratio. However, the difference is only in order of 1 - 2 dB. More efficient code would reduce this difference even more.

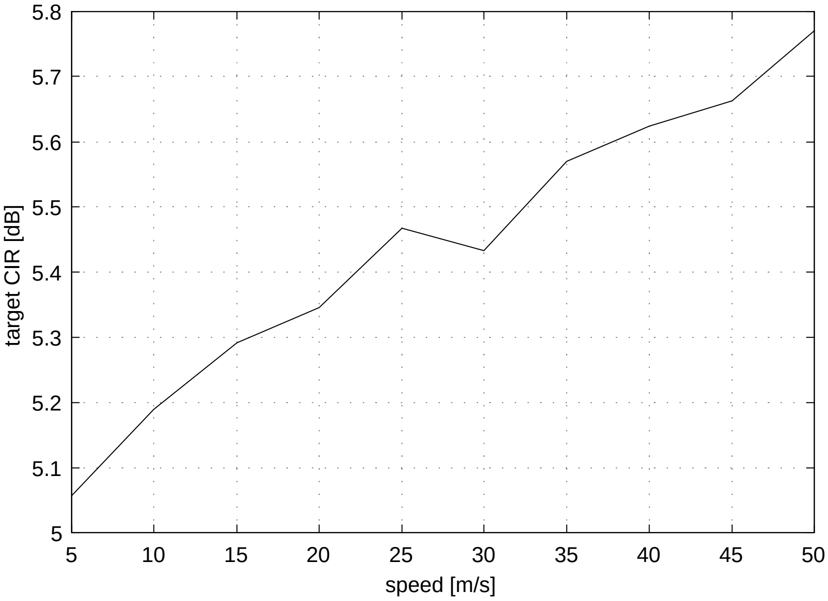

Figure 3.10: Required *target CIR* versus the user speed.

3.7 Chapter summary

The intention of this chapter is to study the link level impact on the system capacity. We validate the simple system model used in previous chapter and provide to the network level the link level parameters that affect the system capacity.

By using information on receiver and channel we derive equations for CIR in down and uplink. The equations are quite similar to the simple equation used in Chapter 2. The interference from other BS is proportional to the attenuation and transmitted power for each user. As a difference the interference is scaled with the cross correlation function that depends on the spreading code not on the coding gain as was assumed in the simple equation. For some spreading codes the cross correlation may be equal to the coding gain but in general that is not the case.

In downlink the interference from the host cell is decreased due to the orthogonality of synchronised spreading codes. The interference is generated only by the signals arriving along other paths than the one where the RAKE finger is synchronised. The decrease of interference depends on channel response. It is interesting to note that also copies of the information signal arriving along different paths generate interference to the synchronised copy of the signal at the RAKE finger.

Similarly as in downlink also in uplink the information signal generates interference to itself. In uplink, however, the receiver does not have gain due to orthogonality of spreading codes.

The interference analysis and model for signal distribution after PC allows us to investigate the impact of the user speed on the *target* CIR. As simulations show for the chosen coding the difference in speed from 0-50 $\frac{m}{s}$, corresponds in difference of *target* CIR in order of 2 dB.

The equations for CIR can directly be used in network planning. These equations include some additional parameters that impact the system capacity.

The requirements posed by link level for the capacity calculation can be summed as follows. For every particular system one has to calculate the average correlation of the spreading codes. Because in some case the correlation is same as coding gain in our test cases we can still use the latter one. The intercell interference depends on power spread in channel this fact should be considered also in network planning. Finally the different speed of the users, different *target* CIR, impact the interference level and capacity of the system. This impact should be considered in some reasonable way.

Chapter 4

Capacity estimation for CDMA network planning

This chapter surveys the capacity calculation for the network planning. The chapter can be separated into two parts: development of an algorithm and testing the algorithm. The capacity calculation algorithm [Section 4.3] is derived by simplifying the exact analytical model developed in Section 4.2.

The purpose of numerical studies is twofold: first to test the suitability of the algorithm and secondly to investigate the capacity changes as function of different variables. The simulations are made for different user distributions [Section 4.4] and for different data rates [Section 4.5].

The chapter ends with a discussion on the impact of the obtained results on CDMA network planning.

4.1 Introduction

In planning process we do not only estimate the channel capacity but also look how many users can be served with given capacity, what is the system capacity. Because users arrival and service time are statistical processes the number of users that can be served is described by probability. In that context the system capacity is described as amount of load that for given channel capacity guarantees the required quality level. For example for voice users we calculate the load in Erlangs that with given channel capacity ensure that blocking probability is under the required level.

The purpose of network planning is to provide enough resources to satisfy demand. The spatial and temporal distribution of demand is defined by users, we can not change it. What we can do is to provide more resources: reduce the load per BS by decreasing service area of BS, adding more BS, or to add more channels to BS. All of this methods assume that exact spatial distribution of demand is known and we can allocate resources accordingly to it.

The capacity of a radio network can be blocking limited or interference limited. The main difference between this two system is the reason for rejecting the users. In an blocking limited system the users are rejected because of lack of available channels, in an interference limited system because of too high interference level.

In blocking limited systems the amount of channels is set during the planning process based on estimation of average interference. After the amount of channels is set the impact of the interference on the capacity is assumed to be negligible and is ignored in capacity calculations. The amount of available channels in an interference limited system is an variable, as long as the CIR requirements are satisfied new users can always be accepted into the network. In that way the number of available channels in the system changes together with the change of interference level in the system

The FDMA and TDMA based networks are traditional blocking limited systems. With introduction of the dynamic channel allocation and frequency hopping TDMA is evolving towards interference limited system.

The planning process of a blocking limited system is modular. After allocating channels to each BS the available capacity of the BS is known and can be used in calculations of the traffic parameters like blocking or delay. The approach separates effectively, estimation of the available transmission capacity and multiplexing users into it. Consequently the planning process can be split into different levels. Each of these levels can be studied separately.

In interference limited systems the capacity varies and for accurate planning the interference and the amount of users in the system should be studied together. In other words estimation of the channel capacity and multiplexing users into it can not be studied independently. The channel capacity and multiplexing users into it can be uncoupled. [Section 4.2] However, for exact calculation the channel capacity should still be calculated for particular distribution and data rates of users. That can be avoided if for the system would exist one channel capacity value describing all configurations. Although not correct the reduction of complexity achieved by calculating a general capacity for all configurations makes it extremely attractive. We propose a methods that allows to calculate such capacity for a CDMA system [Section 4.3]. We test the accuracy of the proposed method by evaluating the capacity for different network configurations. We scrutinize a few test cases: the nonuniformity of users and BS locations in the service area, and different data rates for multiservice.

In real networks the network planner has to deal many different king of load distributions. The nonuniform cases were chosen to test the flexibility of the algorithms in more demanding environment, than uniform distribution of users and BS locations can provide.

The choice of different data rates is motivated by the increasing interest towards integrated service networks. As was indicated in the first chapter users with the high data generate higher interference compared to the users with usual low rate voice connection. Such high interference emitted from one location disturb the uniformity of the demand in the cell. As can be assumed it affects the instantaneous capacity in the system. For planning purposes we investigate how it affects the average capacity.

The intention for testing different cases is not to find the exact capacity of some particular configuration but to check how well the calculations approximate the different cases and how suitable such calculation is for planning a CDMA network.

4.2 Capacity estimation for network planning

In this section we give an analytical description of a method for calculating the system capacity. The method is based on the separation of the estimation of the channel capacity and multiplexing users into it. As an example the method is tailored for calculating Erlang capacity of CDMA. The Erlang capacity is calculated also numerically as function of load and voice activity.

4.2.1 Method for calculation the system capacity of a CDMA system

The system capacity is defined as maximum load that can be applied to the system such that the QoS requirements are not violated. The QoS values are functions of stochastic variables like for example: arrival and service rate of users and available channel capacity. Because of the random nature of these variables the QoS parameters are usually calculated as average values.

In this section we look only at one QoS parameter: blocking probability. The system capacity is defined as maximal load that satisfies the blocking probability requirement.

The blocking probability is calculated as function of two random variables: number of available channels and amount of users in the system. In systems with predetermined channel capacity, like FDMA and TDMA, one of this variables is constant - the number of available channels is known. In such conditions the resulting blocking probability can be calculated directly from the distribution of other variable: amount of active users.

The number of users m in the system is usually visualized as a state. Arrival and departure of voice users is described as birth-death process among this states. The equilibrium solution of the birth-death process provides us with the probabilities of the system being in different states - $\mathcal{P}_m$. That is a vector of the probabilities of m users being in the system - $\mathcal{P}_m$.

When the number of available channels is constant the capacity planning is simply selection of the load. The load is selected to guarantee the probability that the amount of active users exceed the number of available channels to be below the predetermined QoS value. For example, in the system with M channels and blocking probability requirement 2 % this means that one attempts to load the system so that probability of $M+1$ active users being in the system is less than 2 %. For birth-death process with M servers this is calculated by Erlang B formulae and is equal of the system being in the state M [Kle75].

In interference limited systems, like CDMA, all the users can be admitted. However, when too many users has been admitted into the system because of the interference none of them can communicate and some users should be dropped. That is similar to blocking as soon as we admit new user the interference increase so much that nobody can communicate and somebody will dropped immediately. Because the dropping is immediate we can interpret it as blocking.

Blocking is because of the system outage. It can not be described by some constant number that amount of users exceeds. As we saw in Chapter 2. for a given number of users CDMA system may or may not be in outage. In the Chapter 2 we described the channel capacity as a vector. The vector has an element for every number of users in the system. The value of the element describes the outage probability for given number of user in the system.

For calculating the total system outage, blocking probability, the probability of m users being in the system should be multiplied with the outage probability for that number of users and summed over all m.

Let note for given number of users k the probability of system being in the outage by p_{out}^{k}. This probability together with probability of k active users $\mathcal{P}_k$ in the system provide us the total outage probability of the system

$$\mathcal{P}_{out} = \sum_{k=0}^{\infty} \mathcal{P}_k p_{out}^{k}. \tag{4.1}$$

4.2.2 Erlang capacity of CDMA

As an example we calculate the system capacity for voice users with voice activity detection.

Because not all the users are simultaneously active into the system can be allowed more users than there are resources available. For given average arrival λ and μ time the equilibrium solution to the birth-death process provides us with the probability p_m of m users being in the system.

Because of the voice activity from this m users with probability p_m^k only k are active. Probability $\mathcal{P}_k$, that in the system are k active users, is the sum over all m with k active users $\mathcal{P}_k = \sum_{m=k}^{\infty} p_m p_m^k$.

For calculating the total outage probability $\mathcal{P}_{out}$, $\mathcal{P}_k$ should be weighted with outage probability p_{out}^k for this number of users and summed over all k

$$\mathcal{P}_{out} = \sum_{k=0}^{\infty} \left(\sum_{m=k}^{\infty} p_m p_m^k \right) p_{out}^k = \sum_{m=0}^{\infty} p_m \left(\sum_{k=0}^{\infty} p_m^k p_{out}^k \right) . \tag{4.2}$$

The method can summed as follows: calculate the probability of m users in the system, the probability that k of them are active and weight it with the outage probability for k active users.

The first two actions are related to multiplexing users into the system. The third process, estimation outage probability for k active users, is related to estimation of the available channel capacity.

In Chapter 2 we described how to calculate the vector description of the outage. This results can directly be used as vector of probabilities p_{out}^k. For our example remains only to derive an equation for calculating the $\mathcal{P}_k$.

Probability of having k active users in the system

We have to calculate two distributions, m users are in the system, and k of them are active. We calculate the distribution of m by using the M/M/∞ queue. The distribution of k is modelled by binomial distribution.

A CDMA system resembles the M/M/∞ queueing system [Kle75] because of the large amount of available channel codes. For this type of queue the probability of m users being in the system is given by Poisson distribution $p_m = \frac{\left(\frac{\lambda}{\mu}\right)^m}{m!} e^{-\frac{\lambda}{\mu}}$. To be correct CDMA is slightly different than M/M/∞ system. In CDMA the average call service time is less than in M/M/∞ system. The users are leaving the system not only at the end of service session but also they leave cell due to the handover and are dropped due to the system outage. Therefore the average service time from system state with k user to the system state $k-1$ would not be $k\mu$ but function of outage probability at the state k, $\mu_k(k)$. The service time distribution will not be Poisson and standard analyze for M/M/∞ can not be used.

On the other hand in CDMA the probability of visiting the states with higher m is less than in M/M/∞ - some users are dropped before system reaches these states. In that reason M/M/∞ only underestimates capacity of the system and therefore can be used for sake of simplicity.

Users in the system are not simultaneously active - not all of them generate interference to others. The amount of users being active depends on the voice activity. For voice activity factor ν the probability that from m users k are active can be modeled by binomial distribution $p_m^k = \frac{m!}{k!(m-k)!} \nu^k (1-\nu)^{m-k}$. For given arrival λ and departure rate μ the probability that k users are active is

$$\mathcal{P}_k = \sum_{m=k}^{\infty} \frac{\left(\frac{\lambda}{\mu}\right)^m}{m!} e^{-\frac{\lambda}{\mu}} \left(\frac{m!}{k!\,(m-k)!} \nu^k (1-\nu)^{m-k} \right). \tag{4.3}$$

The outage at state k is probability that system is in this state multiplied with outage probability at this state, $P_k p_{out}^k$. The total outage would be sum over outages at each state k

$$\mathcal{P}_{out} = \sum_{k=0}^{\infty} \left(\sum_{m=k}^{\infty} \left(\frac{\left(\frac{\lambda}{\mu}\right)^{m}}{m!} e^{-\frac{\lambda}{\mu}} \right) \left(\frac{m!}{k!\,(m-k)!} \nu^{k} \left(1-\nu\right)^{m-k} \right) \right) p_{out}^{k}. \tag{4.4}$$

For solving equation 4.4 one needs the average arrival rate λ, the average service time μ, voice activity ν, and average outage probability for k active users in the system - p_{out}^{k}.

4.2.3 Computation of the system capacity

We study numerically the capacity dependency on voice activity and load. Change of this two parameters illustrate the stability of the system.

The capacity dependency on load is calculated for both CDMA and TDMA systems. Similarity between this two calculations provide simplifications used in the next chapter in development of the capacity calculation algorithm.

We give the results only for one cell, for the vector capacity of the CDMA is used the results from Chapter 2.

Example of the capacity calculation

Usual measure for the system performance is blocking probability as function of load in Erlangs. In CDMA, with large amount of available channel codes, the limiting factor is not blocking but outage. From the other side in order to keep the outage probability under some limit it is preferable to block the users. The situation can be compared with statistical multiplexing. When not all the users are active at the same time, into the system can be admitted more users than there are channels available. Outage occurs when the amount of active users exceeds available capacity. In this context the equation 4.4 can be applied also to a blocking limited system like for example TDMA. When outage due to the interference is ignored, in a system with m channels outage probability, p_{out}^{k}, would be 0 until $k \leq m$ and 1 for $k > m$.

The TDMA and CDMA capacities can be equalled when to calculate the mean capacity of CDMA. The vector capacity calculated in Chapter 2 describes the cumulative distribution (cdf) function of blocking. Configuration that generates outage for k users generates outage also for the $k+1$ users. We generate the outage probability by selecting the number of users $k+1$ and checking the outage for large number of location configurations for this amount of users - simulating by using Monte Carlo method. This large amount of user configurations contains also the set of configurations where outages occur already for k users. We have generated the cdf of outage for different number of users. The probability distribution function (pdf) is calculated by differentiating the cdf - $\frac{dp_{out}^{k}}{dk}$. The mean CDMA capacity is the mean of the pdf of the outage.

We simulate the CDMA vector capacity in for the similar system as was used in the Chapter 2. Now, however, we used also the orthogonality factor, $\alpha = 0.4$. The vector description of capacity is given in Fig. 4.7 for attenuation factor 4.

When number of channels in TDMA is equalized with average capacity of CDMA the outage probability curves are same (Fig. 4.1). This result suggest that outage of a CDMA system can be calculated as outage of equivalent m channel blocking limited system.

In result for planning process is sufficient to estimate the average number of available channels and multiplex users into it by some method developed in queueing theory.

Capacity dependency on the voice activity

The input parameters for the capacity calculation are only estimations of actual values. It is important to know how sensitive the system is to these estimated values. The sensitivity on load can be deduced from Fig. 4.1. The dependency on voice activity is illustrated on Fig. 4.2. In calculations we set the outage probability to be 2 % and solve the Eq. 4.4 for different values of voice activity.

The system capacity is very sensitive to small differences when voice activity is low. The choice for correct activity value is very difficult. For example when the voice activity

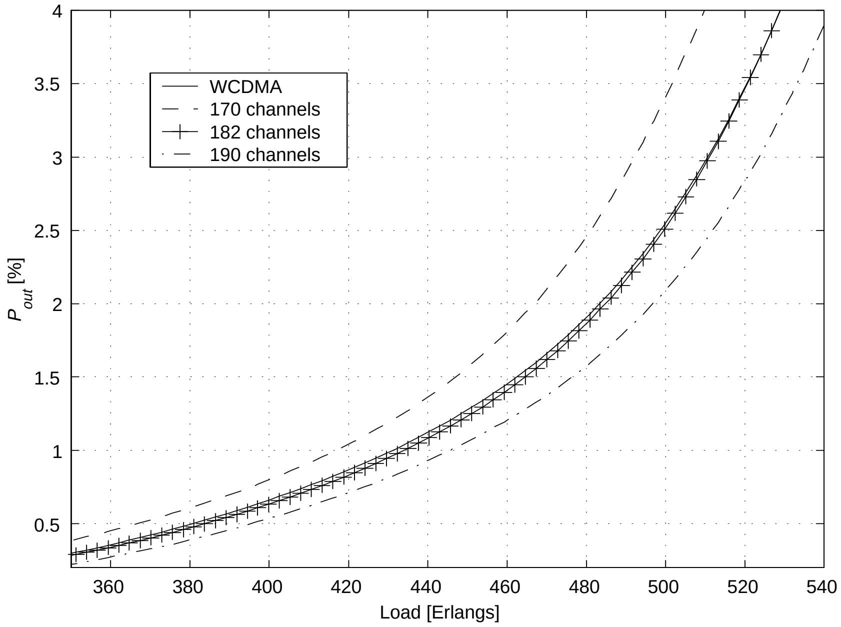

Figure 4.1: System outage probability as fucntion of load for CDMA and TDMA.

is chosen to be 0.4 and is actually 0.5 the network is under dimensioned many Erlangs.

4.3 Algorithm for the capacity calculation

In this section we supplement the analytical treatment with an algorithm for calculation the channel capacity in a real network. The idea here is simply to replace the vector description of the channel capacity by a constant. In result the system capacity can be calculated as for TDMA, by multiplexing users into the available channels. As simulations show in the constant system capacity approximates well the real capacity of CDMA [Fig. 4.1]. In this section we describe how to select the constant channel capacity and how it can be calculated.

As mentioned in Chapter 2 one possible way to get outage probability is to use 'Monte Carlo' simulation. The nature of interference requires to simulate the whole system at the same time. That makes the simulation of big systems prohibitively time consuming.

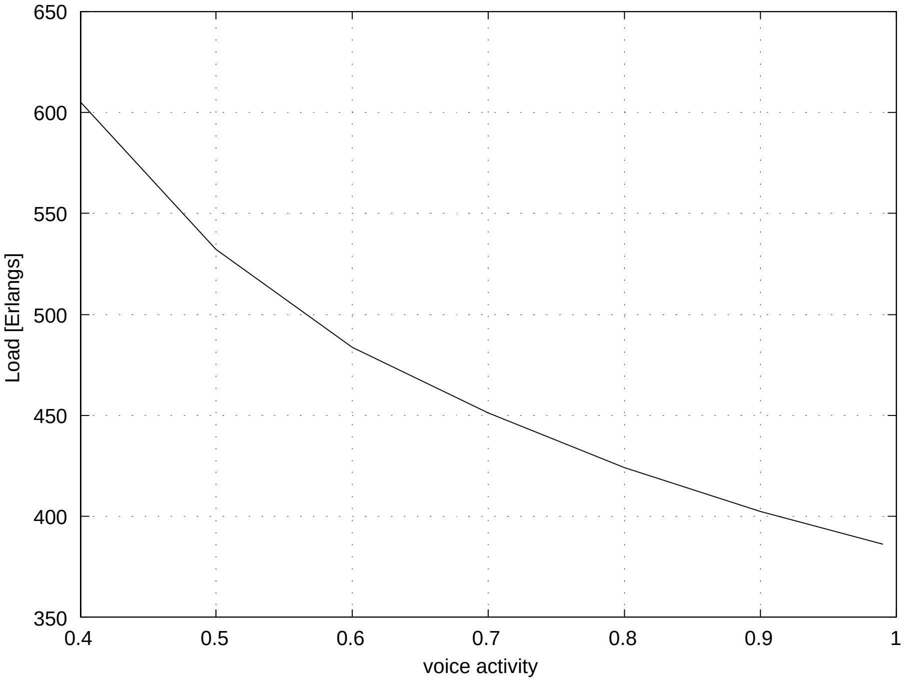

Figure 4.2: Load as function of voice activity

It is preferable to replace the simulation with some other method that allows to estimate the capacity quickly and precisely enough.

We relax the requirement for precise capacity and start to seek for the value which is good enough. As a good estimation we consider the capacity value for which the system is not in outage but also not much overdimensioned.

The precise value of network capacity depends on many parameters. Often the precise value of those parameters is not accessible for the network planner, for example it is difficult to know beforehand the exact attenuation in the channel and users spatial distribution. When to combine this with forecast of traffic increase the capacity value is preferred to be chosen rather conservative. Here we assume that the good value for the channel capacity is less than average capacity for the outage distribution but very near to it. Such value can be obtained directly for the total transmitted power of a BS.

The total transmitted power per BS increases with the number of users in the system [Fig. 2.8]. When outage probability starts to be more than 0 the total transmitted power begins sharply to increase. This relationship allows to approximate the allowable channel capacity with the capacity where transmitted power starts to increase exponentially. In planning process it means that the total transmitted power increase curve should be estimated and from this curve the available capacity is approximated. The direct vector description of capacity is replaced with the constant value fetched from the total transmitted power curve for one BS. The system Erlang capacity can be calculated from the Erlang B formulae by using this capacity value.

The total transmitted power is increased because the equation 2.8 does not have a solution for all positive transmission powers - system has run out of capacity. Although the equation is not solvable for given constraints, PC attempts to find a solution by increasing power for each users. Subsequently when to select the available capacity at the point where total transmitted power starts to increase sharply one can quite certainly expect it to be under average available capacity. This is not very precise but quite a good approximation of the capacity.

In Chapter 2 the average transmitted power was calculated by averaging over many different combinations of user locations. Similar result can be expected when to use the distribution of users, every user is distribute all over the service area. By the service are we mean the whole area covered by all cells. Transmitted signal power from/to one location in the service area is equal to the probability of an user being in that location weighted with the total amount of users in the system.

Using the users density over the service area allows to consider the effects of different transmission conditions from each location in one calculation. The average transmitted power for a given number of users can be calculated by solving only one equation per number of users, not many equations and averaging over them later like in "Monte Carlo" simulation.

4.3.1 Description of the algorithm

The basic ideas of the algorithm were drawn above: the system Erlang capacity is calculated from Erlang B formulae, for that the channel capacity in vector form is replaced by a constant, the constant can be approximated from the total transmitted power from the BS. The average transmitted power for different number of users can be calculated from one equation by using users distributions.

For evaluating the average capacity we split the system into small areas and assign to each area probability of users being in it. That can be seen as a case where each location corresponds to a user. Transmitted power used for communicating with such user is weighted with probability of the user being at the location. For uniform users distribution the weight would be $w_{k_n} = \frac{1}{service\ area}$. The amount of users in the system is considered by multiplying weight at each location with the total amount of users in the system mw_{k_n}.

CDMA capacity in downlink can be described by a matrix equation in the form

$$\begin{array}{c}
m\left(L_{1_1}\left(w_{1_1}\frac{P_{1_1}}{CIR_t}-w_{1_2}P_{1_2}-\ldots-w_{1_k}P_{1_k}\right)-\sum_{n=2}^{N}L_{n_1}I_n\right)-\eta=0\\
m\left(L_{1_1}\left(w_{1_1}P_{1_1}-w_{1_1}\frac{P_{1_1}}{CIR_t}-\ldots-w_{1_k}P_{1_k}\right)-\sum_{n=2}^{N}L_{n_2}I_n\right)-\eta=0\\
\vdots\\
m\left(L_{1_k}\left(w_{1_1}P_{1_1}-w_{1_2}P_{1_2}-\ldots-w_{1_k}\frac{P_{1_k}}{CIR_t}\right)-\sum_{n=2}^{N}L_{n_k}I_n\right)-\eta=0
\end{array}. \tag{4.5}$$

Differently from Eq. ?? power and attenuation are calculated for the location in the cell noted for n-th BS as k.

The average transmitted power should be calculated for different number of m. This process can be simplified by iterating similarly as it was done in chapter 2. When the equation does not have the solution for all positive powers the total transmitted power will have some high value. For the capacity we chose the point where the transmitted power starts to increase quickly. For example we can select for the capacity limit the point where slope of power increase in dB is more than 1. We selected this point heuristically.

4.3.2 Parameters for the algorithm

The algorithm calculates the required signal power to every location. The total transmitted power is calculated by weighting this power with the user probability of being in given location and integrating over all the locations. In order to calculate this parameters as input are required the attenuation in the channel from each BS to each location, user density and *target* CIR.

The attenuation in the channel and user density are also used in planning of TDMA networks [Nok98]. For calculating the attenuation wide variety of methods has been developed. For capacity estimation we just need the value for attenuation and the way how it is attained is not relevant. Therefore in our study we assume that some appropriate methods for calculating the attenuation are available without deeper investigation the way it is implemented.

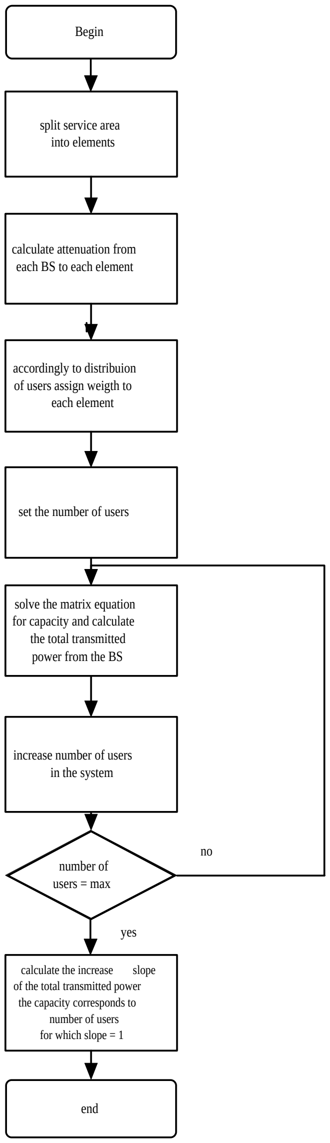

Figure 4.3: Flow chart of the capacity calculation algorithm

Intention of the PC to keep CIR at *target CIR* forces us to review the traditional planning methods used for TDMA networks. In TDMA without PC the selected CIR impacts only the cell coverage area. In most parts of the cell the cell the CIR is significantly higher than the *target CIR,* the service quality is violated only at the cell border. In PC systems we are faced with different situation CIR is kept at the *target CIR* level. This level defines the service quality in the whole cell.

In TDMA the main interference is due to the cochannel interference, as long as the CIR satisfies the given reuse distance we can increase the *target CIR* value without affecting the system capacity. In CDMA where intracell interference is dominant the *target CIR* value defines directly the channel capacity and due that the system capacity.

The capacity estimation in CDMA would be easy if for every users would exist the same *target CIR* value. Unfortunately for every user exist different *target CIR* value. In previous chapter we demonstrate CIR dependency on users speed. The users speed is not constant but given by distribution. The distribution of *target CIR* values can be calculated from the users speed distribution by a random number transformation. For that we use the function of dependency between user speed and CIR calculated in Chapter 3.

The distribution of SIR is given in Fig. 4.4. For the users with the same data rate SIR distribution is related to the CIR distribution simply by scaling with coding gain.

For evaluating the equation 4.5 we would prefer to have some constant value for CIR. Reasonable seems to be to use the mean value of the CIR distribution. We test suitability of the mean *target CIR* in calculation of the capacity in the next section in network level simulations.

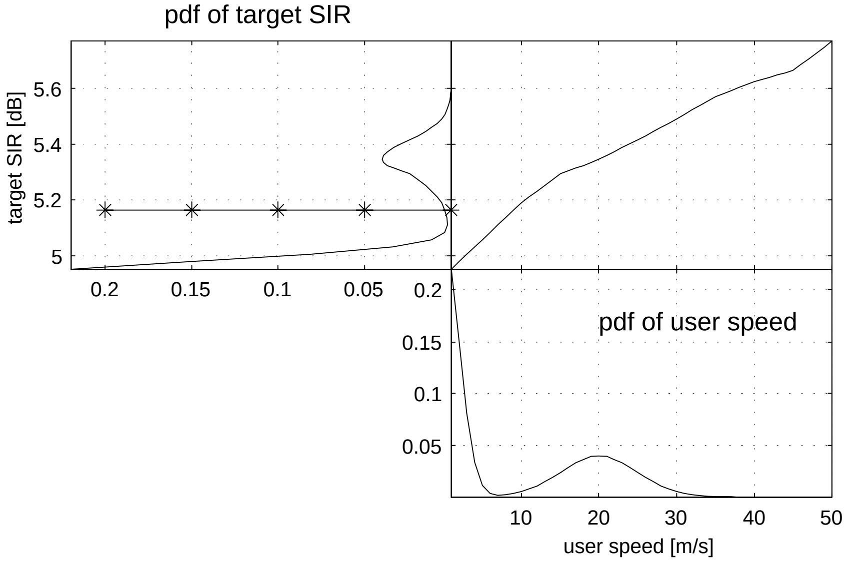

Figure 4.4: Mapping from the speed distribution to the *target SIR* distribuiton. On the figure also the mean value of the *target SIR* distribution is given.

4.4 Simulation and numerical calculations of the capacity for voice users

The method for capacity estimation proposes to replace the Monte Carlo simulation with calculation of the average mean transmitted power. The mean total transmitted power for different number of users allows to estimate the channel capacity. The calculation is easy to carry out for the constant *target* CIR and for fixed data rate for all users. Unfortunately the *target* CIR changes depending on users speed and there is growing interest to implement a multiple data rate networks.

First we scrutinize the system with fixed data rate for all the users. We investigate a possibility to replace the varying *target* CIR with some constant. The resulting method is suitable for calculating the channel capacity in a single service network.

In Chapter 2 we show that the load distribution affects the amount of users that can be served. The load distribution among the BS is affected by attenuation in the channel, distribution of BS, distribution of users. The planning method should be capable to estimate the system capacity for every network configuration. We demonstrate the suitability of the proposed network planning method by simulating few test cases. The test cases are accordingly:

- uniform distributed users with different orders of attenuation,
- nonuniform location of BS,
- nonuniform distribution of users,
- nonuniform distribution of BS and users.

Finally we study a possibility to augment the method of estimating the capacity in network with different data rates.

We do simulations for similar setup as used in Chapter 2. We extend the simple equation for CIR with orthogonality factor discussed in Chapter 3. We set the orthogonality factor to be $\alpha = 0.4$.

When we study different attenuation factors, users and BS are located uniformly. Because of uniformity the capacity is equal for all the BS and therefore in figures is described only one of them. In nonuniform cases the we use attenuation factor 4. The result for attenuation 4 and uniform distribution can be considered as reference case for the simulations below. In order to compare the impact of nonuniformity we give the capacity at each BS in area.

4.4.1 Capacity with changing *target* CIR

The speed of users in the system is not constant but described by a distribution. The *target* CIR depends on the speed of the user. In order to be able to use the method for capacity estimation we assume that all the users have constant *target* CIR and select for that value the mean from the CIR distribution. The simulation shows that the calculation

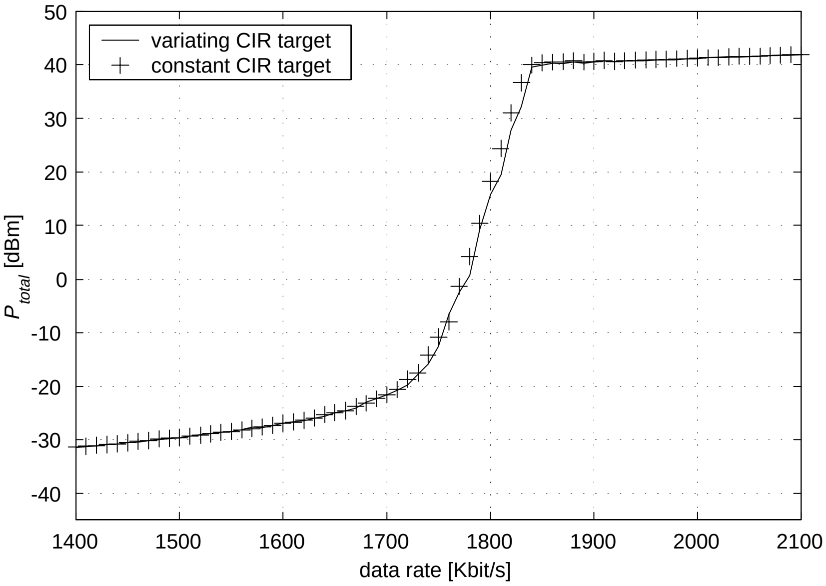

Figure 4.5: Comparison of the simualtion with CIR distribution and calcualtion with mean from CIR distirbution. Mean of the total transmitted power from one BS is given as function of total data rate in a cell.

with the mean of the *target* CIR approximate well the total transmission power obtained by Monte Carlo simulation with *target* CIR depending on the speed [Fig. 4.5].

The SIR distribution is described in Fig. 4.4 and because the spread bandwidth and data rate of all users are constant, $W = 4,096\ MHz$, $R = 10\ Kbit/s$ the coding gain is constant for all users.

Because the users are uniformly distributed the total average transmitted power is same for all BS and in Fig. 4.4 is described only for one cell.

The simulation suggest that in calculations the SIR or CIR distribution can be replaced with the mean value of corresponding distribution. This mean value is used as the *target* CIR for all users.

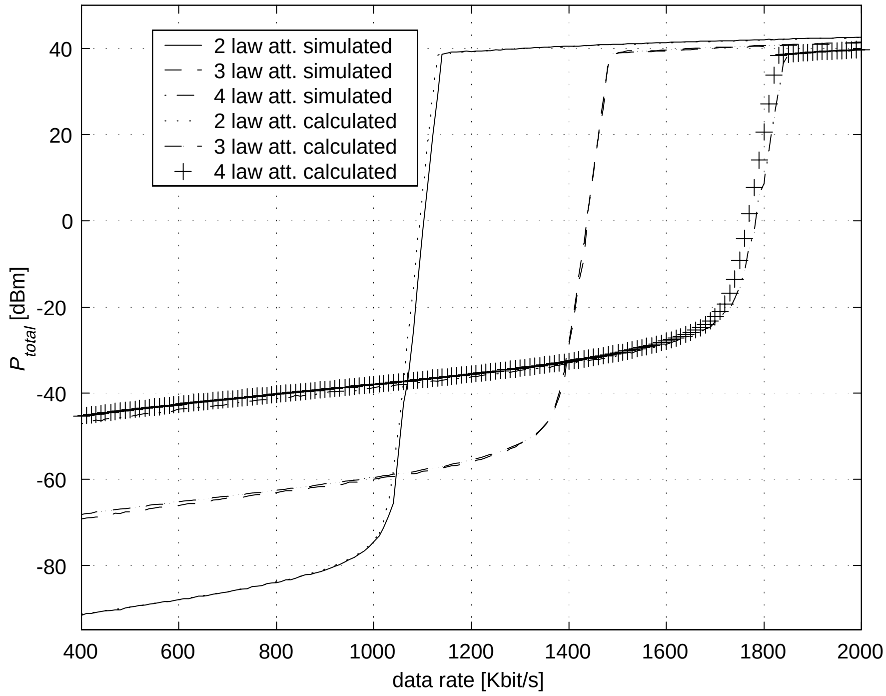

Figure 4.6: Total transmitted power from one BS versus total transmitted data rate in the cell as fucntion of different laws of attenuations.

4.4.2 Uniform location of BS and users with different orders of attenuations

First we analyze how well our method fits to conditions with different attenuations. In that purposes we simulate the average transmitted power for 2, 3, 4 order of attenuation.

As can be seen in Fig. ?? the calculation approximates well the average total transmitted power achieved by Monte Carlo simulation The result can be broadened and predicate that the method is able to predict the average transmitted power for any different mix of attenuations.

Because the signal attenuate quicker and therefore generate less interference to the neighboring cells for higher attenuation the capacity is higher [Fig. 4.7].

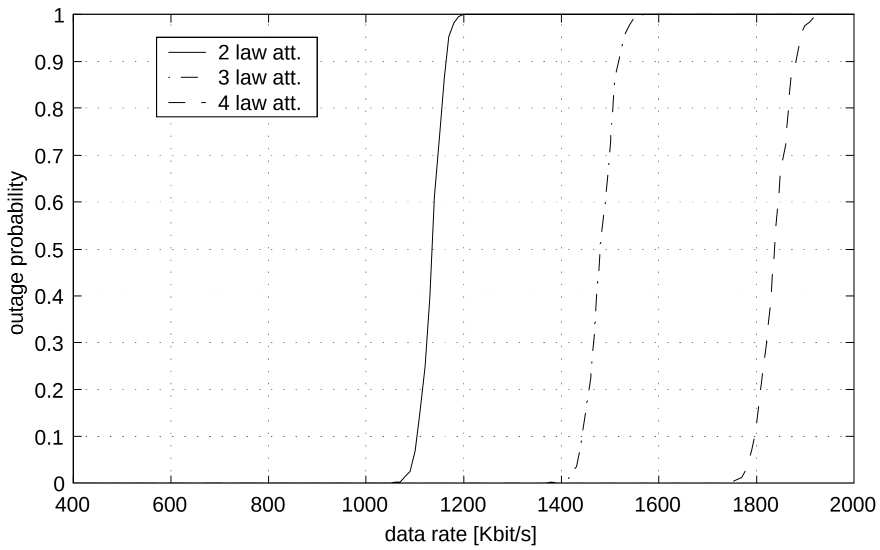

Figure 4.7: Outage probability for different law of attenuation.

4.4.3 Nonuniform location of BS

Even users have uniform spatial distribution the location of BS unbalances the demand in cells. The cells cover different areas and in result there will be different load to different BS.

The location of BS that we use in simulation is described in the Appendix C. In simulations we increase the amount of users in the system so that the users distribution is preserved.

As was expected the interference is not uniformly distributed and the amount of users that different cells can serve is different (Fig. 4.8). The calculation follows very closely the mean from Monte Carlo simulation.

The total amount of users that the system can serve is less compared to the uniform distribution of users and BS.

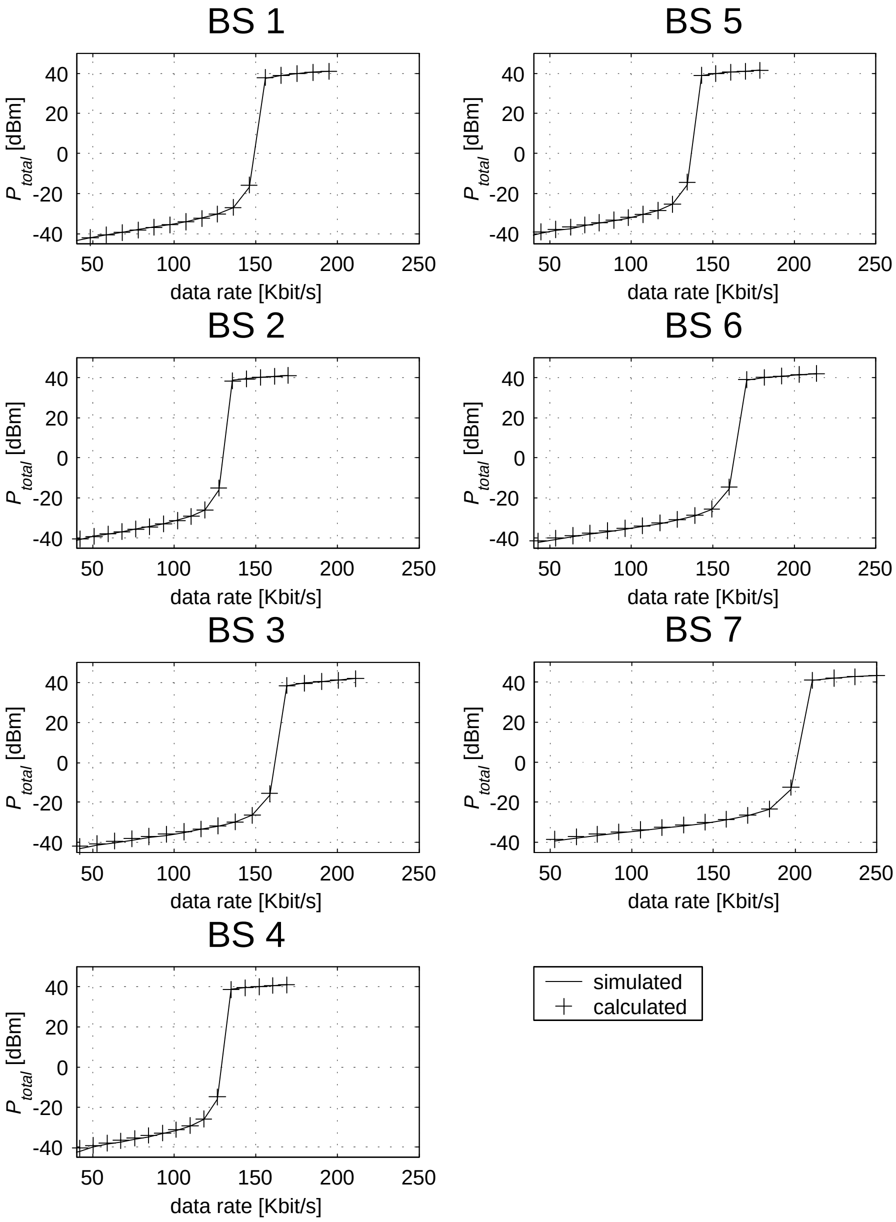

Figure 4.8: Total transmitted power from a BS when BS are located nonuniformly in the service area

4.4.4 Nonuniform distribution of load.

Similarly as nonuniform spacing of BS the nonuniform distribution of users unbalances the load among the BS. The distribution used in simulation is described in Appendix C.

To preserve the users distribution in simulations we scale the distribution for one users with the amount of user in the system. m.

Because the chosen distribution increases the load in the middle cell the amount of users that can be served in middle cell is higher than in neighbours.

The capacity in the middle cell is also higher than for uniformly distributed users. However the higher load in the middle cell increases interference to the neighbours and compared to uniform distribution of users the total capacity in the area is decreased..

4.4.5 Nonuniform distribution of traffic and location of BS

In practice we are often faced with situation where neither BS nor user distribution is uniformly distributed. The nonuniformities from both previous cases are combined. The method for calculating the cell capacity worked well for the previous case as can be expected it is capable to estimate the average transmitted power also for this case.(Fig. 4.10).

The total capacity in the cell is less than for uniform user and BS distribution making it very bad approximation for the network planning. For given distribution the load is unbalanced among the BS each of them is capable to serve different amount of users. Fortunately we are capable to calculate the available channel capacity in each cell very precisely.

4.5 System capacity with data users

For calculating the system capacity we were able to use the Erlang B formulae, because the vector description of capacity was approximated by one value. By selecting the constant value for the channel capacity we effectively separate the estimation of channel

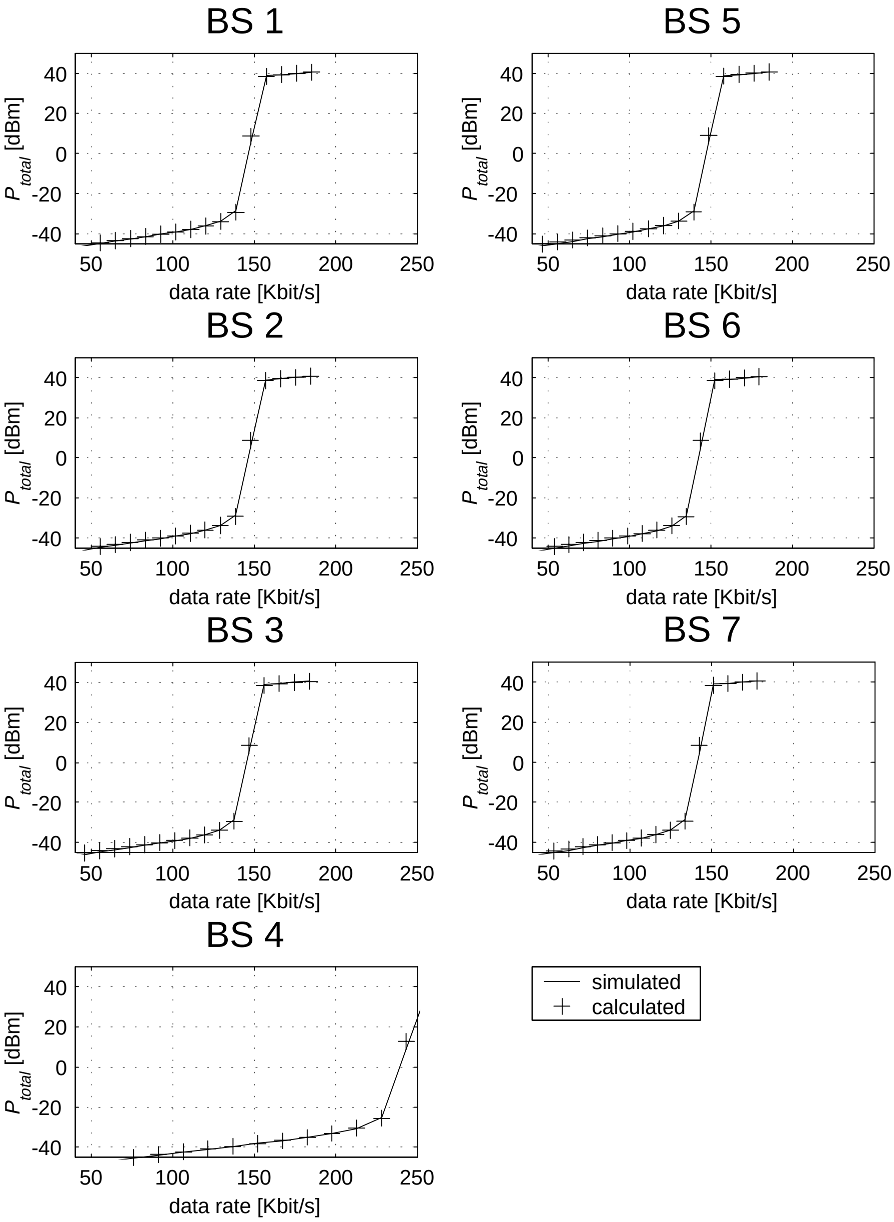

Figure 4.9: Total transmitted power from a BS when distribution of users in the servcie are is not uniform.

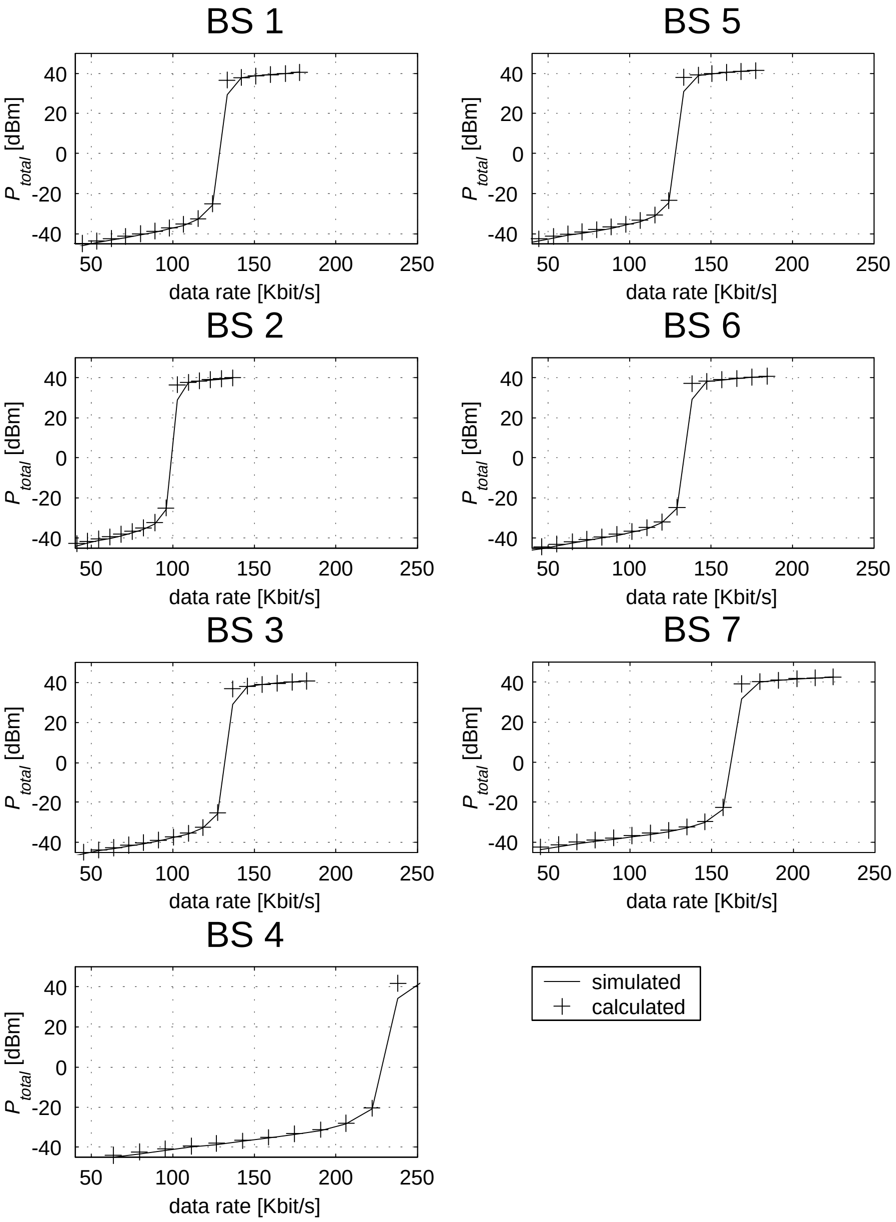

Figure 4.10: Total transmitted power from all BS when distribution of users and BS in the servcie area is nonunifrom.

capacity and multiplexing users into it. Approximation of the channel capacity for multiple data rate users in the system allows to make similar separation. In order to do it we have to study how well constant value reflects the actual capacity of the system.

The problem with high data rate users was stated in Chapter 2: because of the high transmission power one connection with high data rate reduces total amount of users in the system. It does not necessary mean that total bit rate per BS is decreasing, only one user takes bigger part from the available capacity. Correspondingly to other users is less capacity left to share.

When in the system are less users the location of each particular user becomes more important. The system does not benefit from the randomizations occurring for many users naturally. For many users the amount of users located far from BS is compensated with the users located near to the BS. We can assume that distribution is uniform. For few users in the system this assumption can not be done. For example, for two users the total interference generated by them depends where they are located, we can not assume that they compensate each other attenuation, when one is near the other is far from BS and vice versa. When both are to BS the interference to neighboring cells is reduced and available channel capacity is increased. If they are near to cell border the capacity is decreased.

From Fig. 4.7 for constant data rate users the outage probability increases sharply when the amount of users exceeds some limit, Eq. 4.5 does not have a required solution. The approximation of the capacity with constant for different data rate users can be used when similar sharp increase of outage probability exist. The sharp increase of outage means that the actual location of users in not very important and when averaging over many different channels, locations, for many users the capacity becomes a constant.

For testing the impact of high data rate users we do simulations for cases when data users have 10, 20, 40 times the data rate of voice users. We look at total transmission powers and outage probabilities as function of channel capacity in one cell. The channel capacity of the cell is defined as sum of transmitted bit rate to each user.

For given channel capacity we subtract the data rate of the corresponding data users and calculate how many voice users with given channel capacity can be served. For example, with channel capacity 1000 $kbit/s$ and 3 200 kbit/s data users and data rate for voice user 10 $kbit/s$ we have $\frac{1000-3\times200}{10} = 40$ voice users. For these voice and data users we do similar Monte Carlo simulation of total transmitted power from BS as was done above for voice users only. We locate the users, calculate the total transmitted power for them, and repeat this many times.

As can seen from simulations the variation of the total transmitted power increase with increase of data rate of users [Fig. 4.11 4.12 4.13]. From the figures we see that for channel capacity 1700 $kbit/s$ for 3 400 $kbit/s$ data users the variation of total transmitted power is much more that for 3 100 $kbit/s$ data users. For given channel capacity for some location of 400 $kbit/s$ data users the system will be in outage. However, for 100 $kbit/s$ data users the outage does not occur at all, the total transmitted power does not reach the maximum allowed power.

With increase of users data rate the systems starts to be in outage for smaller total data rate (figure **??**). At the same time the average available capacity is higher when users with higher data rate are in the system. All this phenomena are related to the location of high data rate users. With increase the data rate the interference generated by one user increases. Since also the amount of users in the system decrease it becomes more important where the data user is located. In result when user with data connection is near to BS the capacity can be more than capacity of system with uniformly distributed voice users. Accordingly when such users is at cell border the system goes easily to outage. In that reason the average capacity is increasing with increase of data rate of data users.

Because the average channel capacity is higher for data users is seems reasonable to use in planning process estimation of the capacity for voice users. Changes of this capacity due to location of users should be taken care by runtime operation: admission control and congestion control.

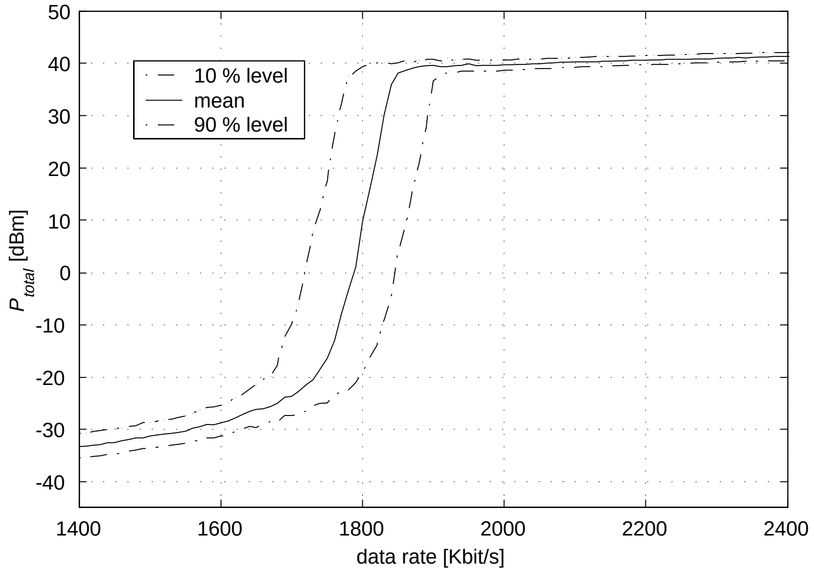

Figure 4.11: Mean, 10 %, and 90 % level of the total transmitted power as function of transmitted bit rate per BS. In the system are 3 with data connection 100 kbit/s.

The amount of different users that the system can serve can be described as solution to the stochastic knapsack problem [Ros95].

4.6 The network planning process

The easiest way to meet demand in the network is to provide enough BS in the area. However economical constraints make that solution often unfeasible. In that reason the network planning is not bare calculation of the system capacity. In practice the network planner is faced with more complex problem: given the load distribution does given configuration of BS satisfy the demand or not. If the load can not be satisfied the network planner has to find where are the bottlenecks and how the service quality is deteriorated.

In TDMA based systems the overload is handled by relaxing the *target CIR* or blocking requirements. These affect the service quality but can be accepted if the deterioration

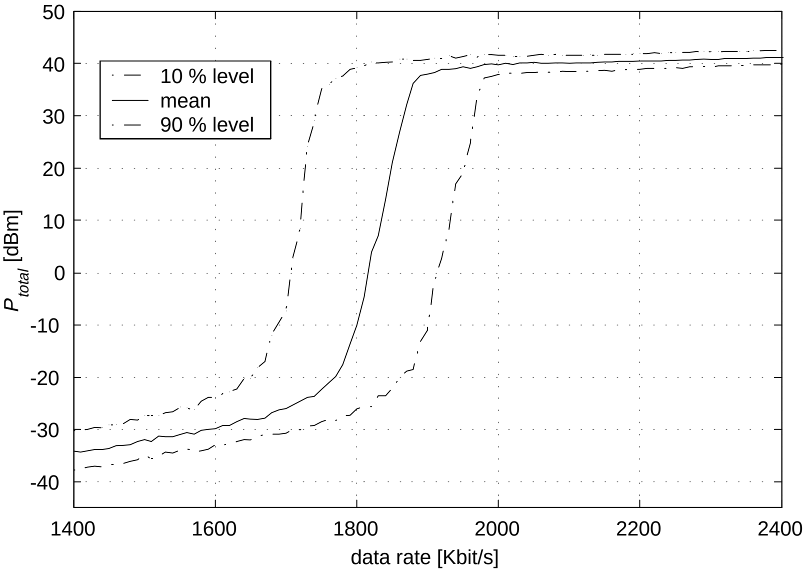

Figure 4.12: Mean, 10 %, and 90 % level of the total transmitted power as function of transmitted bit rate per BS. In the system are 3 users with data connection 200 kbit/s.

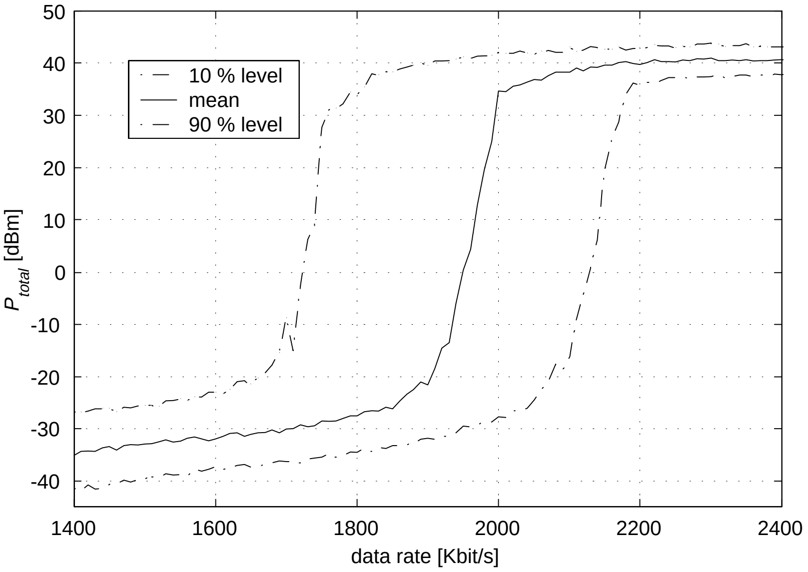

Figure 4.13: Mean, 10 %, and 90 % level of the total transmitted power as function of transmitted bit rate per BS. In the system are 3 users with data connection 400 kbit/s.

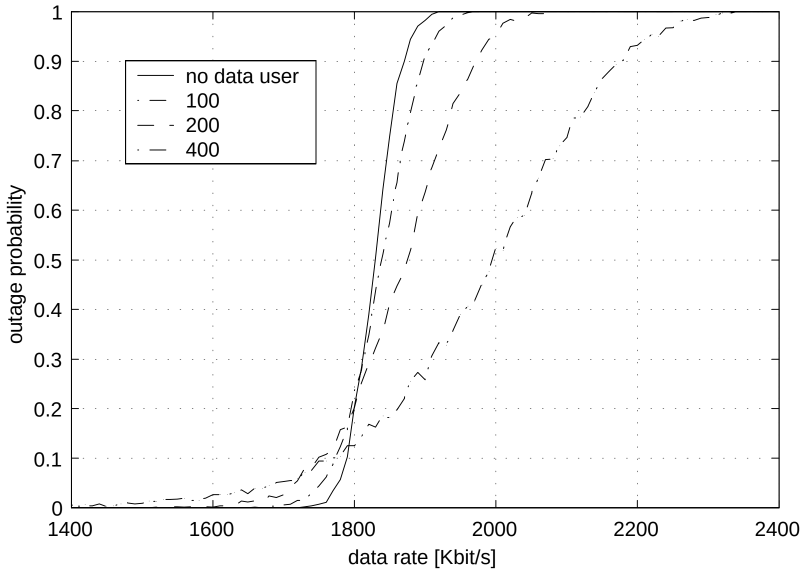

Figure 4.14: Outage probability as function of total transmitted data rate per BS. In the system are 3 users with data rates 100, 200 , 400 kbit/s.

occurs in the areas not very important from the operator point of view. Similar approach can be taken also in a CDMA system, however, impact of changing the *target CIR* or blocking requirements are different than in a TDMA based system.

The correct network planning in CDMA should also incorporate admission control and congestion control. In our analysis we only outline some possible planning strategies and the real time processing is discarded.

By using the method for estimating channel capacity we are easy capable to estimated wether the network can serve the offered load. If it can not the total transmitted power will be maximum for some users. In the locations where the power is maximum allowed the *target* CIR is not satisfied and the system is in outage. Consequently by solving the equation 4.5 the solution directly provides regions where during the overload the users first start to be in outage. These are the areas where during overload the service quality is deteriorated.

Depending on implementation of PC or congestion control in these areas the users are dropped or the *target* CIR is reduced. Relaxing the CIR requirements in CDMA is different than in TDMA. During planning of TDMA we can predict the areas where the *target* CIR is always violated while in CDMA the deterioration of quality occurs only during overload.

When the load is too high the admission control blocks the users. Blocking shapes the distribution of admitted users. As simulations show the distribution of users in the system affects the interference and due that the capacity of the system. We look at two different strategies for admission control: when admission control attempts to uniform (shape) the load and admission control blocks users equally in each cell.

As simulations show BS in CDMA can easily have different load, by increasing load to one BS we have to have less load to neighboring BS. Though that allows easily to deal with nonuniform distribution of traffic the total capacity of the system will be less compared to the case when all BS have equal load. Therefore it is reasonable during planning process design the system so that the load to each BS is equalized. That is achieved by setting different admission control values to different BS. The available channel capacity for setting the admission control values can be achieved by using the method described above.

The planning would for such system would contain first testing the capacity of the system if the demand is higher than available capacity to set the admission control to cut the load in the highly loaded cells. To recalculate the demand in each cell by considering the reduced load. By using new demand the system should be recalculated. When the load still can not be supported the blocking should be increased even more. This process continues until the system can support all the offered load or the load in all cells are equal. When the load in all cells are equal the increase of blocking will be equal to all the cells. The increase of blocking ends until the system is capable to serve the remaining load after blocking.

Other way to meet the demand is to reduce the load in each cell equally. In order to do that, we first calculate the channel capacity for given distribution at each cell. By knowing the channel capacity we calculate the load that the system can support. The admission control is set to guarantee this load, when the demand is higher the call arrivals are blocked in each cell equally.

4.7 Chapter summary

The chapter concentrated on the issues related to the CDMA network planning. We were able to describe network planning for CDMA with similar states as traditional network planning for TDMA system. In order to do that we separated estimation of the channel capacity and multiplexing users into it. The separation was possible because the outage probability described in the Chapter 2 in vector from can be approximated by a constant. This constant is used as channel capacity when users are multiplexed into system. In section 4.2 we show how it can be done for voice.

In Section 4.3 we propose an numerical algorithm that allows quickly calculate the average channel capacity for each BS in the system. The algorithm gives significant speedup compared to simulations. The approximation accuracy is validated with Monte Carlo simulation in Section 4.4.

The different network configurations used for algorithm validation allows also to conclude on the channel capacity variation in the network. Any nonuniformity in the network variates the load and channel capacity among the BS. In some BS more users can be served than in others. However, calculation shows that the channel capacity is maximum when the users and BS are uniformly distributed. When that is not the case the capacity is decreased. Also the capacity decreases when the order of attenuation in the channel decreases.

We use simulations to analyze the impact of different data rates on the available channel capacity (Section 4.5). Though for different data rate users the outage probability depends on location and data rate of users for given simulation environment we can still approximate the channel capacity by a constant. This constant describes the amount of resources where the users are multiplexed. For multiplexing the users well studied methods from queueing theory can be used, for example stochastic knapsack.

At the end of chapter we were looking the network planning process from more practical point of view. How to estimate the outage areas and how to deal with overload conditions. In Section 4.6 we give a verbal description of some methods for CDMA network planning.

Chapter 5

Conclusions

5.1 Summary and conclusions

In this work different aspects of CDMA were investigated from the network planning point of view. The understanding acquired allows us to propose methods for practical network planning.

In CDMA, the system capacity depends on the interference level in the system. In Chapter 2 we examine how the level of interference depends on variables like location, speed, and data rate of users. Because the interference generated by a user depends on his/her location in the cell the available capacity of a CDMA system varies. For the network planning it is important to realize that the planning is based on the average capacity. The system utilisation is pushed to the limit by admission and congestion control by using instantaneous capacity.

Outage of the system and cell breathing related to this issue are the results of system overload. The consequences of the overload are dealt with by using admission and congestion control. During the network planning we dimension the network to guarantee that the overload condition does not occur very often.

Chapter 3 deals with a more precise channel model compared to the one used in Chapter 2. For network planning the equations describing CIR at down- and uplink are provided as well the function of *target CIR* dependency on speed of user.

As the analysis shows, in CDMA downlink the orthogonality factor depends on the channel response. The total gain that the orthogonality factor allows to achieve depends also on user location in the cell. Because of this fact the channel response becomes an important issue that has to be considered in network planning.

We were able to derive the equation for calculating the remaining variation in the channel after optimal power control. As simulations show, the simplest, relay, type of power control comes quite close to the performance of optimal control.

For CDMA capacity calculation we propose to separate the estimation of the channel capacity and the method of multiplexing users into the channel. In order to utilise this separation the channel capacity should be approximated by one value. We propose a method that allows us to calculate that value.

Based on the simulation results we propose the assumption that the channel capacity is the same for multiservice and single service networks. This assumption allows us to carry out the network planning with similar steps as for TDMA: coverage planning, capacity planning. Coverage planning contains estimation of the channel capacity for every cell in the network whereas capacity planning is related to multiplexing users into the resources.

5.2 Further research

The study made in this work provides a good starting point for further investigations. The two major directions for further studies can be classified as: study of the system behaviour and capacity at the network level, and link level studies.

In this work the impact of users movements to the system capacity has not been sufficiently explored. We only show that the system capacity depends on the cell size and user speed. However, the question of how this relationship is valid remains still open. The system outage due to interference is calculated for the optimal case by solving the matrix equation. In practice this equation is solved by power control. During the time that the power control spends for seeking the solution, conditions in the network have changed. Due to the changing conditions also the solution changes and the poewer control attempts to follow a moving target. How well the power control can do this is not at all clear and depends on parameters of the power control and on the speed of all users. This area of research is also related to the times describing outage: the time intervals between outages, and how long the system will spend in an outage.

In this work the network planning was investigated only for networks without directed antennas, and multiuser detection. These are two methods that due to the impact on the interference affect also the capacity and planning. By combining these with planning of a multiservice mobile network we get a whole new not unexplored area of research.

We made the link level study only for the case when the system is not overloaded. The overload generates the new conditions when many assumptions made in this work might not hold any more. For that reason we need specially to study the receiver performance during overload. The overload is not a normal system operational condition. In order to deal with such a situation we have to know how real time algorithms recognise this condition´and what are the best actions to take. This is an area where a lot of work remains to be done.

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Appendix A

Source code of the program for CDMA capacity calculation

The simulation code is written in matlab scripting language, for speeding up the simulations some functions implemented in C.

The code used for the Monte Carlo simulation is modular containing multiple subfunctions. By replacing the subfunctions the same structure of the program is used in all the simulations.

The modular structure of the algorithm allows to use the same program skeleton for Monte Carlo simulation and also for numerical approximation of the capacity.

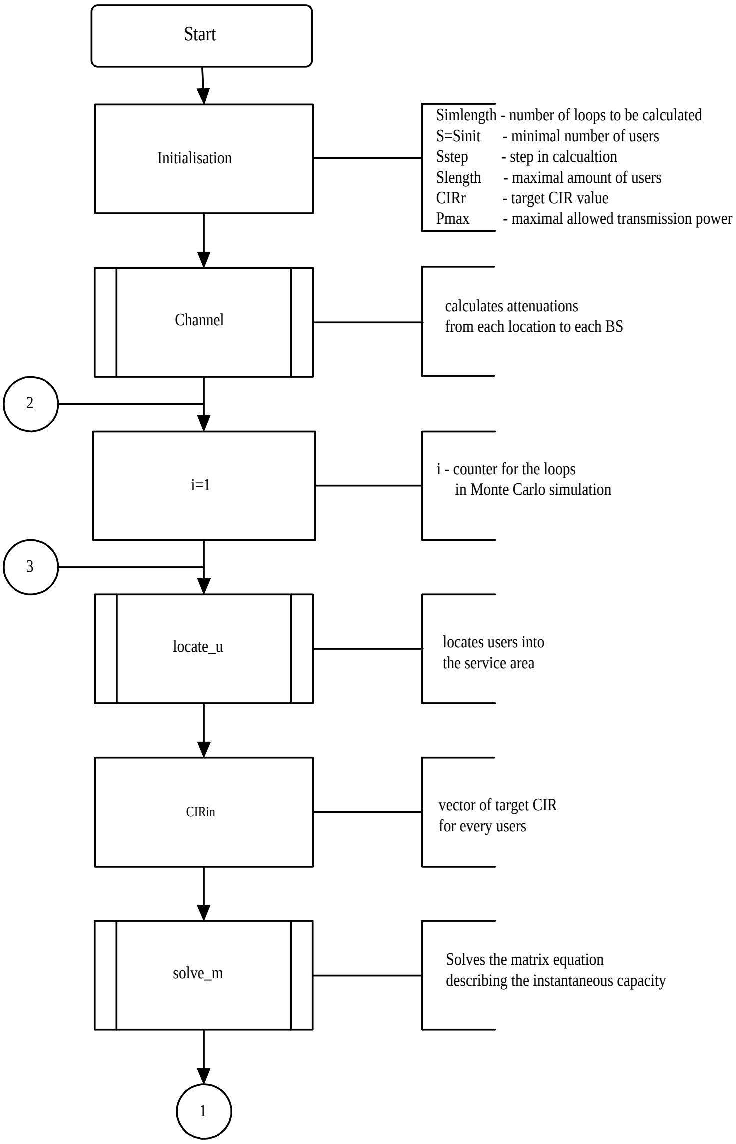

Figure A.1: Flow chart of the channel capacity simulation. Part *1.*

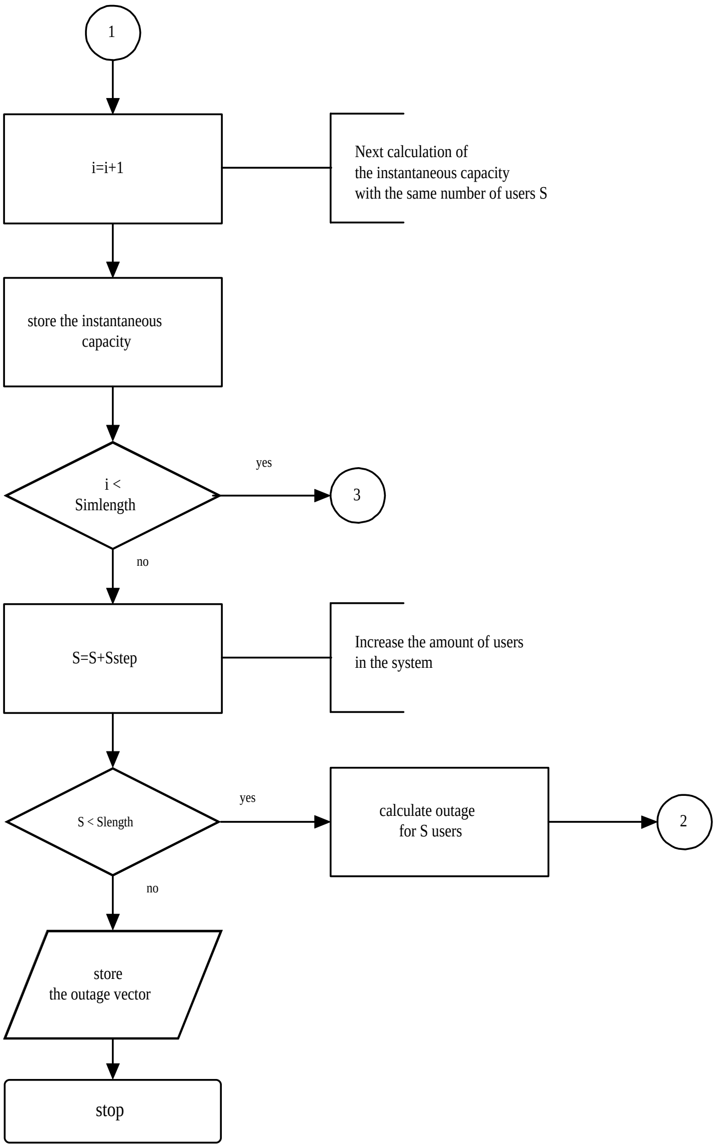

Figure A.2: Flow chart of the channel capacity simulation. Part *1.*

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% c_calc.m
% main function for capacity calculation
% with monte carlo simulation
%
% initiates the service area (channel.m)
% locates users into the area (locate_u.m)
% solves the outage equation
% for given configuration (CIcalcc.dll)
% repeats the procedure for 'simlength' times
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Kalle Ruttik
% 29.10.98
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Initialisation

clear Itot Ps
clear addr Psloc
clear result3 res32 res32l res3210 res3250 res3250 result4

% simlength - number of runs in "monte carlo" simulation
% times - the amount of data users
% datarate - transmission rate of one datauser
% Sinit - initial amount of equivalent data users
% Sstep - precision of capacity calculation
```

```
% Slength - maximal amount of users for which the capacity is calculated

simlength=2;
times=0;
datarate=0;
Sinit=50;
Sstep=20;
Slength=90;

% Pmax - maximal transmitted power
% CIRr - target CIR

Pmax=100;
CIRr=10^((5-10*log10(4096/10))/10);

% Initialisation of the attenuation matrix

[loc,sumatten,tratten,n,m]=channel(1);

Ortho=0.6;

for i=Sinit+times*datarate:Sstep:Slength
    M=i-datarate*times;
    i
     result4(i)=[0];
    clear result3
    for index=1:simlength
% loacte users into cell
        [Psloc,addr,BS]=locate_u(n,m,M,loc,times,datarate);

% set CIR target to each user
        CIRin=ones(1,length(Psloc))*CIRr;
```

```
% solve the matrix equation for given setup
            [Ps,CI,Itot]=solve_m(Psloc,BS,...
                            sumatten(addr,:),tratten(addr),CIRin,Pmax,Ortho);

% collect data
            result3(index,:)=[Itot];
            if sum(Ps>0.9*Pmax)>0
                result4(i)=result4(i)+1;
            end
        end

% form the resulting data vectors
        formdata
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% channel.m
% function for initialisating the service area
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Kalle Ruttik
% 17.06.1999
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% area_type - uniformly(1) or nonuniformly(2)
% distributed BS
% loc - the service are for each BS
% tratten - attenuation from the BS to each location
% in the service area
% sumatten - normalised attenuation from other BS

function [loc,sumatten,tratten,n,m]=channel(area_type)

% the attenuation matrix for each BS

L=atten(50,3,area_type);
[n,m,l]=size(L);

% maps the matirix to the vector

for i=1:l
    suma(:,i)=[1./reshape(L(:,:,i),n*m,1)];
end
```

```
[n,m]=size(suma);

% the BS is sending to the locations where
% the attenuation compared to other BS is minimal

[tratten,loc]=max(suma');
sumatten=suma./repmat(tratten',1,7);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% atten.m
% calulates attenuation from each BS
% to each location in the service area
%
% attenuation is calcuated accordingly
% to the attenuation power law ’att’
% and added a ranom component
%
% the service area size 260x250 points
% 7 BS in the area
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Kalle Ruttik
% 17.06.1999
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% R - radius of a cell
% att - attenuation order
% simtype - uniform(9) or nonuniform(else)
% distribution of BS

function L = atten(R,att,simtype)

% R = 50 r = 43.47 area 260*250

step1=1;
```

```
r = R/2/tan(pi/6);
y = ceil(6*r/step1);
x = ceil(5*R/step1);

% simtype 1 uniform 0 nonuniform location of BS
if simtype==1
      xS = ceil(reshape(repmat([2.5*R,R,4*R,2.5*R,R,4*R,2.5*R],[x*y,1]),y,x,7));
     yS = ceil(reshape(repmat([r,2*r,2*r,3*r,4*r,4*r,5*r],[x*y,1]),y,x,7));
else
     xS = ceil(reshape(repmat([2.5*R,R,4*R,2.5*R,R,4*R,2.5*R],[x*y,1]),y,x,7));
     yS = ceil(reshape(repmat([r,2*r,2*r,3*r,2.5*r,4*r,5*r],[x*y,1]),y,x,7));
end

xM = repmat(1 :step1: x*step1,[y,1,7]);
yM = repmat((1 :step1: y*step1)’,[1,x,7]);
R = sqrt((xM - xS).^2 + (yM - yS).^2);
R(find(~R)) = 1;

% random component of attenuation
xi = sqrt(0.5)*0.8*randn(y,x,8);
xi(:,:,1 : 7) = xi(:,:,1 : 7) + repmat(xi(:,:,8),[1,1,7]);
L =(R.^att).*10.^xi(:,:,1 : 7);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% locate_u.m
% locates users into the service area
%
% generates M users and locates them
% randomly into the service area
% adds to that 'times' amount of data users
% with power calcualted from the 'datarte'
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Kalle Ruttik
% 17.06.1999
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% n - size of the service area
% m - amount of BS
% M - number of users in the cell
% times - amount of datausers
% datarate - datarate of a datauser
%
% Psloc - vector of the transmission powers
% addr - location of users in the service area vector
% BS - structure for BS containing a vector of users
% in the service area of the BS ´

function [Psloc,addr,BS]=locate_u(n,m,M,loc,times,datarate)
```

```
Psloc=zeros(1,n);


% locate the users
addr=ceil(rand(1,m*M)*n);
Psloc(addr)=1;

while(sum(Psloc)<m*M)
    adr=ceil(rand(1,m*M-sum(Psloc))*n);
    Psloc(adr)=Psloc(adr)+1;
end

% locate datausers
adr=ceil(rand(1,times*m)*n);
Psloc(adr)=Psloc(adr)+datarate;
addr=find(Psloc);


% find the users in the service area of BS(i1trloc)
for i1trloc=1:7
    x1=(loc==i1trloc);
    BS(i1trloc).trloc=find(x1(addr));
end
Psloc=Psloc(addr);
```

```
/***************************************************/
/*
solve_m.c
    solving the matrix equation for the CDMA capacity
*/
/*
    The solution is either
    the transmission power to each user or
    maximal allowed popwer
*/
/****************************************************/
/*
Kalle Ruttik
29.10.98
*/
/****************************************************/

/*
Input
Psloc - the relative power needed to communicate with location
BS - matrix of users connected to different BS
sumatten - normalised channel from each BS to each user
tratten - attenuation in the communication channel
CIRr - target CIR level
Pmax - maximal allowed transmission power
Ortho - othogonality factor’
*/

#include ”mex.h”
```

```
#include <math.h>
#include <stdio.h>
#include <stdlib.h>
#define FMAX 10
#define NMAX 50

void mexFunction(
                    int nlhs, mxArray *plhs[],
                    int nrhs, const mxArray *prhs[])
{
     double *Ps, *CI,*Itot;
     double *Psloc,*BS,*sumatten,*tratten,*CIRr,*Pmax,*Ortho;

/* variables for the matrix size */
     int msumatten, nsumatten;
     int nBS;

/* variables for the structure BS */
     int numfields, buflen, num_dims;
     const int *dims;
     char *fnames[FMAX];
     double *Bstrloc[FMAX];
     int Bstrlen[FMAX];
     mxArray *tmp;

     int NrUsers;                         /* number of users */
     int NrBS;                             /* number of BS */
     double *Noisevect;                    /* noisefloor */
     double *Ilocr;                         /* interfence at
                                          every location */
```

```
    double *Intot;                          /* interference
                                            generated
                                            by an BS */
    double Noise, Psinit;
    int *Trloc;
    double endcondition,Psdif;
    int i1,i2,i3;

/* dimension of the input vector */
msumatten = mxGetM(prhs[2]);
nsumatten = mxGetN(prhs[2]);

/* structure BS */
    numfields = mxGetNumberOfFields(prhs[1]);
    for (i1=0;i1<numfields;i1++)
    fnames[i1]=mxGetFieldNameByNumber(prhs[1],i1);
    nBS = mxGetN(prhs[1]);

    for(i1=0; i1<nBS;i1++)
    {
        tmp=mxGetField(prhs[1],i1,fnames[0]);
        Bstrloc[i1]=mxGetPr(tmp);
        Bstrlen[i1]=mxGetN(tmp)*mxGetM(tmp);
        }

/* length of the elements */
    if(msumatten > nsumatten)
    {
        NrUsers = msumatten;
        NrBS = nsumatten;
```

```
     }
     else{
          NrUsers = nsumatten;
          NrBS = msumatten;
          }

/* Dereference input arguments (Get the pointers to the
     input arguments)                                        */
      Psloc = mxGetPr(prhs[0]);
     sumatten = mxGetPr(prhs[2]);
      tratten = mxGetPr(prhs[3]);
      CIRr = mxGetPr(prhs[4]);
      Pmax = mxGetPr(prhs[5]);
      Ortho = mxGetPr(prhs[6]);

/* Create a matrixe for the return arguments */
      plhs[0] = mxCreateDoubleMatrix(1,NrUsers,mxREAL);
      plhs[1] = mxCreateDoubleMatrix(1,NrUsers,mxREAL);
      plhs[2] = mxCreateDoubleMatrix(1,nBS,mxREAL);

/* Dereference output argument (Get pointer to the output vector) */
      Ps = mxGetPr(plhs[0]);
      CI = mxGetPr(plhs[1]);
      Itot = mxGetPr(plhs[2]);
      Trloc = mxCalloc(NrUsers,sizeof(int));
      Ilocr = mxCalloc(NrUsers,sizeof(double));
      Intot = mxCalloc(NrUsers,sizeof(double));
      Noisevect = mxCalloc(NrUsers,sizeof(double));

/* initialisation
```

```
     Noise - noise floor
     Psinit - initial transmisison power */

     Noise=pow(10,(-13.6));
     Psinit=pow(10,(-13));
    for(i1=0;i1<NrUsers;i1++){
         Ps[i1]=Psloc[i1]*Psinit/tratten[i1];
          Noisevect[i1]=Noise/tratten[i1];
     }

/* assigns to each user the BS that it is connected to */
    for(i1=0;i1<NrBS;i1++)
         for(i2=0;i2<Bstrlen[i1];i2++)
              Trloc[(int)(Bstrloc[i1][i2]-1)]=i1;

/* actual calculation
performed 300 times
or until change of transmitted power (Itot[i2]-Psdif) < 0.001
Itot - the total power (inerfrecne from each BS)
Intot[i] - powr from each BS scaled with the channel
to each user i
Ilocr[i] - from the Intot subrracted the useful signal
and reduction of interference due do orthogonality
CI[i] - CIR for user i
Ps[i] - signal to user i at the BS
*/

    for(i1=0;i1<300;i1++)
    {
         for(i2=0;i2<NrUsers;i2++){
```

```
        Intot[i2] = 0;
    }
    endcondition=0;

/* total power (interference) generated form one BS */
     for(i2=0;i2<NrBS;i2++)
    {
     Psdif=Itot[i2];
     Itot[i2]=0;

         for(i3=0;i3<Bstrlen[i2];i3++)
             Itot[i2]+=
                 Ps[(int)(Bstrloc[i2][i3]-1)]*Psloc[(int)(Bstrloc[i2][i3]-1)];


                 if(((Itot[i2]-Psdif)/Itot[i2])>0.0)     endcondition=1;
         }

/* interference is scaled with the channel response */

    for(i3=0;i3<NrBS;i3++){
        for(i2=0;i2<NrUsers;i2++){
             Intot[i2]+=
                 sumatten[(NrUsers*i3)+i2]*Itot[i3];
         }
     }

/* Ilocr - total interference to each user
CI - Carrier to interference ratio
Ps - new signal power */

     for(i2=0;i2<NrUsers;i2++)
```

```
    {
        Ilocr[i2] = Intot[i2]-Ps[i2]*Psloc[i2]-
            (*Ortho)*Itot[Trloc[i2]]+Noisevect[i2];
        CI[i2] = Ps[i2]/Ilocr[i2];


       if(((CIRr[i2])*Ilocr[i2]) < (*Pmax))
            Ps[i2] = (CIRr[i2])*Ilocr[i2];
        else
            Ps[i2] = *Pmax;
        }


       if(endcondition==0)
            break;

    }
}
```

Appendix B

Simulation of the SIR as function of speed

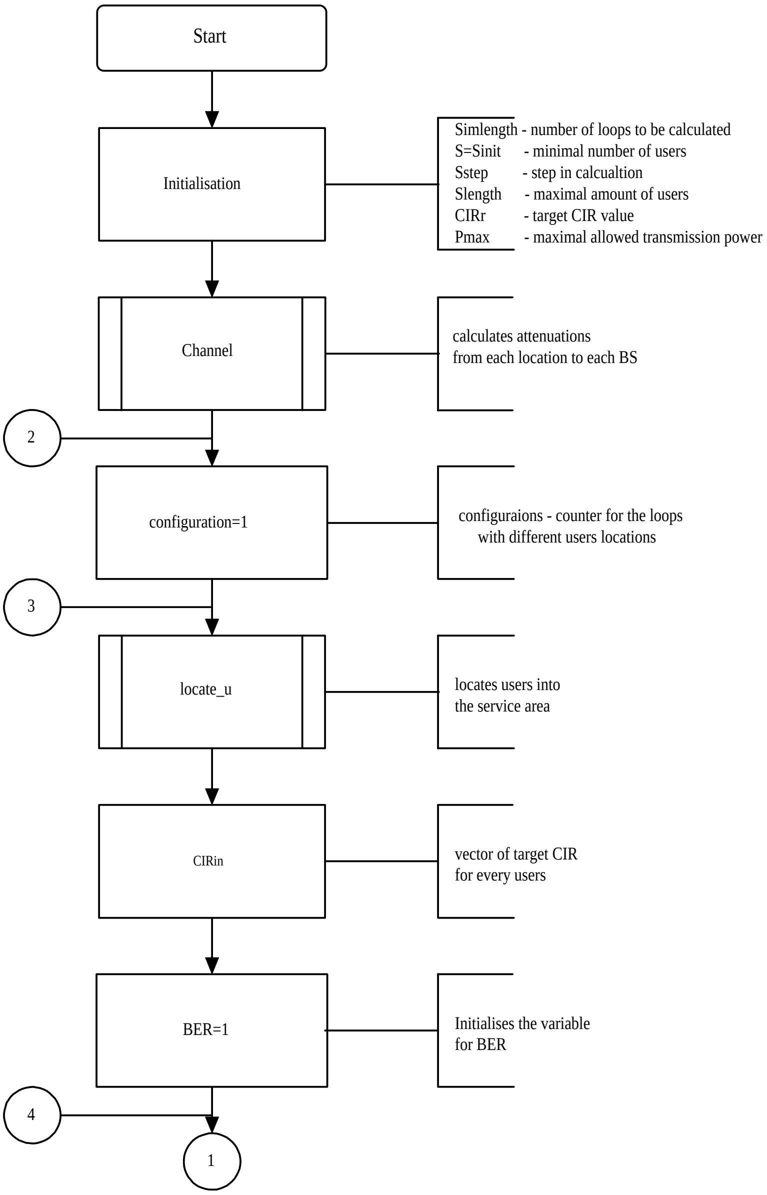

Figure B.1: Flow chart of the simulation program for simulating the value for *target CIR.* Part *1.*

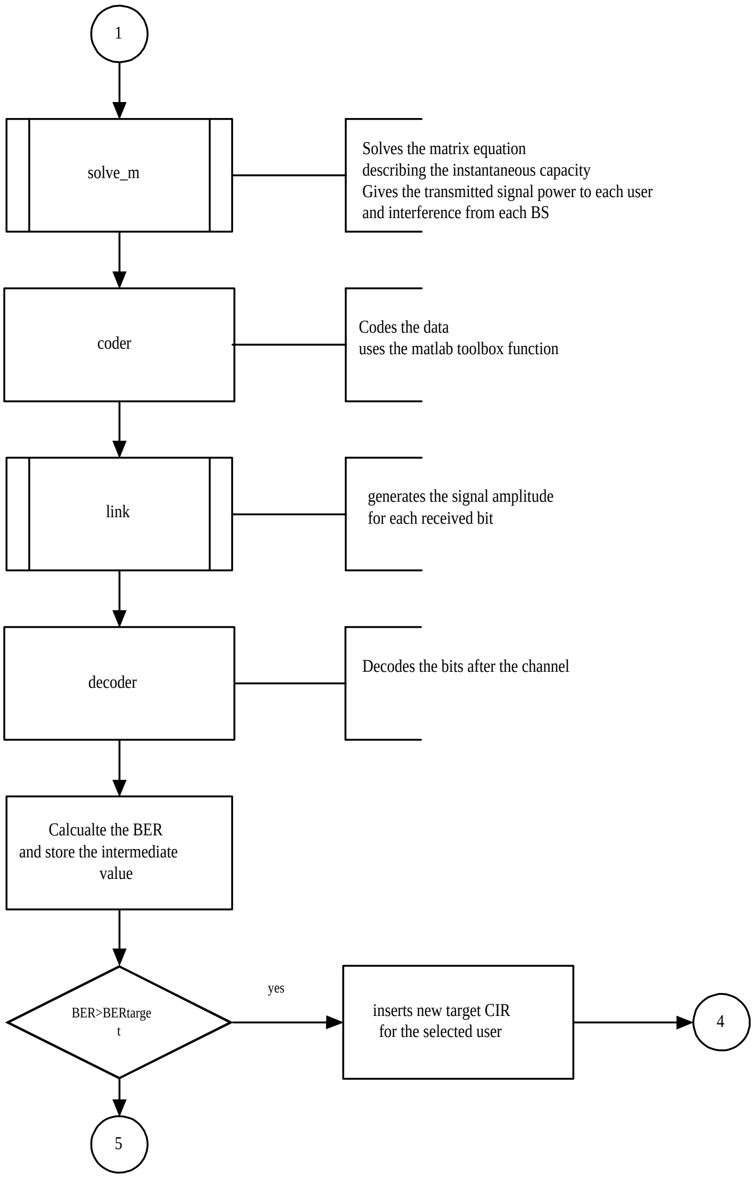

Figure B.2: Flow chart of the simulation program for simulating the value for *target CIR*. Part *2*.

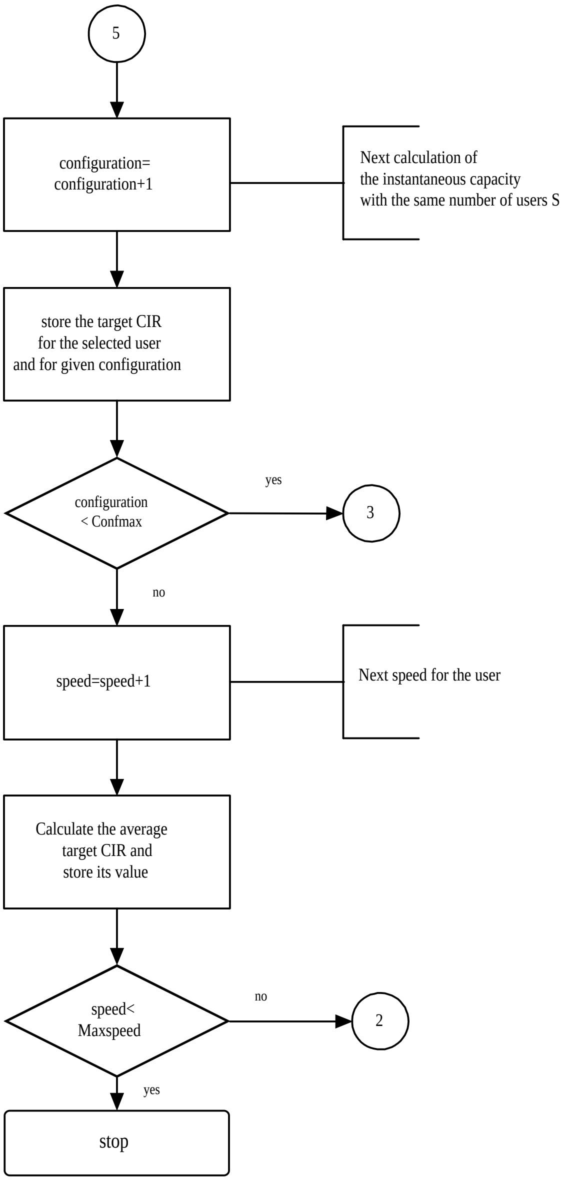

Figure B.3: Flow chart of the simulation program for simulating the value for *target CIR. Part 3.*

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  %
  % targetCIR.m
  % calcualtes the target CIR as function of user speed
  %
  % locates users
  % calcualtes the transmission power to each user
  % based on user speed calcuates the impact of channel
  % if the BER is higher than
  % target BER repeats form beginning
  %
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  %
  % Kalle Ruttik
  % 13.04.1999
  %
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

  clear Itot Intot Ilocr Noisevect Pvect
  clear Psloc Ps
  clear res res2 res3
  clear bits1 bits2 code1
  clear s s1 fingers

  % Initialisation
  M=60;
  times=0;
  datarate=0;
  Bitlen=100000;
```

```
Speedmax=50;
Confmax=100;
endlevel=10^(-3);
BERtarget=10^(-3);
Ortho=0.6
Pmax=100;
CIRr = 10^((5-10*log10(4096/10))/10);
Pmin=1e-13;

Un=1;
mid=4;
Gain=10/4096;

poslen=0:0.00064:0.1;
f=[0.5 0.3 0.2];
fingers=sqrt(f);
nrf=length(f);
tf=[52 66 76];

% Initialisation of the attenuation matrix
[loc,sumatten,tratten,n,m]=channel(1);
for i3=1:1:Speedmax/5
    speedv=i3*5;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% loop detecting the target CIR
%
% 1 calculates the power levels to each user
%
```

```
% CIR calcualtion
% generates a sequence of bits
% codes the bits
% generates the channel response
% decodes the bits
% calculates the error rate
% compares the error rate with the required value (10^-3)
% increase the target CIR value by step repeats from beginning
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% the noise variance after power control
     corr=sum(bessel(0,speedv*pi*2*poslen/0.15).^2);
    sigma=sqrt(f/(2*corr));
    fmean=sqrt((f-2*sigma.^2)/2);
    fingers=fmean;
    sigma1=sqrt(4*sigma.^4+4*(sigma.^2).*(2*(fmean.^2)));

% input bit stream
    [bits1]=randint(Bitlen,1);

    for ir2=1:Confmax
% locate users
         [Psloc,addr,BS]=locate_u(n,m,M,loc,times,datarate);
        locUn=BS(mid).trloc(Un);
        sumaUn=sumatten(locUn,:)*tratten(locUn);
% set CIR target to each user
        CIRin=ones(1,length(Psloc))*CIRr;

        BER=1;
```

```
          ir1=1;
           while BER>BERtarget
% coder
                [code1]=encode(bits1,3,1,'convolution',tf);
                Blen=length(code1);
% signal power to each user based on the matrix equation
                 [Ps,CI,Itot]=solve_m(Psloc,BS,...
                sumatten(addr,:),tratten(addr),CIRin,Pmax,Ortho);


% channel response
                link
                 code2=code1;
                 code1=2*(code1-0.5);
                 code1=samp.*code1+Ires;
                code1=code1>0;
% decoder
                [bits2]=decode(code1,3,1,'convolution',tf,7);
                [n1,BER]=biterr(bits1,bits2);
% endcondition
                CIRin(locUn)=CIRin(locUn)*10^(0.1/10);
% collect data for case ir1
                res1(i3).pb(ir1)=sum(code1~=code2)/Blen;
                res1(i3).pbc(ir1)=r1;
                res1(i3).CIR(ir1)=10*log10(mean(samp)^2/(std(Ires)^2));
                res1(i3).CIRc(ir1)=10*log10(mean(samp)^2/(std(samp+Ires)^2));
                res1(i3).CIRin(ir1)=10*log10(CIRin(locUn)/Gain);

                ir1=ir1+1;
          end
```

```
% collect data for speed case ir2
        res(i3).pb(ir2)=sum(code1~=code2)/Blen;
        res(i3).pbc(ir2)=r1;
        res(i3).CIR(ir2)=10*log10(mean(samp)^2/(std(Ires)^2));
        res(i3).CIRc(ir2)=10*log10(mean(samp)^2/(std(samp+Ires)^2));
        res(i3).CIRin(ir2)=10*log10(CIRin(locUn)/Gain);
    end

% collect data for speed i3
    res2(i3).pb=mean(res(i3).pb);
    res2(i3).pbc=mean(res(i3).pbc);
    res2(i3).CIR=mean(res(i3).CIR);
    res2(i3).CIRc=mean(res(i3).CIRc);
    res2(i3).CIRin=mean(res(i3).CIRin);

    i3

end
```

Appendix C

Configuration of the test networks

In simulations are used two different BS configurations: uniform [figure C.1], and nonuniform [figure C.2].

The function for locating BS and calculating attenuations from each BS to each location in the area is given in appendix A: atten.m. On the figures are given cell coverage as the strongest signal in each location. The bar describes the field strength in dB.

The area size is assumed to be 1000 times 1040 m. In particular figures the law of attenuation is assumed to be 4.

The locations of BS can be find from the figures but are also given in the tables below

BS	x-coordinate	y-coordinate
1	500	173.21
2	200	346.41
3	800	346.41
4	500	519.62
5	200	692.82
6	800	692.82
7	500	866.03

Table C.1: Locations of uniformly located BS.

BS	x-coordinate	y-coordinate
1	500	173.21
2	200	346.41
3	800	346.41
4	400	346.41
5	200	692.82
6	800	692.82
7	500	866.02

Table C.2: Locations of nonuniformly located BS.

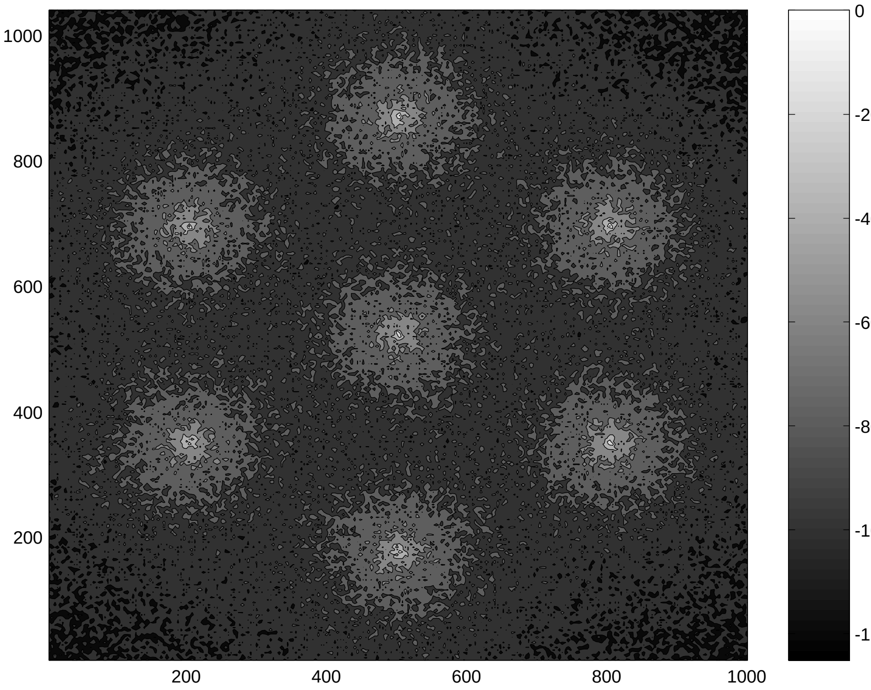

Figure C.1: Attenuations from uniformly distributed BS

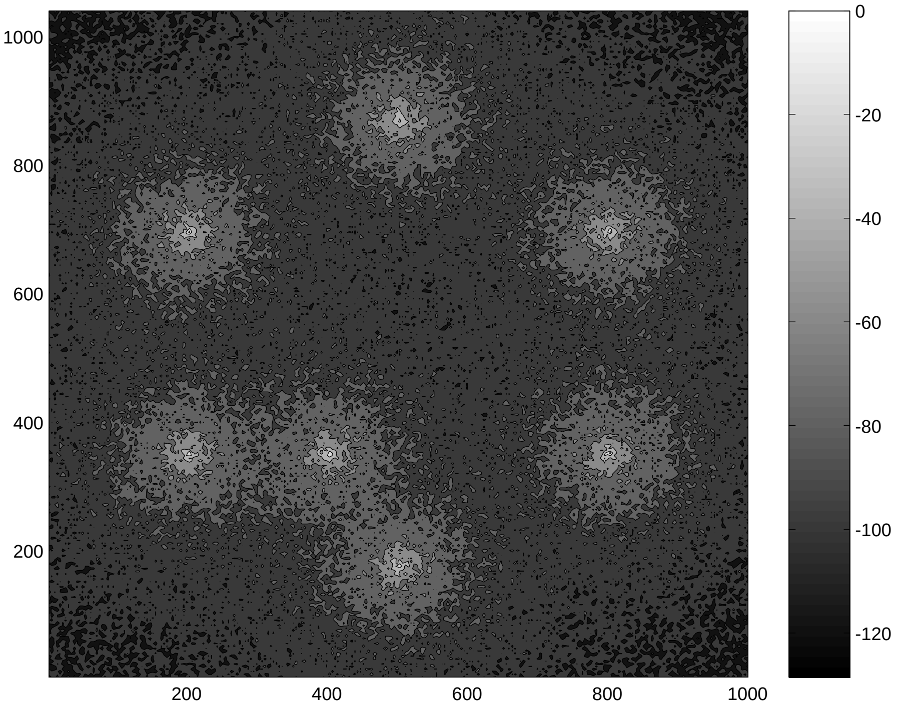

Figure C.2: Attenuations from nonuniformly distributed BS

The nonuniform distribution of users is generted accordingly normal distribution where the mean is in the center of service are and standard deviation is selected to be 70. Matlab script for generating users distribution is given below.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% ulocnou.m
% Generation of the nonuniform users distribution
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Kalle Ruttik
% 16.08.1999
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

std1=70;
y=normpdf(1:250,125,std1);
y1=normpdf(1:260,130,std1);
y=y/sum(y);
y1=y1/sum(y1);
d=(y1’*y);
d=d/max(max(d));

contourf(d)

set(gca,’YTickLabel’,’200|400|600|800|1000’)
set(gca,’XTickLabel’,’200|400|600|800|1000’)

colorbar
```

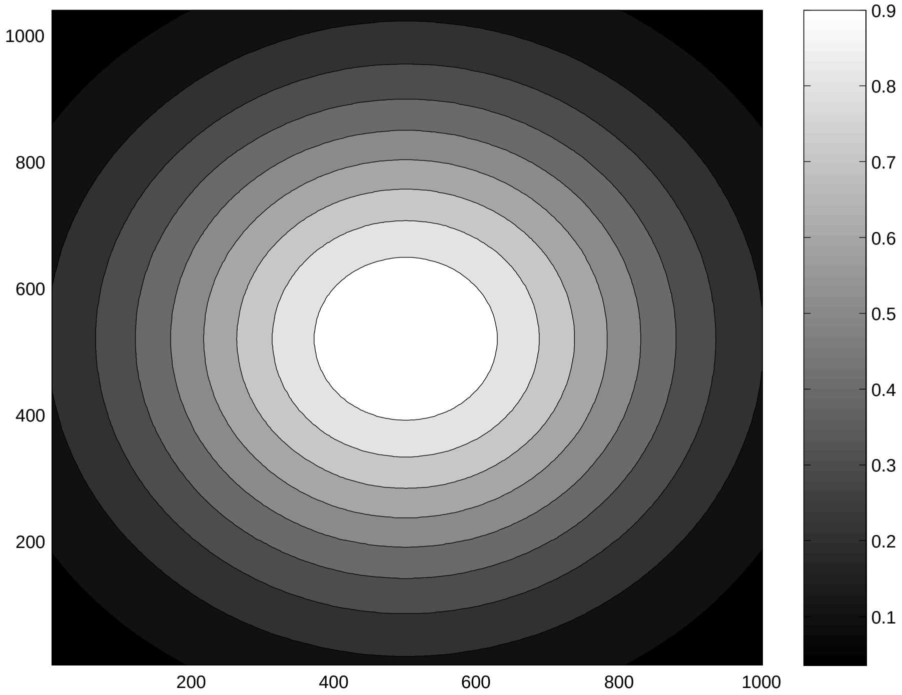

Figure C.3: Noununiform distribution of users in the service area.